

# **Cosmic Evolution Through Uv Spectroscopy**

MISSION CONCEPT STUDY March 4, 2019

**CETUS STUDY TEAM** NASA Goddard Space Flight Center Greenbelt, MD 20771 USA



### Cosmic Evolution Through Uv Spectroscopy (CETUS)

MISSION CONCEPT STUDY Final Report

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#### CECUS Cosmic Evolution Through Ultraviolet Spectroscopy

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#### CECUS Cosmic Evolution Through Ultraviolet Spectroscopy

#### **1 - EXECUTIVE SUMMARY**

We propose that NASA build CETUS, a 1.5-m wide-field UV telescope that will be a worthy successor to Hubble, a companion to multi-wavelength survey telescopes of the 2020's, and a scout for the extremely large ground-based telescopes. With its wide-field camera, multi-object spectro-graph, and high-resolution echelle spectrograph, CE-TUS will not only maintain observational access to the ultraviolet (UV) after Hubble is gone but also provide new and improved capabilities.

These new capabilities of CETUS form a direct match to the Astro2010 panel's recommendation of a more capable UV-optical telescope to follow Hubble (NWNH-PR, p. 298-299) The panel did not identify the capabilities or rank them in priority, but they can be inferred from the Key Scientific Questions that the panel posed (New Worlds New Horizons Panel Reports (NH-PR), p. 247).

We have analyzed these Key Questions and find that nearly half of them, spanning all areas of astrophysics from cosmology to habitable planets, can be addressed by CETUS. **Section 2** takes each Key Question one by one and describes the observations that CETUS will make to address the question. We use the resulting observational scenarios



to identify the Science Drivers leading to Engineering/Performance Requirements for CETUS. **Section 3** then describes how the CETUS instrument is designed to meet those requirements. The mission design is discussed in **Section 4**, and the concept of operations in **Section 5**. Technology status and maturation is discussed in **Section 6**. Organization, partnerships, and status are in **Section 7**. Cost estimation is in **Section 8**, and conclusions are in **Section 9**.

#### 1.1 New kinds of observations by CETUS

"In considering a new facility, we should look not only at how to best provide observational answers to longstanding theoretical questions. Rather, we should also ponder the choice of instruments that will provide novel kinds of observations that could raise new incisive questions".... Harwit (2003)

CETUS will make new kinds of observations (such as those shown in **Table 1-1**), which should not only help answer many of the outstanding Key Questions posed by Astro2010, but are certain to raise new incisive questions.

#### **1.2 Unique Capabilities of CETUS**

CETUS comprises a 1.5-m f/5 telescope and three scientific instruments, all optimized for the UV. The three instruments are: a NUV/FUV camera (CAM), a NUV/FUV/Lyman-UV echelle spectrograph (PSS), and a NUV multi-object slit spectrograph (MOS). The CETUS camera and spectrographs will be familiar to anyone who has observed on one of Hubble's UV instruments (GHRS, STIS, COS,

#### Table 1-1: New Kinds of Observations

| Explore fields of sources as faint as $m_{AB}$ =24.3 or view the cosmic web in Ly $\alpha$ via wide-field (17.4' x 17.4') near-UV (NUV) multi-object spectroscopy (MOS);        |
|---|
| Collaborate with multi-wavelength survey telescopes of the 2020's by contributing wide-field (17.4' x 17.4') NUV and FUV imagery;   |
| Explore the circumgalactic medium of nearby galaxies in phases from cool to hot via Lyman-UV (LUV) (1,000–1,200 Å) / far-UV (FUV) (1,200–1,800 Å) spectroscopy;                 |
| Explore nearby galaxies via long-slit spectroscopy (2"x6') in the FUV; 2.75"x17.4' in the NUV;  |
| Conduct blind surveys with wide-field instruments observing in parallel with the prime instrument making use of a mechanism that enables its own exposure & dithering sequence  |
| Make rapid-response observations of important transients, such as the electromagnetic counterparts to gravitational-wave sources or core-collapse supernovae; slew time <15 min |
| Produce measurements as well as raw & processed observational data archival/distribution system for the astronomical community.   |



| Table  | 1-2: CETUS's three mirror anastigmatic tele- |
|--------|--|
| scope  | images into three UV instruments operating   |
| in the | NUV and FUV.                                 |

| Instrument        | Capability  |  |  |  |  |  |
|-------------------|---|--|--|--|--|--|
| 1.5-m telescope   | Wide field of view accommodating two wide-field                             |  |  |  |  |  |
|                   | science instruments and the echelle spectrograph                            |  |  |  |  |  |
|                   | FUV sensitivity down to 1,000 Å   |  |  |  |  |  |
| NUV multi-object  | Wide field of view: 17.4' x 17.4'   |  |  |  |  |  |
| slit spectrograph | Simultaneous slit spectra of ~100 sources                                   |  |  |  |  |  |
| (MOS) with mi-    | Shutter size: 2.75" x 5.50"   |  |  |  |  |  |
| croshutter array  | Long-slit option: 2.75" x 17.4'   |  |  |  |  |  |
|                   | Wavelength range: 1,800–3,500 Å   |  |  |  |  |  |
|                   | Spectral resolving power: R~1,000   |  |  |  |  |  |
|                   | Limiting sensitivity: $F\lambda = 4x10^{-18} \text{ erg/s/cm}^2/\text{\AA}$ |  |  |  |  |  |
| FUV & NUV         | Field of view: 17.4' x 17.4'  |  |  |  |  |  |
| camera (CAM)      | Wavelength range: 1150–1800 Å; 1,800–3,500 Å                                |  |  |  |  |  |
|                   | Angular resolution: 0.55"; 0.33"  |  |  |  |  |  |
|                   | Sensitivity (1 hour): $m_{AB}=27$ ; $m_{AB}=26$                             |  |  |  |  |  |
| FUV & NUV point   | Field of viw set by slit: 0.2"-2"x360"; 0.2"-2" x 3"                        |  |  |  |  |  |
| slit spectrograph | Wavelength range: 1,000–1800 Å; 1,800–3,500 Å                               |  |  |  |  |  |
| (PSS)             | Spectral Resolving Power (RP): 20,000; 40,000                               |  |  |  |  |  |
|                   | Effective area (cm <sup>2</sup> ): 2000 (max); ~1000                        |  |  |  |  |  |

ACS, and WFC3). However, CETUS instruments have new features that make them more capable than their Hubble counterparts. **Table 1-2** gives a summary description of each instrument. Capabilities in blue font are unique to CETUS.

**Table 1-3** gives a direct comparison of the Hubbleand CETUS science instruments.

The NUV multi-object spectrograph (MOS) on CETUS is a completely new instrument having no

## **Table 1-3:** CETUS will have several advanced capabilities beyond those provided by the Hubble Instruments.

| NUV spectra: like STIS NUV R=40,000 echelle spectra, but has greater |
|--|
| efficiency than STIS which compensates for the smaller telescope     |
| aperture (Kimble & Woodgate, 1997)                                   |

NUV spectra: like STIS NUV imaging spectra, but with a 17.4'-long slit, which is 42 times longer than the STIS 25" slit

FUV spectra: like COS FUV R=20,000 spectra of point sources, but also imaging spectra with 2"x360"-long slit compared to COS 2.5" diameter aperture

FUV spectra: like COS FUV spectra, but with sensitivity in the Lyman-UV down to 1000 Å, whereas COS sensitivity cuts off at 1150 Angstroms

FUV/NUV images: like ACS or STIS FUV/NUV images but with a FOV of 302 sq arcmin, which is 1000 times the ACS/SBC or STIS field of view NUV images: like WFC3 NUV imagery but with a FOV of 302 sq. arcmin,

which is 38 times larger than that of WFC3 FOV of 7.84 sq arcmin.

counterpart on Hubble. The MOS has a micro-shutter array (MSA) placed at the telescope focal plane. The array comprises 380 x 190 shutters, each 100  $\mu$ m x 200  $\mu$ m in size (pitch). Each shutter is individually addressable, so arbitrary configurations of open shutters can be devised.

**Figure 1-1** shows some possible configurations. The open shutters might enclose selected targets; or they may be used in blind searches, e.g. searches for Ly $\alpha$  emitters. In the latter case, the open shutters might be configured as columns perpendicular to the dispersion direction for blind searches. In successive exposures, the columns of open shutters can be moved so as to scan the sky even while the telescope pointing is held steady.



**Figure 1-1:** The CETUS NUV MOS has many uses. As examples, the figure shows: at left, M83 where H II regions (red) are selected targets for MOS spectroscopy. A single exposure would include spectra of the 2175-Å extinction feature, the Mg/Fe ratio of many H II regions as a function of distance from the nucleus. At center:  $R\sim1,000$  spectroscopy of the rest FUV spectra of  $\sim100 \text{ z}\sim1$  galaxies; and at right: schematic discovery spectra of Lyman- $\alpha$  sources at z=0.80 in "Ly $\alpha$  Blobs", star-forming galaxies, or part of the cosmic web. For simplicity, only 3 columns of microshutters are open to the sky (in the red lines). The blue filled circles represent Ly $\alpha$  sources, while the lines represent the stellar continuum.



#### **1.3 Effective Apertures**

Effective aperatures are shown in Figure 1-2 and Figure 1-3.



Figure 1-2: Effective apertures for CETUS NUV Camera, MOS, and Spectrograph compared to STIS.



**Figure 1-3:** (Top) Comparison of CETUS effective area with COS and FUSE. (Bottom) Effective areas of FUV camera filters.

#### 2 - SCIENCE CASE FOR THE CETUS PROBE MISSION

The 2010 Astrophysics Decadal Survey panel (Astro-2010) recommended a "more capable UV-optical telescope to follow the Hubble" (NWNH Panel Reports, p. 296). The CETUS mission concept is a response to that recommendation, promising to provide the means for answering outstanding questions (green font) posed by Astro-2010 as listed in **Table 2-1**.

### 2.1 Science objectives and how they are met by the CETUS Mission

In this section, we describe the application of CETUS to answering key science questions as formulated by Astro2010 panel (NWNH, p. 247). The section titles and quotes in green font are taken from "New Worlds and New Horizons" (NWNH) and "New Worlds and New Horizons -- Panel Reports".

### 2.1.1 Understanding cosmic evolution – galaxies, stars, and planets

#### 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?

### A) Galaxies - Understanding the star-formation history

"A future UV space mission .. will move the subject of galaxy evolution .. to one of integrated measurements of the buildup of dark matter, gas, stars, metals, and structure over cosmic time. [It] will lay the foundation for the ultimate aim of a complete ab initio theory of galaxy formation and evolution." NWNH, p. 7-14

"A Sloan Digital Sky Survey (SDSS)-size spectroscopic survey at  $z \sim 1-3$  would provide essential information about the evolution of galaxy correlations and should provide essential clues to the process of galaxy formation and evolution..." NWNH-PR, p. 97

The era corresponding to  $z \sim 1-2$  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, because:

"[The evolution of the star-formation rate density] says little about the inner workings of galaxies, i.e., their "metabolism" and the basic process of ingestion (gas infall and cooling), digestion (star formation), and excretion (outflows). Ultimately, it also says little about the mapping from dark matter halos to their baryonic components. Its roots are in optical-IR astronomy, statistics, stellar populations, and phenomenology, rather than in the physics of the ISM, self-regulated accretion and star formation, stellar feedback, and SN-driven galactic winds." Madau & 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



| Table 2-1. | CETUS | addresses | nearly h | alfofAS | TRO2010's | Kev    | Scientific O | uestions |
|------------|-------|-----------|----------|---------|-----------|--------|--------------|----------|
| 1abic 2-1. | CLIUD | audicises | nearry n |         | JIK020103 | , ixey | Scientific Q | uestions |

| Cosmology and Fundamental Physics (CFP)   | Galaxies Across Cosmic Time (GCT)   |
|---|---|
| <ul> <li>CFF3 What is uark indiced?</li> <li>Search for missing satellite galaxies predicted by CDM (8214)</li> </ul> | V GCT T HOW GO COSTILL STRUCTURES TOTILI and EVOLVE!<br>Survey of root EUV spectra of z = 0.5, 1.5, aplavias (\$2.11)   |
| Mapping the comic web at z 1 and z 0 in Lyman a (\$21.4)  | Survey of test FOV spectra of $2\sim0.5$ -1.5 yalaxies (32.1.1)<br>Draha of tumon continuum radiation at $z > 1.0$ (52.1.1)   |
| 1921.14) In the cost inclosed at 2~1 and 2~0 in Lyman-a (32.1.4)  | FIDUC OF LYTHATI CONTINUUM FACTOR AND A CONTINUE A |
| Colorfic Noishborbood (CAN)   | FUV/NUV IIIIdyiiiy survey of galdxies at $2 \sim 0.2$ (S2.1.1)  |
|   | Ly <b>C</b> spectroscopic survey at 2~0.5-1.1 (§2.1.4)  |
| GAN T What are the flows of matter and energy in the circumga-  | $\checkmark$ GCT 2 How do baryons cycle in and out of galaxies, what do they  |
| lactic medium?  | do while they are there?  |
| Lyman–UV (LUV)/FUV spectroscopy of the CGM backlit by QSO (§2.1.2)  | Rest FUV spectroscopy of z~1 galaxies/ISM/CGM (§2.1.1)  |
| Ly $lpha$ imaging survey of the low-z universe (§2.1.4)   | $\checkmark$ GCT 3 How do black holes grow, radiate, and influence their  |
| ✓GAN 2 What controls the mass-energy-chemical cycles within   | surroundings?   |
| galaxies?   | FUV/NUV spectroscopic monitor of tidal disruption events (§2.1.3)   |
| LUV/FUV spectroscopy of low-z starburst galaxies (§2.1.2)   | LUV/FUV spectroscopy of z~1-2 galaxies (§2.1.3)   |
| LUV/FUV imaging spectroscopy of galaxy & their outskirts (§2.1.2)   |   |
| LUV/FUV spectroscopy of Quasar/AGN winds (§2.1.2)   | Stars and Stellar Evolution (SSE)   |
| FUV/NUV photometric light curves of the aftermath of neutron-star   | ✓ SSE 3 How do the lives of massive stars end?  |
| mergers (§2.1.3)  | FUV UV light curves of core-collapse supernovae (§2.1.3)  |
| IV imaging spectroscopic survey of IV dust halos (§2.1.2)   | · · · · · · · · · · · · · · · · · · ·   |
| $\sqrt{GAN}$ 3 What is the fossil record of galaxy assembly from the first  | Planetary Systems and Star Formation (PSF)  |
| stars to present?   | $\checkmark$ PSE 4 Do babitable worlds exist around other stars?  |
| NIIV spectroscopy of extremely metal-poor stars (\$2.1.1)   | FILV/NILV spectroscopy of flares of M-type stars (\$2.11)   |
| אסי שבכמשבטאי שרכאווכוווכוי וווכנמר-אסטו שנמש (שב.ו.ו)  | TO WING & Specifoscopy of hares of Millippe stars (32.1.1)  |

feedback. NUV spectra of  $z\sim1$  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.

As recommended by Madau & Dickenson (2014), CETUS will study the physics of the ISM, self-regulated accretion and star formation, stellar and black-hole feedback, and supernovae and blackhole 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 Very Large Telescope MOONS,



**Figure 2-1:** The Keck/LRIS far-UV spectrum of MS 1512-cB58 (top panel) obtained and analyzed by Pettini et al. (2000) provides an excellent test case for simulations of CETUS/MOS rest far-UV spectra (middle and lower panels). The simulations assume a S/ N=10 per resolution element.



and possibly other ground-based observatories to obtain a full picture of the properties of  $z\sim1$  galaxies.

To emphasize the power of far-UV spectral diagnostics, **Figure 2-1** (top panel) shows the Keck/ LRIS rest far-UV spectrum of the z=2.7 galaxy, MS 1512-cB58 analyzed by Pettini et al. (2000). This single, rest far-UV spectrum yielded: a high rate of star formation, SFR~40 M<sub>☉</sub>/yr but an even higher rate of mass-loss, M~60 M<sub>☉</sub>/yr, through a galactic wind having velocity~ 200 km/s, protracted star formation (as opposed to an instantaneous burst), an initial mass function (IMF) consistent with Salpeter IMF with an upper stellar mass limit, M<sub>u</sub>>50 M<sub>☉</sub>, a metallicity, Z~1/4 Z<sub>☉</sub> (both stars & gas), a column density in H I, N<sub>HI</sub>=7.5x1020 cm<sup>-2</sup>, and reddening by dust, E(B-V)~0.1-0.3.

#### B) 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". We still have only small samples of galaxies with detected Lyman continuum escaping and no clear understanding how/why these galaxies are "leaky". For current state-of-the-art in observations, see papers presented at the conference, "Escape of Lyman Radiation from Galactic Labyrinths", and recent papers by Gazagnes et al. (2018), Izotov et al. (2018a,b), and Steidel et al. (2018).

With CETUS near-UV MOS spectra covering 1,800-3,500 Å, one could in principle gather a large sample of galaxies at redshifts just above 1 where Lyman continuum detections or limits could be compared to properties of the galaxies such as stellar mass ( $M_{\star}$ ), star-formation rate (SFR), SFR/area, outflow speeds, Lyman- $\alpha$  equivalent widths and profile shapes, and (using archival spectra from Subaru Prime Focus Spectrograph or ESO's VLT MOONS spectrograph) O/H and nebular emission-line properties.

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 Very Large Telescope MOONS, and possibly other ground-based observatories to obtain a full picture of the properties of z~1 galaxies.



**Figure 2-2:** Program galaxies at z=0.8–1.3 span a wide range in stellar mass and angular size.

CETUS program galaxies are defined as z=0.8-1.3 galaxies and have NUV fluxes  $\geq 4x10^{-18}$  erg/s/ cm<sup>2</sup>/Å.

As shown in **Figure 2-2**, CETUS program galaxies span a wide range in stellar mass and apparent size, with the more massive galaxies generally being larger. The median log stellar mass,  $M_{\star}$ = 9.6, and the median half-light diameter is 0.88". The size of a microshutter appears to be ideal for this program, as it should transmit most of the light from a galaxy, but be small enough to block unwanted background.

Of particular interest are the more massive galaxies, which might show signs of quenching and/ or presence of a massive nuclear black hole: 20% of the targets are more massive than log  $M_{\star} = 10.0$ , and 5% more massive than 10.5.

Simulations indicate that in a 10-hr exposure, the CETUS MOS can obtain S/N~10 R~1000 spectra of galaxies having NUV fluxes  $\geq 4x10^{-18}$  erg/s/cm<sup>2</sup>/Å or equivalently, m<sub>AB</sub>(NUV) $\leq$ 24.3. This sensitivity to faint sources is made possible by a microshutter array (MSA) in the MOS, which blocks astronomical background like zodiacal light and eliminates confusion of spectra from nearby sources.

Catalogs of the COSMOS field (Jouvel et al. 2009, 2011, Laigle et al. 2016) indicate that the surface density of  $m_{AB}(NUV) \le 24.3$  at z=0.8-1.3 is high enough that there should be ~100 such galaxies in the MOS field of view (**Figure 2-3**). However, the filling factor of the MSA is conservatively estimated at ~74%, so we can expect useful spectra of 74 galaxies or fewer. Nevertheless, such massive multiplexing amply justifies long exposures (10+ hr) needed to obtain adequate S/N. **Figure 2-3** shows a schematic of a NUV MOS spectrogram of galaxies at the center of the COSMOS field as imaged by the GALEX UV telescope. The galaxies circled in red are z=0.8-1.3 galaxies with NUV fluxes stronger than  $4x10^{-18}$  erg/s/cm<sup>2</sup>/A as measured by GALEX.





**Figure 2-3:** Simulations indicate that the field of view of a single JWST-size microshutter array (17.4' x 17.4') is sufficient to contain ~100 galaxies for CETUS MOS observations.

The CETUS MOS can obtain S/N=10 rest-FUV spectra of galaxies as faint as  $m_{AB}(NUV)=24.3$  with a S/N and resolution sufficient for quantitative analysis. The simulation shown in **Figure 2-1** is based on the Keck/LRIS spectrum of MS1512cB58 (top panel) analyzed by Pettini et al. (2000). The middle and bottom panels show the CETUS spectrum of cB58 for the case of an unresolved galaxy (middle) and a galaxy with a half-light diameter of 0.9" (bottom). They show how the breadth of spectral features increases with the apparent size of the galaxy. In either case, much information about the stellar population and stellar winds, the interstellar medium, and even the Lyman-forest is largely retained in the CETUS spectrum.

Concurrent imagery of a field by the CETUS camera also contributes to the total yield. As the CE-TUS MOS works its way through a deep field like the COSMOS field, the CETUS camera will obtain FUV and NUV images of the field in parallel. The images will be offset by ~0.8 degrees from the MOS spectrograms. The camera has the same wide field of view (17.4' x 17.4') as the MOS. Although the MOS sets the pointing and total time on target, the camera operating in parallel has full control of the imagery: it will have its own exposure sequence and its own dithering schemes. Hence, it will obtain FUV images as well as NUV images. For example, it may conduct a search for Ly $\alpha$  emission in galaxies as the ACS camera has done for single galaxies (Section 2.1.4).

The images that CETUS obtains will reach far deeper fluxes than those obtained by GALEX images due to CETUS' greater light-gathering power (1.5-m aperture vs. 0.5-m GALEX aperture), and they will have at least 10 times finer spatial resolution (0.55" in FUV; 0.33" in NUV vs. ~5-6" for GALEX).



**Figure 2-4:** A combination of CETUS UV images with X-ray images give a more complete picture of physical properties of galaxies. (Image credit: S. Immler)

The combination of CETUS images with those from X-ray telescopes will be especially fruitful. As shown in **Figure 2-4**, comparison of CETUS UV images with those 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. The CETUS camera has the same field of view as that of the Swift UVOT telescope but will have finer resolution and significantly greater sensitivity. Also, the CETUS camera will operate in the FUV as well as the NUV whereas Swift UVOT observes in the NUV and optical.

Similarly, combining CETUS UV images with longer-wavelength data from telescopes like LSST, Subaru HSC, WFIRST, and radio telescopes will also be fruitful. Consider the following example involving GALEX (UV), SDSS (optical) and the VLA (21-cm). An example is shown in **Figure 2-5**.

#### C) The First Stars

#### GAN3 What is the fossil record of galaxy assembly from the first stars to the present?

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 ( $[Fe/H] \le 3.5$ ). About 80 such stars are known today, and hundreds more are expected to be found among



**Figure 2-5:** Combination of CETUS FUV and/or NUV images with those from optical telescopes (Subaru HSC, LSST, WFIRST, etc.) and radio (e.g. SKA) will bring big surprises and useful insights. Figure reproduced from *https://www.jpl.nasa.gov/news/news.php?feature=6566*. (Image credits: NASA/JPL/Caltech/SDSS/NRAO/L. Hagen and M. Seibert)

ongoing and future surveys (e.g., LAMOST, Sky-Mapper, Pristine, 4MOST, WEAVE, LSST).

Only a few tens of absorption lines are commonly found in the optical and near-IR ( $\lambda > 310.0$  nm) spectra of these stars, so only ~5-10 elements are regularly detected. (See **Figure 2-6**) 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.

With the Hubble Space Telescope (HST), however, we are limited to studying 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.



Figure 2-6: Improvement in metal detections in the most metal-poor stars is enabled by UV spectra. Typically ~8-10 elements can be detected in the optical alone, but UV spectra can enable the detection of  $\sim 20$ elements, probing supernova physics (carbon through zinc,  $6 \le Z \le 30$ ) and Big Bang nucleosynthesis, stellar evolution, and spallation reactions (lithium, beryllium, and boron,  $3 \le Z \le 5$ ). (Figure credit: Ian Roederer)





**Figure 2-7:** The brightest metal-poor stars. Data collected from the JINAbase abundance database (Abohalima & Frebel 2018, ApJS, 238, 36).

2016). Many of the most metal-poor (or iron poor) stars are too faint for HST, as shown in **Figure 2-7**.

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, which would begin to reveal the true diversity of the first stars and first 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 would enable long, *uninterrupted* exposures of these fainter stars for the first time. This would revolutionize our understanding of the first stars, the first supernovae, and the first metals in the Universe.

### D) Planets - Effect of stellar flares on the habitability of exoplanets

#### PSF 4. Do habitable worlds exist around other stars?

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 habitable zone is where the planetary surface temperature is such that liquid water may be sustained for some portion of the "year". The effective surface temperature alone, however, is insufficient to establish habitability or to accurately 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 (Figure 2-8), 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 exo-planets. Spectral features of O<sub>2</sub>, O<sub>3</sub>, CH<sub>4</sub>, and CO2, 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<sub>2</sub>O, CH<sub>4</sub>, and CO<sub>2</sub> 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.



**Figure 2-8:** FUV lightcurves of the "optically inactive" M dwarf GJ 876 (10-s cadence; Loyd et al. 2018), illustrating a flare event in FUV emission lines on 5-minute timescales.



CETUS UV observations will also inform us on abiotic processes affecting the atmospheric chemistry of planets orbiting M-type stars. Photolysis (photodissociation) of  $CO_2$  and  $H_2O$  by Ly $\alpha$  and other bright stellar chromospheric and transition region emission lines (e.g., O VI λ1032Å, C II λ1335Å and C IV  $\lambda$ 1550Å) can produce a buildup of O<sub>2</sub> on planet atmospheres illuminated by strong FUV radiation fields (Tian et al. 2014). Once a substantial  $O_2$  atmosphere is present,  $O_3$  is primarily created through a multi-step reaction, and O<sub>3</sub> photolysis is then driven by NUV and B-band optical photons (Domagal-Goldman et al. 2015; Loyd et al. 2016). Hence, a substantial  $O_3$  atmosphere may arise via photochemical processes alone on planets orbiting stars with strong LUV+FUV and weak NUV flux, i.e., M dwarfs (e.g. Segura et al. 2010). CETUS will provide the essential stellar context for biomarker searches with JWST and TMTs.

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

Much of CETUS research is directed toward the Galactic neighborhood, and for good reason: CETUS can study nearby galaxies and surrounding gas and dust in detail. For the CETUS 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. For this research, 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). As 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. Such galaxies provide excellent test cases for understanding what the local universe consists of, how it works, and how it got that way.

#### A) Galaxies and their outskirts

### GAN 2: What controls the mass-energy-chemical cycles within galaxies?

#### 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 inter-galactic 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.

As an example, we consider the prototypical starburst galaxy M82 and its famous wind. At a distance of only 3.6 Mpc, 1" subtends ~17 pc at the galaxy. The galaxy is seen nearly edge-on, while above and below the galactic plane, the outflow is traced by a filamentary structure of dust, gas, and X-ray emission. **Figure 2-9** shows a composite of Hα and X-ray emission of M82 (Lehnert, Heckman, & Weaver 1999). Note that the surface brightness of the H $\alpha$  and X-ray emission depends on the line-of-sight integral of the square of the gas density, while the surface brightness of resonantly scattered UV line emission depends on the integral of the density. Thus, these UV lines are better probes of the less dense gas known to dominate the outflow energetics, and they can be directly connected to the gas seen in absorption.

The figure also shows the CETUS 6'-long slit poised to sample the UV spectrum of the galaxy and its ejecta in the G120M mode as it is moved pushbroom style across M82 parallel to the galaxy disk. G120M spectra span the wavelength range from 1000 Å to 1350 Å, including O VI 1032Å, 1038Å, Si III 1206.5Å, N V 1238Å, 1242Å, Si II 1260Å, O I 1302Å, and C II 1334.5Å. The G150M mode covers the longer wavelengths. Although the CETUS optics produce a spectral resolving power,  $\lambda/\Delta\lambda=R\sim20,000$ ,



**Figure 2-9:** H $\alpha$  image and X-ray contours of M82 with the CETUS long-slit that will scan the gas and dust in M82 filaments.



the long slit is 2" wide (TBR) so that for extended sources, the resolving power is reduced to R=2,000. This resolving power is well-matched to the line widths measured in H $\alpha$  (a few hundred km/s).

The low redshift of M 82 precludes observations of Ly $\alpha$ , because it lies in the damping wings of the Milky Way absorption-line. However, there are many other bright starburst winds in galaxies at redshifts that provide access to Ly $\alpha$  (e.g. NGC 1482, NGC 3079, NGC 6240, and Arp 220). While these more distant systems have smaller angular sizes than the M82 wind, we expect Ly $\alpha$  emission to be detectable to larger radii than the metal lines due to its greater relative brightness.

#### **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 blueshifted (1000 km/s) Lya emission has been detected in most ultra-luminous infrared galaxies (ULIRGs), often accompanied by blueshifted 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 Ly $\alpha$  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 enable us to study with unprecedented statistics 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). The excellent spectral resolution (~15 km/s) of the FUV spectra will enable us to distinguish between quasar-driven outflows, starburst-driven winds, and tidal debris around mergers. CETUS spectra covering 1000-1800 Å will also provide new constraints on the critically important warm-hot gas phase associated with the cooling shocked ISM predicted in some quasar feedback models. Perhaps more importantly, the excellent sensitivity of CETUS down to ~1000Å will make it possible to explore, for the first time, the molecular gas phase of quasar-driven winds. These data will provide a crucial test of some quasar wind models where the outflowing cold molecular material is proposed to condense out of the shocked ISM.

There are 56 z<0.16 AGN in the Milliquas Catalog (2018) whose line of sight pierces the CGM of a foreground galaxy. CETUS can easily obtain the full FUV spectrum of such a close AGN (100-180 nm) and the absorption spectrum of the CGM of the foreground galaxy in one exposure. And in its long-slit mode, the CETUS FUV spectrograph can obtain the FUV spectrum of the foreground galaxy's cross-section.

#### **UV Dust Halos**

A significant fraction of dust in the Universe resides in the circumgalactic medium (Menard 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 (Menard et al. 2010).

Almost all UV halos discovered so far have been found in moderately deep exposures in the GALEX archive where the sky coverage and large PSF ( $\sim$ 5") limits individual detections to about 30 nearby galaxies. However, stacked GALEX images of galaxies within 100 Mpc indicate that UV halos are ubiquitous and would easily be detected around most inclined, star-forming galaxies by any sensitive UV camera with a resolution better than 1" and a moderate field of view (at least 15'x15'). This makes CETUS the premier instrument to conduct the first true survey of extragalactic dust, which it can do with a modest investment of exposure time.

CETUS is also the only instrument capable of obtaining UV spectra of the gas and dust in these halos. As shown in **Figure 2-10**, CETUS has a spectrograph with long slits capable of obtaining imag-





Figure 2-10: CETUS can obtain imaging spectra of gas and dust in halos of galaxies such as NGC 3079.

ing spectra in the FUV along a slit 6' long, and in the NUV, along a slit 17.4' long. The FUV spectrum will yield information about the state of the gas through spectral lines of Ly $\alpha$  and metals, while the NUV spectrum yield important information about dust e.g. the 2175Å extinction feature (if it has one) and gas through absorption lines of Mg and Fe.

Notional observing programs for CETUS include long-slit FUV spectra to explore the intracluster gas in nearby galaxy clusters such as the Virgo, Coma, and Perseus clusters.

### GAN 1: What are the flows of matter and energy in the circumgalactic medium?

The Warm-Hot Circumgalactic Medium (CGM): The circumgalactic medium (CGM) comprises 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-redshift 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 is out of reach of Hubble's 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 of the CGM to the host galaxy.

CETUS FUV spectroscopic observations will greatly improve our knowledge about the CGM, its interplay with the host galaxy, and the missing baryon problem in three ways:

- Access to the WHIM surrounding nearby galax-1. ies. The CETUS Lyman-UV/FUV spectrograph is sensitive down to 1000 Å, so it can reach the O VI 1032, 1038 doublet arising in the WHIM of nearby galaxies including dwarf galaxies. As COS is restricted to galaxies at z>0.16, it cannot study the CGM of the large population of faint galaxies, and its sample is biased toward massive galaxies. Using Bowen's (2018) QSO-Galaxy Pairs Catalog, we find that CETUS can obtain full LUV/FUV spectra (1,000-1,800 A) of the CGM surrounding over 400 nearby galaxies backlit by a QSO or AGN (Figure 2-11). The FUV spectra include diagnostics of the cool medium from low-ionization metal lines (e.g. Si II, C II lines), the warm medium (e.g. C IV), warm-hot medium (O VI 1032, 1038), and the hot medium, if present ([FeXXI]  $\lambda$ 1354).
- 2. Access to UV spectrum of the host galaxy. What CGM spectra don't yield is information about the galaxies themselves. In fact, we usually know more about the CGM than we do about its host galaxy. This is a great loss, because understanding galaxy evolution depends on knowing how the CGM influences the properties of the host galaxy, and vice versa. CETUS will help us understand the evolutionary connection between a galaxy and its halo (CGM). With a resolution of only tens to a few hundred parsecs in nearby galaxies but a field of view covering the whole galaxy, the CETUS FUV Camera will



**Figure 2-11:** CETUS will observe the WHIM of nearby galaxies that is out of Hubble's reach. (Figure adapted from N. Lehner)

study the microphysics of nearby galaxies (Figures 2-12 and 2-13). About 400 of these galaxies are bright enough for direct spectroscopy with CETUS (after binning). The CETUS FUV spectrograph can obtain a FUV imaging spectra of the cross-section of galaxies in the CETUS sample as shown in Figure 2-14.

3. Reliable Line Spread Function. Measurements of the strength of spectral lines appearing in a Hubble/COS spectrum are vulnerable to systematic errors due to what is formally called "mid-frequency wavefront errors" or "zonal errors" of Hubble's primary mirror (COS Instrument Handbook). Measurements of the COS line-spread function indicate that ~40% of the total strength of a FUV spectral line is hidden in the broad, low-level wings of the line spread function (LSF) as shown in Figure 2-15. This is a particularly insidious problem for measurements of absorption lines like the O VI doublet as the spurious low-level wings of the spectral



Figure 2-12: Most known galaxies less luminous than  $m_{AB}=18$  are nearby so access to the Lyman-UV is essential.



**Figure 2-13:** CETUS images have the field of view and resolution for studying the microphysics of nearby galaxies.



lines cannot be distinguished from the continuum flux. Since the O VI doublet is the only spectral diagnostic of the warm-hot medium, and since the warm-hot CGM may be the dominant component of the nearby universe, this is a vexing problem. A systematic 40% loss in line strength is on the order of the uncertainty in the "missing-baryon" problem, so it is essential that the CETUS primary mirror have better image quality than that on Hubble. Fortunately, as described in **Section 3.3.1**, modern mirror-polishing techniques in industry have greatly improved over what was available at the time for Hubble, so we can expect to obtain reliable measurements of spectral lines in CETUS spectra.

#### The Hot Circumgalactic Medium.

In 2018, Anderson and Sunyaev discovered [Fe XXI]  $\lambda$ 1354-emission in a filament of M87 (**Figure 2-16**). This emission line is indicative of a 1 keV



Figure 2-14: CETUS long-slit (turquoise) imaging spectra can cover nearly all galaxies.



**Figure 2-15:** Spectral lines in CETUS spectra will have Gaussian profiles leading to accurate measurements of line strengths.





**Figure 2-16:** CETUS will study the hot circumgalactic medium through observation of [Fe XXI]  $\lambda$ 1354 (left). CETUS long-slit imaging spectra will show how the [Fe XXI] line behaves as a function of location (right).

(T~10<sup>7</sup> K) plasma. The discovery suggests that CE-TUS may be used to study not only gas in the warmhot phase (the 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 (**Figure 2-17**), Virgo, or the Coma cluster utilizing the spectrograph's long slit to obtain imaging spectra over 6' to map the [Fe XXI]  $\lambda$ 1354 A line emission arising in the warm-hot or hot medium.

The FUV point/slit spectrograph will obtain imaging spectra over a range of 6' in nearby clusters of galaxies such as the Perseus Cluster (**Figure 2-17**). The image shown here was obtained by the Swift X-ray Telescope, and the image size is 17.4' x 17.4', the field of view of the CETUS camera.

This program on the CGM and intracluster gas can only be carried out by CETUS. No other current or planned telescope has access to Lyman-UV/FUV or has a long-slit option to obtain imaging spectra.



**Figure 2-17:** With LUV/FUV imaging spectra, CETUS will explore the warm and hot intracluster medium of galaxy clusters like the Perseus cluster shown here. Image credit: Swift X-ray telescope.

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 can cool 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 continue and extend observations by COS to understand the properties of winds from supermassive black holes (Section 2.1.2); and (2) Comparison of the properties of the CGM and host galaxy will show how the feedback affects the CGM. For example, understanding the ionic phase and temperatures of the gas around star-forming versus quiescent galaxies could tell us about whether the feedback is heating gas or whether it is pushing gas away (thermal vs kinetic).

#### 2.1.3 Understanding Transient Events

#### A) Direct Observations of Electromagnetic Counterparts of Gravitational Wave Events

### GCT 3 How do black holes grow, radiate, and influence their surroundings?

#### Astro2010 Area of Unusual Discovery Potential: Gravitational Wave Astronomy

The joint discovery of gravitational waves (GWs) and electromagnetic (EM) radiation from the binary neutron star (BNS) merger GW170817 was a water-



shed moment for astrophysics (Abbott et al. 2017). The scientific bounty resulting from this single cosmic collision was truly phenomenal: 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, it is possible to measure the Hubble constant 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 UV/blue and and red/IR light curves suggest two distinct components of ejecta (Metzger 2017, Kasen et al. 2017). Indeed, the origin of the UV component remains hotly debated (Arcavi 2018). If due to the radioactive decay of heavy elements (a so-called lanthanide-free blue kilonova), this would have important implications for the relative abundances of r-process material generated in these systems (i.e., first vs. second vs. third r-process peaks). Alternatively, if powered by the cooling of shock-heated material around the merger, this would indicate the presence of a wide-angle outflow. In any case, the observed and predicted peak of the UV light curve only a few hours after the merger puts strong pressure on CETUS to have a rapid-response capability.

Therefore, we have made several changes to the CETUS mission design in order to speed up the response to transients like the GW 170817-like object (or core-collapse supernovae) including:

- Keeping CETUS always on standby, ready to receive an alert from the ground;
- Enlarging the field of regard (FoR) to cover the full hemisphere away from the sun in order to increase the chances that an important transient can be observed;
- Enabling CETUS to slew to any source in the hemisphere opposite the sun within 15 minutes.

These changes are discussed in **Sections 4.1** and **4.3**. We have not carried out a detailed study of the ground system necessary to identify the transient and transmit an alert to CETUS. We postpone this study to a later period, although we note that the Probe concept, TAP, has done such a study.

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. By 2021, LIGO is expected to detect on the order of a BNS merger each month. The accumulation of X-ray-UV-optical-near-IR observations should enable us to explore the diversity of kilonovae, and to develop "pictures" of the aftermath of BNS mergers from different aspect angles, and to put *more precise constraints on the total ejecta mass and composition, a critical factor to ascertain the contribution of these sources to the formation of heavy elements.* 

#### B) Witnessing tidal disruption events

### GCT 3: How do black holes grow, radiate, and influence their surroundings

### Area of Unusual Discovery Potential: Time-Domain Astronomy

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 shown in **Figure 2-18**, a star comes close to an inactive black hole and 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



**Figure 2-18:** Schematic of a tidal disruption event (TDE). CETUS will monitor the FUV spectra of TDE's to faint magnitudes. (Image credit: M. Weiss, CXO)



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 CE-TUS FUV spectrograph to follow and to derive the physical processes involved.

### C) Identifying the Progenitors of Core Collapse Supernovae

#### SSE 3: How do the lives of massive stars end?

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. As shown in **Figure 2-19**, 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 is designed to respond rapidly to reports of a nascent supernovae and can follow the FUV light curve down to an apparent magnitude,  $m_{AB} \sim 27$ .



**Figure 2-19:** CETUS will infer the progenitors of core-collapse supernovae from their FUV light curves. (Image credit: Nakar & Sari, 2010)

#### 2.1.4 Surveys

**CFP 3 What is dark matter?** 

#### GCT 1 How do cosmic structures form and evolve?

#### A) 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. Is the problem that we have not looked hard enough for these dwarf galaxies? To settle the problem, the LUVOIR team suggests a search for dwarf galaxies in the V and R passbands around Milky Way analogues like NGC 3810 (Figure 2-20 Right) using a tiling strategy involving 156 telescope pointings and requiring an observing time of 98 hr. CETUS will make a complementary search for dwarf galaxies in NUV and FUV passbands efficiently and effectively. With its wide field, CETUS will more than cover the LUVOIR search region in 9 telescope pointings (Figure 2-20 Left). The CETUS camera is particularly sensitive to faint, extended objects, because the FUV sky is effectively black, and CETUS' f/5 optics are 23 times more sensitive to faint, diffuse objects than is LUVOIR (f/24).

The Ly $\alpha$  Sky at Low Redshift: H I Lyman-a 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) have found that Ly $\alpha$ -emitters (LAE's) were plentiful at high redshifts, z~3-6. Now, the question is: How has the Ly $\alpha$  sky evolved? CETUS will enable us to answer this question through both imaging and spectroscopy at low redshifts and at z~1, thereby completing the picture of the evolution of Ly $\alpha$  emission.



**Figure 2-20:** CETUS will obtain deep UV images of NGC 3810 and its surroundings in only 9 pointings – much deeper than the shallow image obtained by GALEX shown here (L). To cover the same search area covered by LUVOIR will require 156 pointings (R).





The CETUS FUV camera has 5 long-pass filters (**Figure 2-21**) identical to those in Hubble's Advanced Camera for Surveys (ACS). Two adjacent filters can be used to isolate and study Ly $\alpha$  emission. For example, the f125lp filter, which has a sharp short-wavelength cutoff at 1250 Å, would transmit Ly $\alpha$  emission at z>0.04, whereas the f140lp filter would not. Careful subtraction of the two images then reveals a map of Ly $\alpha$  emitting nebulae in the redshift range, z~0.04-0.15. By the same reasoning, a map of an O VI-emitting galaxy halo at z=0.23-29 can be derived.

This subtraction technique has been applied to ACS images to study selected galaxies called the Lyman Alpha Reference Sample (Hayes et al. 2014, Östlin et al. 2014), and CETUS observers will use this technique too. The difference is that the ACS field of view (34.6" x 30.8") is too small to observe more than one galaxy at a time, whereas the CETUS camera field of view (17.4'x17.4') is over a thousand times larger. The CETUS camera is truly a tool of discovery, and the discovery images can be followed up by spectra with the CETUS FUV point/slit spectrograph (PSS) or the NUV MOS.

The CETUS NUV MOS provides the means to explore the Ly $\alpha$  sky at z~0.5-1.1 by operation of the microshutter array (MSA). A column of microshutters in the MSA in the MOS can be opened to serve as a long slit having dimensions of 2.75"x17.4' giving a sky coverage of 0.80 sq. arcmin and each row of the long slit covering 1,800-3,500 Å (Figure 1-1 right panel). Up to 4 columns of microshutters covering 3.2 sq. arcmin of the sky can be opened to the sky without (stellar) continuum spectra interfering with one another. To study the Lya sky, many more long slits can be opened to the sky say, every tenth column of shutters. The resulting spectral image is a composite of all the open slits image. The contibutions of individual slits can be identified by their position. As there is imaging within each shutter (~8x17 CCD pixels), the redshift of a LAE can be estimated. To scan the sky to **Figure 2-21:** The CETUS FUV camera will use the same FUV long-pass (LP) filter set as Hubble's ACS. (Figure reproduced from the ACS Instrument Handbook)

detect filaments spanning several columns, the set of columns can be closed and the adjacent columns opened until the full 17.4'x17.4' is covered.

#### **B) Multi-wavelength Surveys**

In the 2020's, current and future wide-deep telescopes will be surveying the sky at wavelengths ranging from gamma rays to radio waves (Figure **2-22**). E-ROSITA will perform an all-sky X-ray survey with unprecedented sensitivity and resolution; Subaru's Prime Focus Spectrograph and the Very Large Telescope's MOONS spectrograph will concentrate on understanding the evolution of galaxies at redshifts z=1-2, using optical-IR spectra; the Large Synoptic Survey Telescope (LSST) will map the southern sky discovering billions of new galaxies & stars and detecting transient objects; the Wide-Field Infrared Survey Telescope (WFIRST) and Euclid will make an imaging and slitless spectroscopic survey 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. These surveys will be highly synergistic leading to new, important discoveries.



Figure 2-22: CETUS will collaborate with other survey telescopes to solve important problems in astrophysics.



Using its wide-field UV camera, CETUS will take part in these multi-wavelength surveys. CETUS will provide the critical UV portion of these multi-wavelength surveys to help piece together a more complete picture. Some examples of insight given by multi-wavelength imagery are shown in **Figure 2-22**.

#### 2.2 Science Instrument Usage Matrix

The Science Instrument Usage Matrix is shown in **Table 2-2**.

### 2.3 Key Mission Requirements Derived from the Science Drivers

The Key Mission Requirements are shown in **Ta-ble 2-3**.

### 2.4 Design Reference Mission, and Observation & Science Yield

**Table 2-4** below summarizes the CETUS Design Reference Mission for its first four years of Science Operations. We assume that Science Operations start about 6 months after launch, travel to and insertion into orbit about Sun-Earth L2, and Orbital Verification and Science Commissioning of CETUS have been completed. Four years of science operations is equivalent to ~35,000 hr, but not all those hours can be devoted to science observations due to observation overheads and calibration observations. We therefore allot a total of 30,100 hr to the various science programs on CETUS. **Table 2-4** lists the major science programs and gives for each its allocation (in % and hours), the nature of the target and the CE-TUS scientific instrument (SI) to study it, the time on target whether the target is an individual source or a field (e.g. the 2 sq. degree COSMOS field, which requires 24 pointings to cover it), the number of pointings per observing program (ranging from ~5 to 600 for fields), and the observational yield.

Additional observational yield contributed by parallel instruments: Even Table 2-4 does not give the full picture of the enormous yield of CETUS observations. We need to include parallel observations that will be obtained while the prime instrument is observing its target(s). Below, we consider three observing modes corresponding to when the MOS,

|             | Objectives   | Underst<br>of gal | anding th<br>axies, star | e evolution<br>rs, planets | The Mod<br>Universe: V<br>is; How it v | lern<br>Vhat it<br>works | Surveys: CETUS prime,<br>Multi-Telescope |                     |                    |  |
|-------------|--|-------------------|--------------------------|----------------------------|--|--------------------------|--|---------------------|--------------------|--|
|             | Principal Targets  | z~1<br>galaxies   | Primitive<br>stars       | M-star Flares              | Galaxies &<br>Outskirts                | The<br>CGM               | UV<br>Surveys                            | Rapid<br>Transients | Multi-λ<br>surveys |  |
| Science     | Measurements   | Spectral<br>lines | Spectral<br>lines        | Emission lines, continuum  | Spectral lines, continuum              | Spectral<br>lines        | Spectral<br>lines                        | UV light<br>curves  | UV SED             |  |
|             | Observations by Prime SI   | NUV MOS           | NUV SPEC                 | NUV, FUV<br>SPEC           | FUV SPEC,<br>FUV CAM                   | FUV<br>SPEC              |  |                     |                    |  |
|             | Aperture diameter 1.5 m  | $\checkmark$      | $\checkmark$             | $\checkmark$               | $\checkmark$                           | $\checkmark$             | $\checkmark$                             | $\checkmark$        | $\checkmark$       |  |
|             | Mirror coatings AI/LiF/MgF <sub>2</sub>  |                   |                          |                            | $\checkmark$                           | $\checkmark$             |  |                     |                    |  |
| zd          | $\lambda\lambda$ 100–1000 nm (>400 nm for guider only)   |                   |                          |                            | $\checkmark$                           | $\checkmark$             |  |                     |                    |  |
| LA/0        | FoR > anti-solar hemisphere  |                   |                          |                            |  |                          |  | $\checkmark$        |                    |  |
| 0           | Pointing stability 64 mas 10   |                   |                          |                            |  |                          |  | $\checkmark$        |                    |  |
|             | Slew time $<$ 15 min for 180 deg   |                   |                          |                            |  |                          |  | $\checkmark$        |                    |  |
|             | Parallel Operation of SI's   | $\checkmark$      | $\checkmark$             | $\checkmark$               | $\checkmark$                           | $\checkmark$             | $\checkmark$                             | $\checkmark$        | $\checkmark$       |  |
| NUV MOS     | λλ 180-350 nm; RP ~ 1000@300 nm; MSA<br>~ 190x380 shutters; Shutter = 100 x 200<br>micron (2.75" x 5.50"); FOV=17.4' x 17.4' | $\checkmark$      |                          |                            |  |                          |  |                     |                    |  |
| ≥℃          | λλ 100-180 nm; Slit 0.2" x 3"; RP~20,000   |                   |                          | $\checkmark$               | $\checkmark$                           | $\checkmark$             | $\checkmark$                             | $\checkmark$        |                    |  |
| FR          | Slit-LS 2" x 360"; RP~2000 (ext. sources)  |                   |                          |                            | $\checkmark$                           | $\checkmark$             | $\checkmark$                             | $\checkmark$        |                    |  |
| NUV<br>SPEC | λλ 180-350 nm; Slit 0.2" x 3"; RP<br>40000@300 nm  |                   | $\checkmark$             | $\checkmark$               | $\checkmark$                           |                          |  | $\checkmark$        |                    |  |
| FUV<br>CAM  | λλ 115-180 nm; 5 long-pass filters; FOV 17.4'<br>x 17.4'; Res 0.55" (22 mm); Sub-pix sampling                                | $\checkmark$      |                          |                            | $\checkmark$                           |                          |  | $\checkmark$        | $\checkmark$       |  |
| NUV<br>CAM  | λλ 180-400 nm; 5 filters; FOV 17.4' x17.4'; Res<br>0.33" (12 mm); Sub-pix sampling   | $\checkmark$      |                          |                            |  |                          |  | $\checkmark$        | $\checkmark$       |  |

#### Table 2-2: CETUS Science Traceability Matrix



|          | 3 5 | T1 (   | - ·      | D '     | 1 /     | - 11  |        | <u>c</u> . |  | 1       | 1     | 1.4   | ı •  | •      | •     | •         |                |
|----------|-----|--------|----------|---------|---------|-------|--------|------------|--|---------|-------|-------|------|--------|-------|-----------|----------------|
| Table 2- | .5: | I he S | Science  | Drivers | determi | ne th | e fyne | of ins     | strument   | 's need | ed ar | nd fi | heir | engine | ering | requirem  | ents           |
|          | ••• |        | 50101100 |         | acterin |       | c cypc | 01 1110    | , ci ci il c | 5 meeu  | ea ai | 14 0  |      | Ungine | er mg | requirent | <b>U</b> 1105. |

| #  | Science Driver   | Implications/ Engineering Req.   | Ref. to<br>Section 3               |  |
|--|--|--|------------------------------------|--|
| SD 1   | Wide field imagery and multi-object spectroscopy over 1045"x1045" field        | 0.4" (~1-pixel) resolution over WFOV of camera & MOS; Opto-mechani-<br>cal stability                           | 3.3.2<br>FWHM Fig.<br>3.3.3        |  |
| SD 2   | Massive NUV Spect. survey z~1 galaxies; Lyo emis-<br>sion survey at z~1        | NUV wide-field multi-object spectrograph with Next-Generation micro-shutter array                              | 3.3.2<br>Detector                  |  |
| SD 3   | LUV/FUV survey of the circumgalactic medium (CGM)                              | AI/LiF/ALD MgF <sub>2</sub> -coated mirrors of telescope & FUV spectrograph                                    | 6.2                                |  |
| SD 4   | Robust FUV spectral features   | Precision polishing of OTA primary $\rightarrow$ <<< HST mid-spatial frequency errors                          | 3.2, 3.3.1                         |  |
| SD 5   | High sensitivity of UV optics  | Large aperture     Control of: molecular, dust & humidity contamination         » Al&T Faring & Launch; Flight | Distrib<br>3.2, 3.3,<br>3.6.3, 3.7 |  |
| SC 6   | Survey of extended sources by imaging spectroscopy                             | Extensive FOV; long slits  | 3.3.2, 3.3.4                       |  |
| SD 7   | NUV/FUV survey of rapid transients: neutron-star<br>binary mergers; supernovae | UV light curves potentially starting within an hour of the event   | 5.1                                |  |
| SD 8   | Highly productive surveys via parallel observations                            | Internal mechanism to dither while holding telescope pointing steady   | 3.3.2, 3.3.3                       |  |
| SD 9   | Science-ready CETUS data for astronomical community                            | Measurements of calibrated images and spectragrams   | 5.1                                |  |
| SD 10  | Sensitivity to faint diffuse sources   | Fast f/ratio   | 3.3.1                              |  |
| SD 11  | Sensitive low-noise UV detection   | NUV selection of CCD; FUV selection of MCP; Low noise, radiation resilient electronics for both NUV/FUV        |                                    |  |
| Abbreviations: FOV-field of view; QE — quantum efficiency; OTA — optical telescope assembly; Al-Aluminum; LiF-lithium fluoride; NUV — near-UV; FUV- far-UV; f/ratio — focal length/diameter of telescope primary |  |  |                                    |  |

#### Table 2-4: The Design Reference Mission is baselined for 4 years and 30,010 hours

| Observing Program                   | Allocation<br>(% / hours) | Target (field,<br>source) / SI                 | Tobs<br>(hr/target)                              | Pointings per<br>program        | <b>Observation Yield</b>                                       |
|-------------------------------------|---------------------------|--|--|---------------------------------|--|
| z~1-2 galaxies                      | 40% / 12,004              | Field/NUV MOS                                  | 20 hr  | 600                             | 42,000 spectra of z~1 galaxies                                 |
| Modern universe                     | 30% / 9003                | Bkg QSO/FUV SPEC                               | 9 hr   | 400 QSO's, 400<br>host galaxies | 400 LUV/FUV spectra of the CGM and host galaxies               |
| Survey/Exploration                  |                           |  |  |                                 |  |
| Transients                          | 9.3% / 2800 hr            | TBD / CAM, SPEC                                | 100 hr (rapid),<br>multiple 20 hr<br>(not rapid) | 20, 40                          | UV light curves, spectra                                       |
| Lya survey                          | 2% / 600 hr               | TBD /FUV CAM (5<br>filters)                    | 5 hr   | 120 pointings (10 sq. degrees)  | continuum subtracted images of<br>Lyα covering 10 sq deg       |
| Search for galaxy satellites        | 0.6% / 180 hr             | NGC 3010 field + 2nd<br>galaxy field / NUV CAM | 10 hr  | 3x3 pnt/galaxy                  | NUV image of the field areound 2 galaxies like the MW galaxy   |
| Gal clusters, filaments             | 1% / 300 hr               | fields / FUV SPEC-LS                           | 15 hr  | 20                              | LUV/FUV imaging spectra of the environs of galaxies & clusters |
| M 82 + others                       | 1 % / 300 hr              | M 82 and outskirts /<br>FUV SPEC-LS            | 3 hr per<br>pointing                             | 90 pnt (step-<br>stare)         | LUV/FUV imaging spectra of M83 and its ejecta                  |
| UV Dust Halos                       | 1.0 % / 300 hr            | edge-on galaxy / NUV<br>MOS-LS spectrum        | 20 hr  | 5 pnt/galaxy                    | NUV MOS long-slit spectra at 5 positions above/below galaxy    |
| Multi- $\lambda$ surveys            | 10 % /3000 hr             | Deep drilling field<br>(DDF) /CAM              | 4 hr   | 750 pointings><br>62 sq. deg.   | FUV/NUV images of DDF's, each covering 300 sq. arcmin          |
| CETUS director's discretionary time | 5%/1518 hr                |  |  |                                 |  |

Abbreviations: MOS=multi-object spectrograph, SPEC=point/slit spectrograph, CAM=camera, FUV=FUV, NUV=NUV, LS=long slit, pnt=pointing(s)

Camera, or spectrograph is prime. We assume that the observing efficiency of each instrument is 90% including overheads (small slews, read out of detectors, setup of instrument for next integration, etc.) Hence, the total observation yield contributed by the prime and parallel instruments is well over 100%.

The MOS is prime: In this case, the MOS will typically be in survey mode, obtaining the NUV



(rest FUV) spectra of  $\sim$ 70 z $\sim$ 1 galaxies simultaneously. The NUV camera will observe in parallel to obtain images of galaxies at z=0-2 before or after the MOS observes that region. The FUV camera will obtain images for studies of UV morphology of galaxies at z=0-0.4. Observing efficiency: 180%.

The Camera is prime: This will be the case when CETUS participates in surveys of selected deep fields. See *https://www.astro.princeton.edu/~dns/deep.html* for more information. The NUV MOS will observe in parallel in long-slit mode to obtain imaging spectra in search of Ly $\alpha$  (and possibly O VI) emitters at z $\sim$ 1 as described in Section 2.1.4. The multiple long slits will scan the sky during long exposures by the camera. The FUV point/slit spectrograph will observe in long-slit mode in search of Ly $\alpha$  (and possibly O VI) emitters at low redshift. However, the 6'-long slit cannot scan the sky. Observing efficiency: 270%.

The FUV point/slit spectrograph (PSS) is prime: The PSS will typically (but not always) be obtaining LUV/FUV point-source spectra of a background AGN/QSO whose line of sight pierces the CGM of a foreground galaxy or obtaining an imaging spectrum of the galaxy itself. In either case, both wide-field instruments will be observing in parallel. The NUV/FUV camera may study the UV morphology of galaxies in its field of view, and the NUV MOS will observe wide-fields (302 sq. arcmin) with multiple 17.4'-long slits to search for Ly $\alpha$  emitters. Observing efficiency: 270%.

Maximizing the science yield of CETUS observations: Maximizing scientific return from NASA missions is clearly of concern to NASA as it held a workshop in October 2018 on this very topic. In the case of CETUS and other survey telescopes, the main route to maximizing scientific return is to make measurements on CETUS images and spectra and to make these measurements immediately available to the astronomical community. Quantitative measurements are essential for deriving distributions of various parameters and examining possible correlations with other parameters.

Following typical NASA practice, the CETUS science operation center will perform Level 1 and Level 2 data processing. Level 1 processing consists of receipt of telemetry with checks for and correction of telemetry errors, and formatting the packetized data into an image or spectrum. Level 2 processing includes removal of the instrument signature and conversion of the data to physical units. NASA typically does not require Level-3 processing, which in this case would consist of measurements and data archival in a publicly accessible relational database, but it is essential if CETUS is to have a strong scientific impact. The work of the (probably distributed) CETUS science centers is described in **Section 4.5** (Science Operations).

#### 3 - INSTRUMENTATION – ENGINEERING IMPLEMENTATION TO FACILITATE SCIENCE

#### 3.1 Satisfying Science Flowdown of Requirements

The desired science objectives and subsequently defined CETUS capabilities drive the design and configuration of the CETUS architecture resulting in a broadly capable UV WFOV telescope and complement of instruments. Thus, CETUS is optimized for both a comprehensive UV spectral survey of as many as 100,000 galaxies with redshifts with z between 1 and 2, and for specific spectroscopic goals, some requiring agile response to different sectors of the sky, with different solar view factors. **Table 3-1** summarizes the flowdown of requirements, as they affect the OTA and the heritage based technical requirements on each of the instruments.

#### 3.2 Top Level Features of CETUS

The CETUS Payload design and capability are science driven, and with industrial involvement during the study, many payload elements are advanced to a level more commonly associated with mid-Phase A (**Figure 3-1**). Several key design tenants have been employed. Each element of the study led by a recognized expert in the discipline.

• Experience-based trades guided the study, referencing HST and other relevant missions. The level of complexity was managed in the study, paralleling Design-to-Cost methods used on many Earth observing missions.



**Figure 3-1:** The CETUS telescope and science instruments have been designed to meet the requirements set by the science goals.



| #     | Science Driver  | Implications   | Status   | Reference                          |
|-------|---|--|--|------------------------------------|
| SD 1  | Wide field imagery and<br>multi-object spectroscopy<br>over 1045"x1045" field     | • 0.4" (~1-pixel) resolution over<br>WFOV of camera & MOS;<br>• Opto-mechanical stability  | <ul><li>Wide field by design</li><li>Best focus via hexapod on telescope secondary</li></ul>   | 3.3.2<br>3.3.3                     |
| SD 2  | Massive NUV Spect. survey<br>z~1 galaxies; Lyα emission<br>survey at z~1          | • NUV wide-field multi-object<br>spectrograph with Next-Genera-<br>tion micro-shutter array  | <ul> <li>SAT program in progress to raise TRL of NG-MSA from TRL<br/>4 to TRL5 by 2021</li> <li>JWST MSA can be used if TRL insufficient</li> </ul>  | 3.3.2                              |
| SD 3  | LUV/FUV survey of the<br>circumgalactic medium<br>(CGM)                           | <ul> <li>Al/LiF/ALD MgF<sub>2</sub>-coated mirrors<br/>of telescope &amp; FUV spectrograph</li> </ul>  | <ul> <li>SAT program in progress on mirror coatings</li> <li>Planning of upgraded/new mirror-coating facilities —in progress</li> </ul>  | 6.2                                |
| SD 4  | Robust FUV spectral features  | <ul> <li>Precision polishing of OTA<br/>primary → &lt;&lt; HST mid-spatial<br/>frequency errors</li> </ul>   | <ul> <li>Contemporary deterministic polishing</li> <li>Proposals from qualified suppliers</li> </ul>   | 3.2<br>3.3.1                       |
| SD 5  | High sensitivity of UV optics   | <ul> <li>Large aperture</li> <li>Control of: molecular, dust &amp;<br/>humidity contamination.</li> <li>Al&amp;T Fairing &amp; Launch; Flight</li> </ul> | <ul> <li>OTA 1.5m diameter</li> <li>Minimize number of reflections</li> <li>High Reflectivity coating</li> <li>Detailed plans for fabrication and alignment, integration</li> <li>Test from the component to the system level</li> </ul>   | Distrib<br>3.2, 3.3,<br>3.6.3, 3.7 |
| SC 6  | Survey of extended sources by imaging spectroscopy                                | Extensive FOV     Iong slits   | NUV imaging spectroscopy via 1044"-long MOS slits<br>LUV/FUV imaging spectroscopy via 360"-long slit in design   | 3.3.2<br>3.3.4                     |
| SD 7  | NUV/FUV survey of rapid<br>transients, neutron-star<br>binary mergers, supernovae | • UV light curves potentially start-<br>ing within an hour of the event  | Upgrades to spacecraft & solar panels in design<br>• Enlarged FoR covering 2π steradians of sky<br>• Dual-axis high-gain antenna continuously pointed at Earth<br>• Upgrades to Near Earth Network (NEN) planned<br>• Reaction wheel assemblies (RWAs) sized to enable 180<br>deg. slew in ~15 min.<br>• Thermal control of optical metering | 4.1, 4.2                           |
| SD 8  | Highly productive surveys via parallel observations                               | <ul> <li>Internal mechanism to dither<br/>while holding telescope pointing<br/>steady</li> </ul>   | • TRL 8-9 mechanism for M2 optic (mirror or grating) of Offner relay in wide-field instruments   | 3.3.2<br>3.3.3                     |
| SD 9  | Science-ready CETUS data for astronomical community                               | Measurements of calibrated images and spectrograms   | • In initial planning  | 5.1                                |
| SD 10 | Sensitivity to faint diffuse sources  | • Fast f/ratio   | • OTA baseline is f/5, and relays for both MOS and CAM are 1:1, preserving f/5   | 3.3.1                              |

• In progress:

• e2v "Euclid" CCD + e2v electronics

#### Table 3-1: The Science Drivers and Traceability Matrix define the CETUS Implementation Requirements.

 The three instruments, Multi-Object Spectrometer (MOS), Camera (CAM) and Point/Slit Spectrometer (PSS), shared technology in optical configurations, mechanisms, and detectors. While there means the mean differences in mechanism the herein

NUV selection of CCD

• FUV selection of MCP

• Low noise, radiation resilient

may be minor differences in packaging, the basic technology is common to all instruments.The CETUS approach is to have a single Interface

Sensitive low-noise UV

detection

SD 11

- Control Document (ICD) governing the entire space element including Payload and Spacecraft. Thus common electronic control and data paths are established for the detectors and devices used in CETUS.
- · Each instrument is designed to integrate into (or

removed from) the payload with minimal interference to the other instruments. This accommodates instruments developed from diverse sources, and protects the schedule/cost should one instrument be delayed for any reason.

• The baseline opto-mechanical design leaves manageable margins of performance, making dimensional response to thermal environments, to gravity release and test extrapolation more forgiving, and requiring lower authority of control. We believe adequate margins minimize the likelihood of cost/schedule growth.



- Following the requirements flowdown, orbit and operational scenarios, the design uses materials known for their temporal and thermal stability. M55J structural material closely matches the coefficient of thermal expansion (CTE) of extremely stable ZERODUR<sup>®</sup> OTA mirror substrates, Thus, the design is nearly athermal by passive means, and is augmented with mild heater controls to ensure a robust optical metering performance.
- The TRL of all components of CETUS will be 6 or larger at the onset of development. In the baseline configuration, there is only one component below TRL 6:
  - » 1) the Next Generation Micro-Shutter Array (NGMSA) - Development continues beyond the JWST Micro-Shutter Array (MSA) under SAT funding, and very promising results have been reported leading to a much better packaged device with much more robust shutters than that will fly on JWST NIRSpec. TRL 5 for the NGMSA should be achieved by 2021. However, CETUS has an offramp to using the JWST TRL 8 Micro-Shutter Array (MSA) should the NGM-SA not be matured sufficiently by Phase A.
- » 2) The LUV baseline of LiF coatings on the OTA mirrors to allow throughput down to 100 nm is TRL 9 using current technologies and care to preclude absorption of water in the coatings. However, we have been investigating a more robust process which would further alleviate coating environment/ degradation concerns. Atomic Layer Deposition (ALD) could allow protection of LiF coatings at the size of the Primary Mirror. Presently high quality ALD coatings have been developed for sizes that cover all CETUS Mirrors other than the 1.54-m diameter Primary Mirror having reached half the diameter of the CETUS primary. Though the ALD process is not currently at TRL 6, an SAT proposal for improved UV coatings has recently been awarded. Separately the CETUS team has had conversations with Collins (Danbury) about a larger ALD facility and received an estimate to implement ALD in a large coating chamber they already have in their plans.

The CETUS Space Element is illustrated in **Figure 3-1**. **Figure 3-2** shows the simplicity of CETUS satisfying a wide range of compelling science drivers.



**Figure 3-2:** The wide field CAM and MOS on CETUS, coupled with a wide-field-of-view Three Mirror Anastigmat (TMA) telescope perform at several factors of 10 better than Hubble considering the collecting area times the solid angle viewed. Both the CAM and MOS relay the OTA image to the large detectors using an Offner-like one-to-one magnification approach. While details of the two Offners differ, the approach for alignment and test will have distinct similarities. Similarly, the same Micro-Channel Plates (MCP) and Charged-Coupled Devices (CCD) detector types will be used, with similar electronics, but with some details of the mechanical packaging different.



#### 3.3 Payload: Telescope and Three Instruments

CETUS will continue space-based vacuum ultraviolet scientific exploration of the Universe. Its 1.5-meter aperture wide field-of-view telescope with its complement of 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. **Figure 3-3** shows the relative locations of the telescope, instruments, and SC Bus.

Note the detailed optical design is presented in Woodruff et al. (2019, submitted to JATIS on 10/11/18), and is briefly described here-in.

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. The selected Sun/Earth L2 location enables continuous, uninterrupted viewing of stellar objects. A typical observation with the MOS and the Camera will be  $\sim 10$  hours long with detector read-out every 30 minutes to minimize cosmic ray/charged particle pixel detections. In this orbit, CETUS is about 1.5 million km on the anti-sun side of the Earth. The Sun. Earth. and Earth's moon are each always on the sun side of CETUS and thus light from them will be excluded from entering the OTA by its sunshield. With an 85-degree solar exclusion angle, a full  $2\pi$  steradian anti-sun hemisphere of the universe is available for viewing at any given time. Viewing the full  $4\pi$  steradian view of space is accessible over a one-year time frame because of the Earth's orbital progression about the Sun (Purves, 2017; Hull, et al., 2018).



**Figure 3-3:** Shared-splitting of CETUS OTA FOV provides simultaneous observing with all science instruments for highly time efficient data collection. The PSS long slit (blue) and the OTA alignment pinholes are fed by fibers; each conjugate with a Wide Field Sensor.

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 Ly $\alpha$  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 **Figure 3-3** and **Figure 3-4** 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



**Figure 3-4:** 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.



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 proceed with no interference if problems in any one instrument arise).

#### Coatings

Each mirror, grating, and window will use surface coatings that are high efficiency over their respective wavelength range. Each fused silica window and order sorter will be coated with a single layer anti-reflective coating. Ly $\alpha$  enhanced Al+MgF<sub>2</sub> reflective coatings, as used on HST, will coat the mirrors of the camera, the MOS, and the NUV PSS and the gratings of the MOS and NUV PSS. The dichroic mirror coatings in the MOS will transmit visible light to the light trap to reduce red-leak in the spectrograph spectrum. The OTA mirrors and the LUV/FUV PSS mirror and gratings will be coated with LUV-enhanced Al+LiF (Quijada, et al., 2014; Fleming, et al., 2017). See **Section 6.3** for further coating technology discussions.

#### 3.3.1 Optical Telescope Assembly

The OTA design form is an all-reflective Three Mirror Anastigmat (TMA) telescope with a flat field – the minimum number of mirrors needed to achieve full field correction. A two-mirror OTA would not achieve the required image quality over the required FOV. The corrected field-of-view of the F/5 OTA is ~  $1.1 \times 0.65$  degrees. The 1.5-meter diameter OTA entrance pupil/aperture stop is at the front surface of the F/1.448 primary mirror (PM).

The OTA has a centrally obscured on-axis aperture. The three conic mirrors of the OTA share a common optical axis. To physically separate the optical light beam reflected by the tertiary mirror (TM) from the beam incident on the TM, the OTA is used off-axis in field. The OTA is tilted by 0.45 degrees relative to the OTA optical axis. thereby providing physical access to the TMA focus region and to the real exit pupil of the OTA.

A 700 mm Cassegrain back focal distance provides depth enabling design of a stiff Stable Member (SM) main structural assembly on which the PM, the SM support truss, and the instrument complement are supported. Figures 3-4 and 3-5 illustrate the resulting OTA design. The TMA Focal Assembly lies at TMA focus. The SM is supported by six struts that extend from the PM housing to the SM mount. The OTA is properly baffled to off-axis sources with a Main Baffle (MB), surrounding the 1.5-m light beam extending from the PM to beyond the SM with classical Cassegrain central baffles: the SM cone baffle and the PM central baffle. In addition, the Sunshield Assembly surrounds the MB and extends from behind the PM to well beyond the SM. Its outward end is angled at 45 degrees to exclude sunlight from entering the OTA even at a solar exclusion angle of 85 degrees. A reusable door, that opens for science operations and closes for safing and orbit maintenance propellant firings, seals this truncated end when these operations are performed and during launch. This door provides contamination control as do other design features including pre-flight N<sub>2</sub> purge, temperature control of optics at



Figure 3-5: MOS: Mirrors, mechanisms, flat-field calibration sources and FPA interface.



temperatures warmer than other coldest surfaces, screening of materials for low outgassing, and other system controls.

### Mid Spatial Frequency (MSF) Improvement of CETUS beyond the State-of-the-art for HST

The CETUS study has addressed the MSF performance of CETUS in our design. Hubble tool-path errors on the primary mirror led to a 40% UV degradation of the STIS Line Spread Function (LSF), and this can be alleviated with contemporary deterministic optical finishing methods. The CETUS team includes both the designer of UV Spectroscopy instruments for Hubble, and the Director of the Tinsley (now Coherent) facility with responsibility for optical fabrication of all the JWST mirrors, and the NASA technologist for Terrestrial Planet Finder Coronagraph. As such, our study is based on proficiency in control of MSF errors on mirrors.

CETUS has addressed the control of MSF pupil errors with leaders in the optical fabrication world, including Arizona Optical Systems, Coherent, Collins Aerospace (Danbury) and Harris (Rochester). We have addressed the multiple causes of MSF errors, and their control. Competitive proposals were obtained from both Collins and Harris, and this is included in the CETUS implementation plan. While there are relevant talents at AOS and Coherent, we solicited quotations from the two most experienced providers in the US of large high-quality mirrors, Harris and Collins. Both have provided quotations for the Primary Mirror Assembly compatible with the requirements on MSF expressed to them. Thus we expect CETUS to be superior to HST in LSF, and capable of providing the best to date of astrophysical ultraviolet spectroscopy.

#### **Design Process Overview**

Early in the trade study, the optical attributes were defined as summarized in Table 3-1 in Section 3.2. The CETUS optical design fulfilled all the requirements with Table 3-1, including efficient packaging for AI&T of the payload and the spacecraft. It also incorporated "Lessons Learned" from the Hubble Space Telescope. Furthermore, because CETUS is dedicated to the ultraviolet, a spectral region where reflectance of coatings is low, basic to this design was minimizing the number of reflections. Thus fold mirrors were avoided, even if convenient for packaging. Embedded in this optical design are paths for the subsystems of wavefront error sensing (allowing controls), for fine guidance, and for calibration. Each SI was designed and optically optimized.

The design was then reviewed by our industrial partner, Arizona Optical Systems. Before the optical design was ready, the CETUS team ensured each optical instrument, subsystem and OTA were testable, and defined test methods. An example is a paper on the AI&T of the OTA.

The design was refined by an alignment sensitivity study, addressing and allocating errors:

- Optical design residuals across the fields of view
- Joint design performance of all three instruments, and optical subsystems, across the OTA FOV
- Effects of manufacturing error on the mirrors, addressing Low, Mid and High Spatial frequencies (LSF, MSF and HSF). Modern deterministic small tool techniques now used for optical finishing ensure that MSF errors will have a minimal effect on the quality of spectroscopy of CETUS.
- Effects of metering change are derived from:
  - » Gravity release.
  - » Creep due to launch loads and micro-yield on metallic fixtures.
  - » While hygroscopic release is minimal with CFRP based on modern cyanate ester resins, residual creep will happen, as will with epoxy joints. Because of this, to avoid contamination on optical surfaces, heaters are included in the design which a) slightly bias warm all optical surfaces with respect to structural and baffle elements, and b) can periodically provide additional heat on each surface to redistribute the small residual of hygroscopic materials.
  - » Creep due to material aging.
  - » Change in thermal boundary conditions due to changes in view factors to the sun. This is largely mitigated by a) very stable boundary conditions with respect to the solar view factor, by b) using materials with the lowest known dimensional response to changes in temperature for both the optics, and mitigated by c) sensors and proportional heaters at critical nodes. Tolerances on actuated heating is very loose due to items (a) and (b).
  - » Perturbations from other requirements for internal cooling (CCDs) or heating from power dissipation.
- From the extensive design study, sensitivity derivatives have been balanced and converted into a comprehensive error budget. All terms of this error budget are accommodated, often with as much as a 50% margin, ensuring excellent performance. Accommodations include optical fabrication budgets (For the Telescope Primary Mirror, especially

CECUS Cosmic Evolution Through Ultraviolet Spectroscopy

at MSF), and a robust "materials based" thermal design. All errors in the error budget are testable.

#### **Optical Performance**

The first order parameters for the OTA and spectrometers were first modeled in Excel<sup>®</sup> spreadsheets using closed form algebraic equations. (Woodruff, et al. 2018). The first order parameters of the OTA are readily determined in this way. The spectrometer parameters are traded-off with closed-form expressions for spectral dispersion and spectral resolving power. Similar logic is applied to the Camera and MOS. In all cases, the resultant parameters were modelled in ZEMAX® for optimization and to verify the Excel<sup>®</sup> closed-form models. The ZEMAX<sup>®</sup> models were exercised to predict image quality for the nominal system and develop optical tolerancing coefficients for the error budgets and to develop requirements for mechanisms. The ZEMAX<sup>®</sup> models generated STP files for mechanical CAD packaging.

Design tolerances and their effect on system image quality are understood and allocated across the system through application of systems engineering tools. The process considers effects of OTA errors on the effective resolution and spectral purity at TMA focus of each science instrument. A second part of the process considers effects of internal Science Instrument (SI) errors on the image quality at the SI detector. Where possible, we modified SI design to ease requirements of the OTA.

The optical design of the OTA plus all instruments, as toleranced via error budgets, fully satisfies the science requirements for image quality, spectral resolving power (**Figure 3-6**), spectral throughput, and parallel observations (see Woodruff et al., 2018 for full details).

#### 3.3.2 NUV Multi-Object Spectrometer

Figure 3-5 shows the design of the MOS. The MOS imaging spectrometer observes numerous stellar objects simultaneously recording the spectral content of each object at one-pixel R~1000 over the spectral range from 180 to 350 nm (with oversampling through the use of dithering). The F/5.24 MOS reimages a 1045 x 1045 arc sec portion of the OTA FOV via a three-mirror, all-reflective, Offner-like, nearly one-to-one, imaging spectrometer (Kendrick, Woodruff, et al., 2017, 2018). The three-mirrors are nominally concentric with M1 and M3 concave radius of curvature 800 mm and M2 convex with radius of curvature 400 mm. The M2 mirror is a convex spherical diffraction grating with 140 grooves per mm blazed at 250 nm. Mirrors M1 and M3 are high-order aspheric mirrors. To reduce



**Figure 3-6:** The Full Width Half Maximum (FWHM) of the 3 instruments is shown at two wavelengths illustrating the wide field imagery and multi-object spectroscopy achieved at 0.40" resolution.

fabrication complexity, we maintain a spherical convex figure for the MOS M2 diffraction grating. Simultaneous spectral imaging of numerous objects is enabled by the configurable MSA located at the sharp image provided by the OTA at the TMA focal plane. The MSA has 380 by 190 individually selectable rectangular apertures. (See Section 6.1 for further description of the MSA.)

A 4 K x 4 K, e2V Euclid CCD273-84 with 12- $\mu$ m pixels detects the spectrum of every selected object thereby providing time efficient parallel observations of the galaxy field. The effective resolution element width of the 12- $\mu$ m pixel images at the TMA focal surface is 396 mas in the field.

The CCD housing is a vacuum enclosure with a  $MgF_2$  vacuum window similar to how STIS and



ACS are sealed. Placed between the M3 mirror and the CCD is a 2 µm thick UV-grade fused silica order sorter that absorbs light of  $\lambda < 160$  nm effectively blocking second and higher order light. Following Euclid's heritage, a heat pipe connected to a cryogenic radiator cools the CCD light sensitive surface to the ideal "low dark noise" temperature of -120 C while maintaining the window at room temperature. The vacuum permits ground testing and alignment in a 1-atmosphere environment without going to the cost of testing only in a vacuum. In-flight the external window being room temperature does not accumulate frozen out contaminates. Periodically the window temperature is increased slightly by heaters adjacent to the window to boil off accumulated contaminates. Heat from each heat pipe (Thermal Electric Coolers are also being considered) is dissipated to space via radiators. To reduce programmatic cost and risk, the same basic CCD assembly design is used in the NUV camera and the NUV PSS. The only design differences relate to the window material type and tilt.

The M2 convex reflective diffraction grating is supported on a tip/tilt/focus mechanism. The MOS can be focused independently of the OTA and the camera. The OTA focuses at the field location of the PSS by adjusting the OTA SM based on error signals generated by WFS. The center WFS sensor is optically conjugate to the PSS slit array. Tip/tilt adjustment enables dithering the image at the FPA to sense detector pixel sensitivity variations and enhance observing efficiency.

#### 3.3.3 NUV/FUV Camera

**Figure 3-7** shows the Camera in more detail. The FUV and NUV Camera (CAM) image numerous stellar objects simultaneously in their respective spectral region. The F/5 CAM reimages a 1045 x 1045 arcsec portion of the OTA FOV via a three-mirror, all-reflective, Offner-like, one-to-one imager. The three mirrors are nominally concentric with M1 concave radius of curvature 776.985 mm, M3 concave radius of curvature 657.935 mm and M2 convex radius of curvature 409.949 mm. All three mirrors are high-order aspheric mirrors.

Simultaneous spectral imaging of numerous objects is enabled by the camera mirrors relaying the sharp image provided by the OTA at the TMA focal plane to the two camera detectors, respectively. The two bands (i.e., FUV and NUV) share the three powered mirrors, but are selected by a plano fold mirror on a Mode Select Mechanism which lies between mirror M3 and the detectors. To maximize throughput of FUV photons, the FUV mode is selected by removing this fold mirror reflects the field to the NUV detector. Each mode incorporates an 8-position filter wheel slightly in front of the respective detector providing multi-spectral imaging.

Following experience from design of ACS-HST instrument, the NUV filters are air-spaced (i.e., vented) dual element filter with coatings on each of the four plano surfaces to define the in-band spectral throughput and block out-of-band signal from the bandpass upper wavelength to the red-cutoff of the CCD and from the bandpass lower wavelength to the blue cutoff of the CCD (Brauneck, et al., 2018).

The image in the FUV mode is sensed by a 2K x 2K sealed CsI photocathode solar blind Micro-Channel Plate (MCP) detector with 20- $\mu$ m effective resolution element (resels). The MCP housing is a vacuum enclosure with a MgF<sub>2</sub> window. The detector operates at room temperature. The effective resolution element width of the 20- $\mu$ m resels as images at the TMA focal surface is 550 mas in field. The image in the NUV mode is sensed by a 4 K x 4 K, e2V Euclid CCD273-84 with 12-micron pixels, similar to the MOS CCD. The CCD housing is a vacuum enclosure with MgF<sub>2</sub> window. Identical to the approach used for the other two CCDs, heat



**Figure 3-7:** Camera: Mirrors, mechanisms, flat-field calibration sources and FPA interface.



pipe transports heat to a cryogenic radiator to cool the CCD light sensitive surface to T < -120 C to reduce noise due to dark current while maintaining the window at room temperature.

As in the MOS, the M2 mirror is supported on a tip/tilt/focus mechanism, so the CAM can be focused independently of the OTA and the MOS. Tip/ tilt adjustment enables dithering the image at the FPA to correct detector sensitivity variations.

#### 3.3.4 LUV/FUV/NUV Point-Slit Spectrograph (PSS)

**Figures 3-8** and **3-9** show the design of the PSS in more detail. The LUV/FUV Rowland-like Spectrograph (the long slit imaging spectrograph part of the PSS) and the NUV Echelle spectrograph (the point source portion of the PSS) taken together comprise the CETUS Point/Slit Spectrograph (PSS). The PSS records high spectral resolving power spectra of selected sources that the OTA images on the shared entrance slit at the TMA focus. The OTA light passes through the entrance slit and then diverges at F/5 to one of two mirrors: a fixed NUV parabolic collimation mirror feeding the NUV echelle spectrograph and a selectable LUV/FUV relay mirror. The NUV Echelle design is similar to designs in GHRS-HST and STIS-HST. The LUV/FUV design applies COS-HST heritage with a single optic, the disperser, for photon efficient spectroscopy. To select the  $R \sim 40,000$  NUV mode, the LUV/FUV relay mirror is withdrawn from this diverging beam. The NUV parabolic mirror collimates the diverging beam reflecting it to the plano NUV--the low risk Echelle. The spectra is then imaged as an echellogram by the off-axis parabolic cross-disperser, as was done in ST-GHRS and HST-STIS.

The NUV spectrograph is a Czerny-Turner configuration. The cross-disperser uses a Wadsworth aplanatic configuration, with angle of diffraction near zero at wavelength band center. The resulting  $3^{rd}$  order spherical aberration and  $3^{rd}$  order are zero at bandcenter focus position.

The resultant F/15 beam images onto the NUV CCD. The NUV echellogram images on the 4 K x 4 K, e2V Euclid CCD273-84 with 12-µm pixels. (This is the same detector type that the MOS and NUV Camera use.) This mode achieves spectral resolving power, R~40,000, over the spectral region 178.04 nm to 353.67 nm, with 2.5-pixel effective pixel width (30 µm resolution at the detector). The CCD housing is a vacuum enclosure with UV grade fused silica window. The window provides order sorting absorbing  $\lambda < 160$  nm effectively blocking





second and higher order light. As for the MOS and camera CCD, the NUV PSS CCD light sensitive surface is cooled to -120C via a heat pipe transporting heat to a cryogenic radiator.

The effective resolution element width of the 12- $\mu$ m pixel images at the TMA focal surface as 349 mas in field. Using a 2.5-pixel resolution element width, instead of 1-pixel, relaxes the requirements on the OTA image quality.

When using either of the two LUV/FUV modes (G120 or G150), a mechanism inserts the LUV/FUV relay mirror into the diverging beam from the OTA thereby blocking light into the NUV PSS. The LUV/FUV gratings are selected by a Mode Select Mechanism which inserts and registers in alignment the selected grating. The full spectral region of 100 nm to 180 nm is split into two portions, one per grating. The current baseline splits the spectra into 100 to 142 nm and 130 nm to 180 nm, respectively. The baseline uses Al+LiF reflective coatings on the TMA mirrors and LUV/FUV relay mirror and gratings.

The image in the LUV/FUV mode is sensed by an open CsI photocathode solar blind, curved Micro-Channel Plate (MCP) detector with 22- $\mu$ m effective resels width. The detector active MCP is 200 mm long by 70 mm wide. The MCP housing is a vacuum enclosure with a vacuum door that is opened on-orbit. The detector operates at room temperature. The effective resolution element width of the 22- $\mu$ m resels images at the TMA focal surface is 173 mas in field.

The PSS modes share two entrance slits that are located in the FPA Focal Assembly. The slits are: L1 which is 1.6 arc sec wide (Y) by 360 arc sec long (X) and S1 which is 1.0 arc sec diameter. The centers of the slits are separated by 2.7 arc sec in the dispersion direction (Y). The Y separation is small, since the corrected field is small.

#### 3.3.5 Wavefront Sensors

Wavefront sensing will be performed periodically to assess the optical alignment quality and image fidelity of the OTA. If alignment tune-up is indicated, the SM alignment will be adjusted deterministically to correct the OTA optical alignment and therefore the image quality of the OTA. When wavefront sensing is performed, light to the science instruments is blocked by a Pupil Insert Mirror that rotates into the region between the OTA TM and TMA focus where the real OTA exit pupil lies. This reflects the OTA field to five WFS detectors (downstream from the FGS pickoff) which determine OTA misalignment in WFE Zernike coefficients. These error signals are used to adjust the SM in five degrees of freedom to optically align the OTA. This sensing does not interfere with the view of guide starlight sensing by the FGS, thus pointing control is not interrupted. Therefore, LOS stability, which is essential to wavefront sensing, is maintained.

Adjustment of the OTA SM allows correction of a limited number of image errors: third order coma, defocus, and image plane centering and tilt. With a wide FOV OTA, care must be exercised when adjusting the SM. A correction based on a single field location could lead to errors at other field points. We use five wavefront sensors distributed over the full reach of the OTA FOV to break this degeneracy.

Each WFS lens images the OTA entrance pupil onto its WFS which consists of an array of detectors. For example, if each WFS is a Shack-Hartmann type sampling the pupil with a 50 x 50 array of sensors, the wavefront will be characterized at up to 25 cycles per aperture, assuming Nyquist sampling. This is more than sufficient sampling to control third order coma, focus, and image plane tilt and decenter. The WFS technology could be a Shack-Hartmann, a shearing interferometer similar to those made by Phasics, or potentially some other approach, such as Phase Diversity used in other space missions (e.g., JWST) and ground telescopes.

#### 3.3.6 Wavelength Calibration and Flat Fielding

The in-flight Wavelength Calibration System (WCS) images a large number of known wavelengths into the PSS for wavelength calibration. When wavelength calibration of the PSS is performed, light to the science instruments is blocked by a Calibration Insert Mirror (CIM) that rotates into the region near Cassegrain focus. This directs light from the wavelength calibration source to and through the PSS entrance slit. The spectrograph optics then disperse and image the calibration spectrum. This design provides wavelength calibration input using a STIS/GHRS-type Pt/Cr-Ne hollow core lamp. Again, FGS fine pointing control is maintained during this operation.

In addition, flat field source light floods each FPA to sense pixel/resels sensitivity variations and stability. Flat field lamps are mounted within each science instrument, respectively, to directly illuminate the subject detector. For FUV channels we plan to use a Xe line lamp like we used on GHRS. For NUV channels we plan to use Kr or deuterium line lamps like we used on STIS.

#### 3.3.7 Fine Guidance Sensor (FGS)

Two Fine Guidance Sensors, each with a 1127 x 1127 arc sec FOV, provide fine pointing error signals to the attitude control system which in-turn body points the OTA line-of-sight (LOS). The two



fine guidance sensors view OTA fields-of-view (see **Figure 3-3**) that are separate from those viewed by the science instruments (and WFS and WCS operations), so sensing does not interfere with science observing. This enables LOS control during science observations.

Each FGS uses an H4RG CMOS 4096 x 4096 pixel FPA with 10  $\mu$ m x 10  $\mu$ m pixels at F/5. The angular pixel width is 275 mas/pixel. The FGS FOVs are selected by fixed plano pick-off mirrors near Cassegrain focus. A series of lenses image the FOV on its FPA. The FGS outputs provide error signals to body point the OTA LOS jitter to less than 40 mas (1 sigma).

### 3.4 Detector and Device Selection, Trades, and Performance

The different scientific instruments use detectors with pixel width of 12  $\mu$ m (CCD), and resels width of 20  $\mu$ m (FUV MCP), and 22  $\mu$ m (LUV PSS). The effective pixel widths, as re-imaged by the SI optics, at the TMA focal surface are presented in **Section 3.2**. For reference, if widths corresponding to these pixel/resels sizes (12, 20, and 22  $\mu$ m) were placed at TMA focus (i.e., at focal length of 7,500.0 mm) the angular widths are 330, 550, and 605 milliarc sec (mas), respectively.

For the NUV, we originally considered a CCD similar to that in Hubble's WFC3 (e2v CCD43) because of its high TRL. Since then, e2v has developed improved CCD's that are better suited for CETUS: CCD 273-84, a 4Kx4K CCD with 12-µm pixels that was developed for Euclid and has been space-qualified. More recently, e2v has developed CCD272 for the Solar UV Imaging Telescope (SUIT), a variant of the Euclid CCD that is customized for UV sensitivity. Figure 3-10 shows the predicted transmission of the CCD window with a custom AR coating by e2v. Since the internal efficiency is essentially 100%, the transmission is a proxy for the CCD quantum efficiency. Laboratory measurements to support these predictions are expected in the spring of 2019. E2v will work with Mullard Space Sciences Laboratory to supply the CCD electronics as well.

For the FUV, we have chosen micro-channel plate detectors (MCP's) developed by Berkeley Space Science Labs (SSL), who developed the FUV detector for Hubble's Cosmic Origins Spectrograph (COS). Funded by NASA's Strategic Astrophysics Technologies (SAT) program, Berkeley SSL has made numerous major improvements in its FUV detectors (**Table 3-2**) that enable the CETUS FUV camera and Point/Slit Spectrograph to meet their science performance requirements. For example, the low-gain operation

ability results in a greater count lifetime which was a COS limitation. Berkeley SSL will provide the MCP detectors and associated electronics.

Dithering incorporated to improve resolution: The resolution of both the NUV MOS and NUV camera is set by the subtense of a CCD pixel ( $12 \mu m$ , or 0.33 arcsec). To properly sample a pixel, it is necessary to dither, i.e. to make small movements of the field incident on the detector format. Real detectors have hot pixels, blemishes, non-uniform response, etc., so it is also necessary to move the scene by several pixels on the detector format. We can combine these offsets with the sub-sampling offsets to construct a dithering pattern.

Our implementation of dithering uses the M2 optical component of the Offner relay (i.e. the convex grating in the MOS, or the convex mirror in the camera) to achieve dithering by non-integer pixels. The target in the MOS or CAM stays at exactly the



**Figure 3-10:** The CETUS CCD is expected to have a high quantum efficiency at wavelengths as short as 180 nm, based on custom window coating for e2v's CCD272.

| Table 3-2: Improvements | in the | CETUS | FUV | De- |
|-------------------------|--------|-------|-----|-----|
| tector Over HŜT/COS     |        |       |     |     |

|                             | FUV CETUS MCP                              | FUV HST/COS MCP  |
|-----------------------------|--|--|
| Detector type               | XS (cross-strip), Csl<br>photocathode      | XDL, Csl photocathode  |
| Spatial resolution          | 20 micron FWHM                             | 35 micron FWHM (dis-<br>persion); 65–550 micron<br>FWHM (X–disp) |
| Low gain oper-<br>ation     | 106  | 107  |
| Higher dynamic range        | Multi-MHz rates                            | 60,000 global count-rate<br>limit                                |
| Ultra low MCP<br>background | < 0.05 event/sec/cm <sup>2</sup>           | <1 event/s/cm <sup>2</sup>                                       |
| High UV QE                  | 50% @115nm,<br>30%@200 nm                  | 26% @ 133 nm, 12% @<br>156 nm                                    |
| Solar-blind cutoff          | ~350 nm                                    | > 239 nm   |
| Long stable<br>lifetimes    | >4x10 <sup>13</sup> events/cm <sup>2</sup> | 4 lifetime positions due to gain sag                             |
| Format size                 | up to 200 mm x<br>200 mm; no gaps          | 2x85mm x 12 mm; 9-mm<br>gap                                      |



same position at the telescope focal plane throughout the exposure. The fine guidance sensor would not see any movement in the guide stars. There is no need for a fine steering mirror. There is a need, however, for a precise mechanism on M2.

Ball Aerospace has built several versions of such a precise tip/tilt/focus mechanism for several instruments on Hubble (COSTAR, STIS, ACS, WFC3), so this mechanism is TRL 9. The Hubble Office at GSFC has the engineering drawings for each. CE-TUS Co-I Woodruff calculates that tilting the convex grating/mirror by 1" produces a shift of the MOS spectrogram/image of  $3.72 \,\mu\text{m}$  at the detector. There is also a need to record the M2 offset for use by the wavelength calibration routine in post-observation data processing; otherwise, it would seem that there are apparent shifts in wavelength.

### 3.5 Optomechanics and Trades to Optimize Performance within Cost Constraint

Early in the design effort, we established optical and mechanical designs appropriate to the science requirement flow-downs. The CETUS design incorporates elements that reduce programmatic cost and risk when CETUS progresses to final design and to operation. These include:

- · Imaging and spectroscopic requirements
- Optical design consistent with these requirements
- Selection of heritage materials optimized for optical stability in thermal environments
- Heritage based optical packaging, sufficient for requirements yet cost effective
- Built in ways to test in 1-g and correct for 0-g operating conditions
- A plan based on a single universal Interface Control Document (ICD), minimizing cost, complexity and allowing for reuse of electronics and logic
- Independent interchangeability of each instrument fed by the telescope
  - » Consistent with distributed industrial/laboratory responsibility in instruments
  - Consistent with foreign contribution of one or more instruments (CNES is already considering contributing the PSS instrument)
  - » Minimum impact on cost/schedule should there be a delay in one instrument
  - » Consistent with a descope if necessary, for cost control
- Design-to-Cost has been the starting paradigm following science requirement flow-downs. All major optomechanical trade studies have considered alternate approaches, including from GSFC Concurrent Design Laboratories, and we have made closure decisions with the mantra "better is

the enemy of good enough". While upgrades may be considered at extra cost, the design presented here is sufficient to successfully address all baseline CETUS science requirements.

This effort was experience-based, going directly to industrial contractors and laboratories collectively expressing broad and detailed heritage in most aspects of the CETUS Observatory. Thus, we have advanced the CETUS design in several areas close to a Phase A level, and well beyond an initial parametric design. For many elements of the system, the CETUS team has developed comparable-based costs from established companies, typical of those who would build CETUS. These costs do carry corporate margin to deliver.

### 3.5.1 Technical approach consistent with both performance and reliable costs/schedules

The CETUS design has allowed for industrial costing, often by the method of comparables and traceability. Critical mechanical parts of the system, as configured, will operate near room temperature. CETUS has been designed not only for operation and launch, but also for testing in the laboratory pointing perpendicular to the gravity vector. With established rotational shear metrology, the uncertainty of analytic gravity backouts become nearly negligible. Similarly operating critical elements of the metering structure (those metal based) at near room temperature will minimize thermal uncertainty terms in the error budget.

CETUS is expected to be very stable at L2, and its "survey mode" solar view factors are nearly constant in this mode, a considerable simplification compared to Hubble. Once in orbit, we have the ability to focus, both at the instrument level and the telescope level. Thus gravity release residuals, material aging, launch load creep, and operational conditions can be addressed.

#### 3.6 Payload Mechanical/Electrical/Thermal Design

#### 3.6.1 Payload Mechanical/Structural Design

The CETUS science payload structure was designed to provide rigid support of telescope and instrument optical elements and of the instruments. To minimize any mechanical and thermal distortions between the OTA and the instruments, we baselined an all-composite structure based on a flight-proven M55J fiber/ Cyanate-Ester resin construction. **Figure 3-11** shows the CETUS payload structure components. The 33cm thick Stable Member serves as the primary mirror bench and the main structure component of the forward metering structure. The Stable Member also





**Figure 3-11:** The full Payload (left, and cut-away view showing instruments right) has been modeled independently at NGIS and at GSFC. All dynamic requirements are satisfied.

serves as an interface structure for the aft optics tower and science instruments.

The forward metering structure holds the primary mirror and the secondary mirror using a proven M55J composite hexapod truss assembly. Invar 36 is baselined for optical interface fittings to minimize thermal CTE mismatch between the Zerodur optical elements and the M55J structure. Also, part of the forward metering structure is the Main Baffle assembly, which uses M55J/Cyanate-Ester barrel and stray light vanes, and Invar 36 fittings. The interior of the baffle assembly is painted with Z306 black paint to provide maximum stray light protection for CETUS instruments. Surrounding the Main Baffle assembly is the Outer Sun Shield, which acts as a main thermal barrier for the CETUS OTA.

The aft optics tower holds the tertiary mirror, PSS, and Wavefront Sensor assembly, and connects to the Stable Member through M55J composite hexapod truss. The camera, MOS, and FGS subassemblies attach to the backside of the Stable Member using kinematic mounts. As CETUS instruments may be developed and built by a consortium of partner institutions, the CETUS payload structure is designed to easily integrate fully qualified instrument assemblies to the payload structure with ample available space for alignment of each instrument assembly to the optical assembly.

Each instrument housing is designed using a flight proven M55J composite construction to provide rigid support of optical elements and to maintain critical alignment tolerances using kinematic mounts. Each instrument housing also accommodates all detector assemblies, including detector Front End Electrics (FEE), and various mechanisms such as Tip/Tilt/Focus mechanisms and other required mechanisms.

A preliminary analysis of the CETUS payload structure verified the structural soundness of design. The results show that the lowest frequency first mode is 29.4 Hz, which indicates the structure is stiff enough to be viable.

#### 3.6.2 Payload Electrical Design

Each CETUS instrument is connected to a single Main Electronics Box (MEB), which provides all power and control interfaces to operate the instrument. To meet the requirements of NASA Class B risk classification, each MEB is based on a single fault tolerant dual string redundant architecture. In addition to MEBs for Camera, MOS, and PSS, two additional MEBs are allocated for OTA control and auxiliary instrumentation including FGS and Wavefront Sensors. Each MEB is about 10 kg in mass and requires 48 watts of power. **Figure 3-12** shows the CETUS payload electrical block diagram.

#### 3.6.3 Payload Thermal Design

The CETUS Payload thermal design satisfies three implicit requirements:

- 1. Optomechanical stability of the end-to-end optical system: This is accomplished by minimizing the sensitivity via selection of "best materials" for thermal stability, and supplementing this with low-authority easily achieved proportional heater networks placed at sensitive nodes.
- 2. The optics will operate "warm biased" with respect to surrounding structural components, and operate near room temperature and under





Figure 3-12: The electronics are redundant to meet NASA Class B risk classification.

near isothermal steady state conditions. This flows from the optical throughput requirements, which are partially driven by in-service molecular and particulate contamination issues. Furthermore, the temperature of the optical surfaces can be increased by another approximately 10 °C to periodically redistribute any residual contamination. In addition, mechanisms (e.g., the Secondary Mirror Hexapod), are maintained at operational temperatures.

3. The CCDs require cold operation at approximately -120 °C (TBR). The design cools the CCD cavities, and the associated front-end electronics (FEEs), via heat pipes and conductive paths to radiators looking at cold space.

The CETUS equilibrium temperature fields have been analyzed, for an L2 orbit, and looking at cold space. **Figure 3-13** Illustrates the passive thermal analysis of CETUS. The front end of the Sun Shield Assembly is angled, with the high side of the scoop always favoring the sun direction. While CETUS can point in the anti-sun direction, typically it will point approximately 90 degrees to the sun in survey mode with the MOS and CAM. There is no requirement to make CETUS Payload isothermal, but temperature stability of the non-isothermal condition is required. Only the mirrors will be maintained at near isothermal conditions with supplemental heating. When thermal equilibrium is achieved, CETUS WFS methods will "phase up" the alignment of the system for sufficient optical performance.

**Requirement #1:** Stability, is achieved by first using materials that first have extremely low coefficients of thermal expansion (CTEs). The baseline material selection is ZERODUR<sup>®</sup> mirror substrates and M55J Carbon Fiber Reinforced Polymer (CFRP) metering structures. Not only are these material CTEs lowest available for space, but also ZE-RODUR<sup>®</sup> and M55J can be tailored to the CETUS operational temperature band, and also matched closely to each other. This passive approach will be complimented by active heater circuits placed near metallic components in the metering path. Only a





Figure 3-13: Thermal analysis of the CETUS Observatory in survey-mode operation at L2 shows a manageable distribution of temperatures.

very low precision of thermal control is needed, and space payloads routinely require thermal control over two orders of magnitude better than that needed by CETUS. With these "best" materials, coupled with easily achieved thermal control, the reserve in the error budget for thermal control is nearly a factor of two, which we regard to be highly robust.

**Requirement #2:** Warm biased mirrors are easily achieved via radiative transfer via thermofoil heater arrays on the back of a thin aluminum emissive plate located a short distance behind the mirror. Nominal "bias" temperature and "contamination redistribution" temperatures are achieved with modest power requirements.

Requirement #3: Cooling CCDs and FEEs are achieved via a combination of heat pipes and conductive interfaces to external "cold space" radiators sized to achieve the low-noise operating temperatures of the CCDs. Where heat pipes are involved, they will lie in the horizontal position during detector tests in the thermal-vacuum (T-V) chamber. Thermo-Electric Coolers (TECs) will be carried as a possible high-heritage alternate, available for consideration in the next study phase.

All requirements can and will be tested robustly during the sequence of thermal vacuum (T-V) tests.

#### 3.7 Alignment, Integration, and Test

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The CETUS study generated a comprehensive OTA AI&T test flow. Components will be integrated into the CETUS system as shown in the overall flow diagram, Figure 3-14. OTA PM and SM will



Figure 3-14: CETUS Optical Telescope Assembly AI&T Flow.



be integrated and aligned, as depicted in **Figure 3-15**, using a double pass wavefront test with an autocollimating flat. The OTA TM and the instruments will then be integrated and aligned.

Alignment for the CETUS OTA and instruments will utilize (Computer-Generated Hologram (CGH) alignment techniques. Non-symmetric three mirror anastigmatic telescopes such as CETUS present alignment challenges due to degeneracies that occur because there are different degrees of alignment having nearly the same signature in the wavefront. For example, the aberration of coma in the wavefront could come from either a decenter or a tilt of any of the aspheric mirrors. The correct alignment state must be determined for each mirror, as correcting, again for example, coma, with the wrong mirror creates higher order aberrations, with higher order field dependence. This complexity is avoided by first aligning the primary-secondary pair using the Front End Field Diverse Autocollimation Test (FEFDAT). Next, the full OTA is aligned with a similar test.

The field diversity provides unambiguous information on the state of the alignment for this pair of mirrors. Taking the primary mirror as the datum, we have only the secondary mirror tilt, decenter, and focus to determine. While a single field point will show degeneracies, measurements across several field points sort this out. CGH simultaneously provides five field points for testing across the FOV in auto collimation. Importantly, the CGH creates all five field points from a common CGH, with multiple patterns, avoiding alignment degeneracies.

A similar alignment will be used for the instruments. An example is shown in **Figure 3-16** for the camera, utilizing a CGH providing nine field points. This again allows the various alignment degrees of freedom to be measured and avoids any field-dependent degeneracies.

System wavefront testing will take place with fiber optics aligned to the TMA focus. Single-mode fibers provide excellent point-sources, which will overfill the system aperture. These sources enable full-aperture system wavefront testing of the system wavefront, including the OTA, as well as the Camera and MOS.

The more expansive AI&T flow with the integration of the Science Instruments, FGSs, and WFSs with the telescope and subsequently the entire Science Payload with the Spacecraft bus is shown in



**Figure 3-16:** The CAMERA's aspheric-based Offner Relay is straight forward to align with methods established at AOS. The test CGH has multiple field points. On the right is the resulting conspicuous fringe appearance of just 10  $\mu$ m decenter of M2.





Figure 3-16: The CETUS Observatory AI&T has been initially planned through integration with the Launch Vehicle.

**Figure 3-16**. The Observatory (Science Payload and Spacecraft bus) integration with the Launch Vehicle is the last step.

#### 4 - MISSION DESIGN

#### Introduction

Mission design for a space telescope such as CE-TUS basically consists of developing the most cost effective means for a set of science instruments to carry out its intended set of science 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 developing this set of designs is to define the instrument "accommodation requirements", which for CETUS can be summarized as follows:

- Instrument envelope (Shown in Figure 4-1) of about 5 m long and 2 m in diameter
- Instrument mass of ~1,084 kg and power requirement of ~1,200 W
- Room temperature thermal (~293 K) environment
- Science Data Downlink of about 27 Gbit/day

- Anytime up-link of command to quickly slew to observe a transient event
- Instrument pointing accuracy of ~0.1 arcsec
- Instrument slew of 180 degrees in less than 15 minutes after commanded
- Instrument Field of Regard (FoR) of about 2  $\pi$  steradians of sky in the anti-Sun direction at any time and 4  $\pi$  steradians of sky in a year or less.
- Duration of observations: 5-year design life with 10-year goal

Key features of the CETUS mission and the corresponding rationale are summarized in **Table 4-1**.



Figure 4-1: The CETUS Science Payload's three UV instruments are fabricated and integrated independently and can operate simultaneously on-orbit.



| Table 4-1: Key features | of the | CETUS | mission | and |
|-------------------------|--------|-------|---------|-----|
| rationale               |        |       |         |     |

| CETUS Mission<br>Feature   | Rationale  |
|--|--|
| Orbit about the Sun-<br>Earth L2                                       | <ul> <li>~2 π steradians of sky visible at any one time</li> <li>4 π steradians visible over any 12 month period</li> <li>Relatively easy to reach and maintain orbit</li> <li>Reasonable cost of communications</li> <li>Thermally benign with Sun/Earth light always from roughly the same relative direction</li> </ul> |
| 5-year mission<br>design life with<br>consumables for 10<br>years      | • Longest mission duration that avoids signifi-<br>cantly more expensive design  |
| Dual wing solar ar-<br>rays (SAs) with single<br>axis articulation     | <ul> <li>Supports Field of Regard (FOR) over 2 π<br/>steradians of sky</li> <li>Keeps Cp near Cg, minimizing rate of momen-<br/>tum buildup</li> </ul>   |
| Oversized Reaction<br>Wheel Assemblies<br>(RWA's)                      | <ul> <li>Slew to view any transient in FOR within 15<br/>minutes after commanded</li> </ul>  |
| Two-axis articulated<br>High Gain Antenna<br>(HGA)                     | • Can communicate with ground at high data rates while CETUS is observing anywhere in FOR  |
| On-board Celestial<br>Navigation for<br>onboard Orbit<br>Determination | • Eliminates costs of tracking by ground system  |
| Near-Earth Network<br>Ground System                                    | <ul> <li>Adequate performance and less expensive<br/>than Deep Space Network</li> </ul>  |
| Recoverable Falcon 9<br>Launch Vehicle                                 | Adequate and proven performance, adequate fairing size, low price  |

#### 4.1 Orbit

The orbit selected for CETUS (**Figure 4-2**) is approximately centered on the Sun-Earth Second Lagrange Point (SEL2). 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 SEL2 orbit provides a good view of about 2  $\pi$  steradians of the sky at any point in time, and 4  $\pi$  steradians over 6 months bringing the following benefits to CETUS:

- The FoR provided by the orbit will allow CETUS to always see some part of the Subaru Hyper Suprime Camera (HSC) field where it is to carry out its primary UV spectroscopic survey.
- The large FoR will facilitate the CETUS GO program because there will be no shortage of opportunities for CETUS to observe any specified GO target.
- The large FoR also means that CETUS will always have a better than 50% probability of being able to observe any short-lived transient event.



**Figure 4-2:** 4x34 degree L2 Earth Vehicle (LEV) Angle Notional CETUS Orbit.

• The FoR also enables Celestial Navigation (in which small star-tracker-like cameras facing in the anti-sun direction measure the positions of known Near-Earth Objects (NEOs)) which CETUS can use to determine it position and esentially eliminate the expense of DSN ground station tacking.

It will be practical at any time to send CETUS a command to slew to and observe a transient event. Also, since a SEL2 orbit is about 1.01 AU from the Sun, the SC will be able to use high-heritage solar arrays (SAs) and thermal control technologies that have been refined by the many SC that have flown under similar conditions.

#### 4.2 Ground Stations and Operations

The mission design goal is for CETUS to be able to use the most cost-effective ground stations that can handle its regular downlink science data, plus provide on-demand command uplink capability to enable CETUS to almost immediately slew to and observe transient events. The combination of the relative proximity of a SEL2 orbit and non-extreme downlink requirements (~27 Gb per day) allows CE-TUS 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.

#### 4.3 Spacecraft Bus

The CETUS SC-Bus is depicted in **Figures 4-3** and **4-4**. The reference design for the CETUS Engineering Concept Design Package (ECDP) costing process was developed in the GSFC Mission Design Lab (MDL).





Figure 4-3: Spacecraft/Payload Assembly.



Figure 4-4: CETUS Observatory.

#### 4.3.1 NGIS SC-bus

To obtain an independent estimate of SC bus costs, a functionally identical SC bus design was developed by Northrop Grumman Innovative Solutions (NGIS), and is decribed below. The NGIS LEOStar-3 product line is being used on Joint Polar Space System-2 (JPSS-2), Space Test Program Satellite-6 (STPSat-6) and Landsat-9 in both LEO and GEO. It is used for high value, long life missions that require a precision Attitude Control Subsystem (ACS), wideband communication, redundancy and robust fault management. The product line uses a common architecture that can accommodate mission specific requirements. Fourteen have been launched and five are in production. The NGIS CE-TUS SC configuration is shown in **Figure 4-5**. The design is completely redundant and uses Technology Readiness Level (TRL) 7 to 9 hardware with no new technology development required.

The CETUS Spacecraft Bus reserves the volume inside its center cylinder volume for the CETUS payload and uses its center cylinder to support the payload. The interfaces between the payload and spacecraft are kinematic and adiabatic. The space-



**Figure 4-5:** CETUS Observatory showing CETUS PL & SC configuration.

craft Outer Sun Shield Assembly (OSSA) surrounds and protects the payload. This arrangement provides a consistent thermal environment for the payload. The five payload Main Electronics Boxes (MEB) mount on a spacecraft equipment panel. The star trackers and gyro are mounted on the payload Stable Member to provide a tight linkage between spacecraft pointing and payload boresight.

The CETUS spacecraft (SC) accommodates both the Payload (PL) and Launch Vehicle (LV) Dynamic Envelope (DE). NGIS high heritage SCs are the basis for the CETUS SC). Features of this design are:

- SC TRL levels range from 7 to 9 with no new technology development for low risk.
- Redundant SC elements with 5 years of SC design life and 10 year goal).
- SC provides center volume for CETUS PL and uses composite center cylinder to support the PL like the NGIS GEOStar-2 and -3 product lines.
- SC does celestial navigation using 3x Malin ECAM50 cameras and Goddard Image Analysis Navigation Tool (GIANT) SW.
- 30 days between RWA desaturation events.
- Preliminary analysis indicates 40 milli-arcsec jitter and drift requirement can be met with closeloop control system using PL FGS, and SC gyro and RWAs.
- The SC employs S-Band command and telemetry links using LGA and HGA, and 15 Mbps Ka-band wideband data downlink using HGA.
- The SC employs redundant Integrated Electronics Modules (IEM) with a RAD750 CPU and cPCI



Backplanes for SC C&DH, and a redundant Payload Interface Electronic (PIE) with 512 Gb Flash Memory Cards for the CETUS PL interface.

- Flight Software (FSW) uses VX-Works RTOS, C++ and autocoded ACS SW.
- Mono-propellant blowdown propulsion system, pointing away from the PL for minimum contamination.
- 3290 W (EOL) SA with two wings and 78 Ahr Li Ion Battery.
- SC includes the Observatory Outer Sun Shield Assembly (OSSA) and door.

The Spacecraft Bus design meets the performance requirement of the CETUS mission with significant margin as show in **Table 4-2**. This margin reduces risk and provides flexibility to accommodate changes.

CETUS uses techniques developed on other LEO-Star-3 programs to reduce LOS jitter and uses existing LEOStar-3 product line avionics. Six Honeywell HR14-50 Reaction Wheel Assemblies (RWA) are baselined, so zero crossings can be controlled. They are only operated in the lower half of the speed range to minimize jitter. There are two solar array wings with one-axis drives designed for 15° cosine loss. The L2 orbital drift is only 0.08°/hr, so the solar array wings are fixed during observations. A 1-m Ka-Band High Gain Antenna (HGA) with a Ka-Band transmitter and 10W TWTA provides mission data downlink. An S-Band system provides 24/7 communications capacity for command, telemetry and ranging using an S-band Transceiver with omni antennas. The Command and Data Handling (C&DH) Subsystem uses a proven Integrated Electronics Module with a RAD750 CPU and cPCI backplane for spacecraft functions, and a Payload Interface Electronics (PIE) for payload interfaces and data storage. These avionics meet the L2 radiation requirements. FSW uses the Vx-Works Real Time Operating System (RTOS), C++ code and ACS autocode. The Propulsion Subsystem uses a mono-propellant, blowdown approach with 8 thrusters for orbit changes and 8 for RWA desaturations. The Electrical Power Subsystem (EPS) uses a proven Power Distribution Unit (PDU) for power control, battery charging, and power distribution and switching, a 3290 W (EOL) solar array and 78 Ahr Li Ion batteries.

Based on our approach and the reasonable changes to the NGIS product line design, the CETUS SC is low risk.

#### 4.3.2 MDL SC-bus

**Mechanical:** Besides providing the science PL with its needed services (such as power, pointing, and communications) another design objective for the SC Bus is to keep its shape and mass within limits that allow the CETUS Observatory (the combination of the science PL and SC Bus) to be compatible with as economical a launch vehicle as possible. In the case of CETUS, this led to giving the SC Bus a kind of donut shape that allows the lower part of the relatively long science PL to fit inside of the "donut hole", as shown in **Figure 4-5**. This allows the use of relatively shorter LV fairings and helps keep the observatory Cg low enough to be within LV limits. The 5 m fairings available on most LV can accommodate this width.

As shown in **Figures 4-3** and **4-4**, other major aspects of the SC-Bus mechanical design include:

| b contraction where while coord we die netre beway private. |                   |            |        |                                      |  |  |
|---|-------------------|------------|--------|--------------------------------------|--|--|
| Requirement Description                                     | <b>Rqmt Value</b> | Perf.      | Margin | Comment                              |  |  |
| CETUS Observatory Wet Mass                                  | 3375 kg           | 2640 kg    | 22%    | Falcon 9 capability to L2            |  |  |
| CETUS SC Dry Mass   | 1252 kg           | 1074 kg    | 16%    | Uncertainty based on status          |  |  |
| S-Band Command UL using HGA w/ranging                       | 2 kbps            | 2 kbps     | 18 dB  | 18m NEN GT and at L2                 |  |  |
| S-Band Telemetry DL using HGA w/ranging                     | 2 kbps            | 2 kbps     | 14 dB  | 18m NEN GT and at L2                 |  |  |
| Ka-Band Wideband Downlink Using HGA to NEN                  | 15 Mbps           | 15 Mbps    | 6.8 dB | 18m NEN GT and at L2                 |  |  |
| Mission Delta V   | 102 m/s           | 102 m/s    | NA     | Fuel based on 3375 kg mass           |  |  |
| Fuel  | 224 kg            | 272 kg     | 18%    | Tank size margin                     |  |  |
| Slew and settle within 2p FOR                               | 15 min            | 5 min      | 67%    | Six RWAs                             |  |  |
| Jitter and Drift over 30min observation (1 sigma)           | 40mas             | 29mas      | 27%    | Preliminary 1 axis analysis          |  |  |
| SC Pointing Knowledge (1 sigma)                             | 2 arcsec          | 1.5 arcsec | 25%    | 2 for 3 star trackers                |  |  |
| RWA Desaturation  | 7 days            | TBD        | TBD    | Six RWAs                             |  |  |
| 7 Days of Science Data Storage                              | 183 Gb            | 512 Gb     | 180%   | Flash Memory in PIE                  |  |  |
| Solar Array Size  | 2562 W            | 3290 W     | 22%    | w/15% SC and 30% payload uncertainty |  |  |

**Table 4-2:** CETUS Spacecraft has appropriate margin for early stages of conceptual study. The performance characteristics can be estimated at this time for all but three of the parameters, and the CETUS team is confident that these will close easily at the next study phase.



- The sun shade has an angled opening to minimize stray light and a multi-use door to minimize contamination during launch and to protect the optics from direct sunlight in the event of a temporary loss of attitude control.
- Dual deployable SA panels, each with a single axis drive so that the observatory can get full power when pitched anywhere from 90 to 180 degrees from the Sunline. The SA panels are located to minimize the Cp-Cg offset for any pitch angle in order to minimize the propellant required to unload reaction wheel momentum.
- The deployable high gain antenna is on a two-axis gimbal so that it can be pointed at Earth for communications passes without requiring the whole observatory to change its orientation.

**Thermal:** The thermal design of the SC-Bus is straightforward. **Figure 4-6** shows some representative operational temperature distributions. **Section 3.6.3** described the PL thermal design approach which drives some of the SC-Bus parameters such as size and location of radiators for temperature control of PL detectors and electronics. The thermal design is slightly "cold-biased", which means it is designed to passively keep the observatory cool enough when exposed to maximum sunlight. Then heaters are used to keep temperatures high enough when the heat load is reduced due to pointing farther away from the Sun. The result is that the thermal control can be implemented by a conventional arrangement of MLI and heaters controlled by thermocouples.

**Propulsion:** The requirements placed on the propulsion system are relatively modest, being on the order of about 100 m/s of total delta-V capability over the goal lifetime of 10 years. This is because the LV places CETUS on a trajectory that naturally evolves into something close to the target SEL2 orbit, meaning that the required initial maneuvers are just mid-course corrections. Maintenance of the SEL2 orbit also requires only a modest amount of annual delta-V, and the propulsive requirements for unloading momentum are minimized by locating the solar arrays to minimize the effective Cp-Cg offset. Thus, the CETUS propulsion system can have the relatively simple and straightforward mono-prop arrangement.

Attitude Control System (ACS): The ACS can be implemented with simple and conventional hardware. The performance requirement can be summarized as:

- pointing control of 0.1 arcsec RMS
- pointing stability of 40 mas RMS over a 30 min exposure
- Slew 180 degrees in 15 min

The attitude actuation requirements can be met with a set of Honeywell reaction wheels. These reaction wheels and the other ACS hardware components are conventional, high TRL items that are essentially off-the-shelf. This relative hardware simplicity on the SC-Bus is enabled by the specialized fine guidance attitude sensors built into the WFOV UV telescope.

Besides attitude control hardware, the ACS includes the Celestial Navigation (Cel-Nav) hardware which consists of simple, high-TRL off-the shelf items. The basic purpose of the Cel-Nav is to allow CETUS to determine its location in space and thus avoid the cost of getting additional time from ground stations.

**Electrical Power System (EPS):** The EPS is implemented in a relatively straightforward fashion, in



**Figure 4-6:** Several pertinent thermal cases have been analyzed showing that performance will meet the error budget allocations for distortions due to soaks and gradients.



part because CETUS is essentially 1 AU from the Sun, which in turn means that very conventional components can be used. The solar arrays use highly efficient (~30%) triple junction GaAs solar cells and are capable of generating ~2,600 W at EOL (10 years from launch). The arrays, which consist of 2 wings with single axis gimbals, are deployable in order to facilitate fitting the stowed CETUS observatory into a conventionally sized LV fairing.

Communications System (Comm). The CETUS communications system is implemented with high-TRL space and ground hardware. It has some unique aspects that are summarized as follows:

- CETUS uses the lower cost NASA NEN ground system (as shown in Figure 4-7) as opposed to the DSN which has been used by all NASA previous (WMAP) and planned (JWST) missions to SEL2 orbit. Advancing technology and the relatively modest CETUS downlink requirement rate (~26 Gbit/day) basically allow CETUS to use the NEN instead of the more expensive DSN.
- With its 2-axis gimbals, the CETUS HGA can always be pointed at Earth regardless of where CE-TUS is pointing to perform it science observations. So CETUS can always listen for commands (sent at the very low data rate of ~100 bps) to quickly slew to and then observe an unexpected transient event.

**Command & Data Handling (C&DH):** The C&DH system is shown in Figure 4-8, and for mission reliability it is also redundant.

Flight Software (FSW): The CETUS FSW is built around the modular, GSFC-developed CORE FSW architecture. CORE allows any number of application specific software modules (subject to the constraints of processor speed and memory capacity) to be hosted by an operating system and supported by a number of general-purpose algorithms (e.g., memory management). For CETUS a total of about 100,000 SLOC of FSW will be required, of which ~70% will be reuse, and ~30% will be new or re-engineered.

#### 4.4 Launch Vehicle (LV)

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 one spacecraft (DSCOVR) into a SEL1 orbit, which from a LV perspective requires the same kind of trajectory capability as a SEL2 orbit. However, the mass and stowed volume of the CETUS observatory (Science PL and SC Bus) will need to fit within the Falcon 9 fairing size shown and mass capability to a SEL2 orbit, which are shown in **Figure 4-9**. As illustrated in **Figure 4-9** and the mass margin shown in **Table 4-2**, CETUS is compatible with the Falcon 9 capabilities with margin. The length of the fairing allows an efficient optical design that doesn't require any fold mirrors for packaging.

#### 4.5 Mission Summary

Overall, the CETUS mission implementation consists of high-heritage, high-TRL, conventional hardware components for not only the SC-Bus, but also the LV and NEN-based ground system. The SC-Bus has a "donut-hole" configuration to reduce the overall observatory length, which has been used on many larger SC busses, and its configuration is one that has been done before (e.g., Hubble). It is also beneficial in reducing the moment of inertia in the transverse axes and enables minimization of the Cp-Cg offset, reducing momentum build-up. The





Figure 4-8: Key spacecraft systems are redundant.



**Figure 4-9:** The Falcon 9 fairing and payload dynamic envelope provide margin for the CETUS mission and the Falcon 9 provides margin in launching the mass of the CETUS observatory into a SEL2 orbit.

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.

#### **5 - CONCEPT OF OPERATIONS**

#### **5.1 Science Operations**

CETUS science operations include long-range planning of CETUS observing programs, schedul-

ing CETUS observations, post-launch data processing and archival of CETUS data.

**Long-Range Planning:** CETUS is essentially a survey telescope serving the astronomical community. Long-range planning is relatively simple, since surveys usually involve repeated observations or a selected field. We do not foresee a major General Observer program in the first ~4 years, although individual observing programs may be carried out via Director's Discretionary Time. We envision a small

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number of steering groups for major programs, e.g. survey of the CGM. The steering groups would start during the development of CETUS and continue into the post-launch period. In the development phase, each steering group would be responsible for reviewing hardware development, continually assessing the scientific capabilities of CETUS, and planning for science verification and calibration. In the operations phase, each steering group would formulate an overall plan for executing science and calibration to be carried out in the next six months. A major exception is the steering group for transients. That group would formulate criteria for selecting alerts to be acted upon, which involves interrupting one of the on-going surveys, and for developing canned observing procedures to be stored on-board CETUS for different types of transients.

**Scheduling:** Scheduling of CETUS observations for hand-off to Mission Ops would be similar to that of other astronomical space telescopes.

Post-launch Data Processing: NASA typically requires a science operations center to carry out what is called Level-1 and Level-2 data processing. Level 1 processing consists of receipt of telemetry data and correction of telemetry errors, and formatting the packetized data into an image or spectrogram. Level 2 processing includes removal of the instrument signature and conversion of the data to physical units. NASA typically does not require Level-3 processing, which for CETUS would consist of measurements and archival of these measurements in a relational database, but it is essential for CETUS to maximize its impact. Quantitative measurements are essential for deriving distributions of various parameters and for examining possible correlations with other parameters.

Consider the high-impact paper (2003 citations and counting) by Kauffmann et al. (2003) on active galactic nuclei (AGN) observed in the Sloan Digital Sky Survey: "We find that AGN of all luminosities reside almost exclusively in massive galaxies and have distributions of sizes, stellar surface mass densities and concentrations that are similar to those of ordinary early-type galaxies in our sample." To come to these conclusions, the authors must have made use of measurements of at least 20 parameters on 122,000 galaxies in SDSS images and spectra.

Detailed, robust measurements will be made on CETUS images and spectra; they will be stored along with raw and processed observational data in an archive available to the greater astronomical community. The archive will include a relational database of measurements enabling users to answer scientific questions and make discoveries. CETUS will draw from publicly available algorithms and software being developed for other surveys to derive software pipelines for CETUS data such as "The Hyper Suprime-Cam Software Pipeline" (Bosch et al. 2017), ProFound and ProFit (Driver 2018), Software Pipeline for CGM and IGM spectra (U. MD/Gatane 2018).

#### **5.2 Mission Operations**

The basic concept underlying CETUS operations is that the three science instruments operate together. Joint operation of science instruments is made possible by the comprehensive optical-mechanical design of CETUS in which the wide-field instruments - the NUV MOS and the FUV/NUV camera – have separate apertures at the telescope image plane. The LUV/FUV/NUV PSS spectrograph entrance slit lies at the middle field telescope location, midway between the apertures of the widefield instruments. The middle optic of the Offner - a convex grating in the MOS, a convex mirror in the camera - has an attached tip/tilt/focus mechanism that enables dithering of the spectrogram (MOS) or image (camera) on the detector format while the telescope pointing remains steady. This innovation enables the three instruments to operate to their fullest extent: independently and simultaneously. Given a time on target of ~90% afforded by the orbit about L2, the total observing efficiency of CETUS 3x0.90= 2.7.

What distinguishes the prime instrument in any given observation from the resultant parallel instruments is that the prime instrument sets the telescope pointing on the sky and the time on target. As shown below, the prime instrument is related to the scientific campaign:

- in the massive spectrographic/imaging campaign at z~1-2, the NUV MOS is prime;
- in the campaign on z~0 galaxies, their outskirts, and the CGM, the FUV PSS spectrograph is prime;
- in UV observations for a multi-wavelength observing campaigns, the NUV/FUV camera is prime.

One possible exception to joint operation concerns transients requiring rapid response (on target within an hour of an event; ~45 min mission operation time to command; <15 min slew ane settle) such as catching the early phases of mergers of neutron-star binaries or catching supernovae on the rise. In this case, there is no time to check for bright sources in the field of view, so the NUV camera will be the sole instrument, at least at the start. The CETUS NUV camera is similar to the UVOT telescope on



the Gehrels Swift satellite. Both have a wide field, and both utilize a CCD, which has no requirement for bright-object protection. The difference between the two is the much higher sensitivity of the CETUS NUV camera.

The other exception is the FUV PSS spectrograph operating in long-slit mode. If the long slit is used to scan across a region (called push-broom mode), then it will operate alone. However, the information content of the resulting spectrogram (pointing vs. wavelength) covering 100-142 nm (or 130-180 nm) more than compensates for any loss in "observing efficiency".

The objective of the CETUS Concept of Operations (Conops) is to enable CETUS to accomplish its observational goals from its design orbit and within its design mission lifetime. The main CE-TUS observational goals are to:

- Obtain NUV spectra of ~10<sup>5</sup> galaxies and other surveys in predefined fields over the course of its design mission lifetime while using no more than ~80% of its observing time,
- Use the remaining ~20% of its observing time for other studies consisting of a General Observer (GO) program and the observation of transient Targets of Opportunity (ToO)

The main CETUS orbit and lifetime considerations are that:

- CETUS will be in a SEL2 orbit for a design lifetime of 5 years, although it will have sufficient consumables (primarily propellant) to operate for 10 years
- In this orbit CETUS will be able to  $\sim 2 \pi$  steradians of the sky at any given time (Its Field of Regard or FoR) and  $4 \pi$  steradians of the sky over a time interval of  $\sim 6$  months
- The CETUS FoR is large enough that:
  - » At least some part of the pre-defined survey fields will always be in view
  - » There is at least a 50% probability that CETUS will be able to observe a ToO
  - » A very wide range of GO programs can be easily accommodated

Thus, CETUS will spend  $\sim 22,000$  hours (0.5 x 24 x365 x 5) of its design mission lifetime on the galaxy evolution survey. Using the cadence summarized in **Table 5-1**, the CETUS Camera and MOS instrument will be able to operate in parallel, obtaining every 10 hours FUV and NUV multi-bandpass images, plus spectra of about 100 galaxies with a sufficiently high SNR.

This cadence will result in spectra of ~220,000 galaxies (along with the accompanying multi-band-pass images of the same fields) over its 5-year mission design life, which satisfies the galaxy evolution observational goals (defined in **Section 2.1**) with a generous margin.

There are indications that a ToO will be detected about every 2 weeks and will be followed for an average time of about half a week, which results in <sup>1</sup>/<sub>4</sub> of the design mission duration being used for ToOs. Thus, the remaining 22,000 hours of design mission observation time can be split about 50/50 between ToO's and the GO program.

**Table 5-2** provides the basis for an approximate upper bound on the amount of data that will be generated over a 24-hour period. It assumes that the maximum data volume is generated when using the MOS in parallel with the camera. Later consideration of operational inefficiencies and possible data compression algorithms is expected to reduce the data volume, but this upper limit will be used for the initial definition of the communications requirements.

**Table 5-1:** A typical cadence with the Camera and MOS will enable several hours of FUV/NUV multi-bandpass images and spectra of about 100 galaxies.

| 1. Slew (<1 deg.) to next field   |
|---|
| 2. FGS Acquires Guide Star  |
| 3. CETUS uses FGS to adjust pointing and place pre-selected MOS targets on their assigned MSA shutters                              |
| 4. Assigned MSA shutters (~100) are opened and assigned camera filter is rotated into place   |
| 5. Camera and MOS in parallel take an exposure that lasts up to 30 min  |
| 6. If desired, camera and MOS images may be dithered and a new camera filter may be rotated into place while detectors are read out |
| 7. Steps 5 and 6 are repeated 20 times to get a total MOS integration time of ~10 hours which is needed for an adequate SNR         |

## **Table 5-2:** A conservative estimate of the amount of science data generated in a day has been used to size storage and downlink rates.

| Description                                      | Value                 |
|--|-----------------------|
| Number of MOS CCD Pixels in each Row and Column  | 4096                  |
| Bits per CCD pixel after A2D Conversion          | 16                    |
| Number of Bits produced per CCD readout          | 2.68x10 <sup>8</sup>  |
| Time between CCD readouts/integration time (sec) | 1800                  |
| Number of CCD readouts per 24 hours              | 48                    |
| Number of CCD bits per 24 hours                  | 1.29x10 <sup>10</sup> |
| Number of CCD bits per 24 hours (Gb)             | 12.88                 |
| Increase due to operating camera in parallel     | 2                     |
| Total number of bits in 24 hours (Gb)            | 26                    |



Given a down-link data rate of 8.5 Mpbs, about 30 Gb of science data can be down-linked in ~1-hour to a ground station, which is an amount that provides a margin on the maximum amount of data that the detectors are expected generate daily.

One of the benefits of a SEL2 orbit is that it is close enough to Earth to potentially be able to use a NEN ground station, which is less costly than a DSN ground station. In the case of CETUS, the communications subsystem on the CETUS SC-Bus is sized to support this down-link data rate to a NEN ground station with an 18 m dish. Currently 18 m NEN ground stations are in White Sands and are also expected to be installed at Hartebeesthoek, South Africa.

In parallel with the daily science data downlink, the NEN ground station will also be able to up-link commands and collect CETUS ranging data. CETUS FSW will combine this ranging data with information from the onboard Celestial-Navigation (CelNav) cameras, thus permitting CETUS to perform its own Orbit Determination (OD) and avoid the cost of additional GS tracking. The OD data will in turn be used to plan the orbit maintenance burns. These maneuvers are combined with momentum unloading burns and are performed once per week.

A final aspect of the CETUS conops is the provision for receiving "any-time" alerts of transient ToOs. Because the CETUS HGA antenna is mounted on a two-axis gimbal, it can be pointed toward Earth at all times. The beam-width of the CETUS HGA is sufficient for it to receive at any time a fastenough (>=100 bps) command uplink from any NEN ground station. There are enough NEN ground stations around to world for there to always be one in sight of CETUS. The CETUS attitude control system has a large enough reaction wheel assembly (RWA) to slew to any point in its FoR in less than 15 minutes. Thus, CETUS should begin observing a ToO within 1-2 hours of the approval of the ToO.

#### 6 - TECHNOLOGY DRIVERS AND TECHNOLOGY MATURATION ROADMAPS

The critical technologies for the MOS and the NUV/FUV Camera are listed in **Table 6-1**. During this current CETUS probe design study several technical complexities were eliminated by design simplifications including the deletion of a NUV/FUV dichroic beamsplitter. The MSA is the key technology for further development that is proceeding at GSFC with several design improvements and scale-ups already demonstrated and further array fabrication optimizations being addresses in a recently awarded 3-year SAT. Similarly, advancements in MCPs design and qualifications are benefiting the maturation of the CETUS design.

| Table 6-1:   | The pertinent | <b>CETUS</b> optica | al technologies | are mature of | r will be a | advanced to mee | et CETUS |
|--------------|---------------|---------------------|-----------------|---------------|-------------|-----------------|----------|
| schedule red | quirements.   | *                   | c               |               |             |                 |          |

| Technology   | Heritage/ Comments  |
|--|---|
| Next-Generation Micro-Shutter array  | • JWST NIRSpec MSA space qualified with 365x172 array with 100x200 micrometer shutters [TRL 8 which will be baseline if NGMSA not TRL 6 at Phase A]   |
| <ul><li> 380x190 shutters baselined</li><li> With 100x200 micrometer</li></ul> | • NG MSA pilot demonstrated with 128x64 array so current TRL is 3-4; NASA/JHU sounding rocket experiment with MSA planned for July 2019.  |
| rectangular shutters   | • GSFC currently has 3-year SAT grant which is maturing NGMSA to TRL 5 by 2021 and developing 840x420 array for LUVOIR and HabEx (scale-up applicable to CETUS - though CETUS can accept an even smaller, simpler design).  |
| Micro channel Plate (MCP)<br>detector with high guantum                        | • The CETUS FUV MCP detectors made by U.C. Berkeley Space Sciences Lab are the same technology as flown on the Hubble COS spectrograph.   |
| efficiency in the FUV  | <ul> <li>CETUS FUV Camera MCP uses Csl photocathode (~50x50mm) with MgF2 window – TRL 6+</li> <li>CETUS PSS FUV MCP uses Csl photocathode (200x70 mm) windowless – a 200x200mm MCP has recently flown on a University of Colorado rocket experiment. Csl in windowless MCP detectors have flown many times – this is just a scale-up requirement</li> <li>Sounding rocket programs have and continue to provide verification of comparable MCPs – CU's DEUCE (2017.</li> </ul>  |
|  | 2018) and NASA/JHU's planned July 2019 36.352 UG.   |
| High UV-reflectivity coatings<br>on mirrors                                    | <ul> <li>Telescope optics — LiF coatings from 100 nm+ are the baseline at TRL9 (Copernicus, FUSE). Potential future option of more robust LiF coating which is protected by thin ALD layer — SAT in-progress and another just awarded being monitored as protected Al/LiF coatings progress. Collins has large coating chamber planned which could be modified to apply ALD coating on CETUS OTA PM.</li> <li>Optics in instruments requiring NUV &amp; FUV coatings – Materion (Barr) and ZeCoat are proficient in making special multi-layer UV coatings at these wavelengths and applicable coatings have been demonstrated on small samples. Facilities exist for coating CETUS-size optics.</li> </ul> |





Figure 6-1: NGMSA 840x420 and JWST arrays size comparison: front (left) and back (right) side of array.

#### 6.1 Next-Generation Micro-Shutter Array (MSA)

The MSA is the essential component of the NUV multi-object spectrograph (MOS). A first-generation MSA is already incorporated in JWST (Li, et al., 2017). The size of this MSA array (35x38 mm<sup>2</sup>) and the size of each shutter (100  $\mu$ m x 200  $\mu$ m) are suitable for use by CETUS. The CETUS optical design and packaging assumes the JWST MSA (Figure 6-1), which is TRL 8. However, the enhancing technology of a Next-Generation MSA (NGMSA) is beneficial to assure greater reliability over a long-duration mission. Such a NGMSA is under development (Kutyrev, Moseley, Greenhouse, 2018), first supported by NASA's APRA program and now, as part of NASA's SAT program. Planned flight opportunities for small prototype NGMSA devices (64x128 shutters; Figure 6-2) include a NASA/ JHU sounding rocket 36.352 UG scheduled for July 2019 with a mission to obtain multi-object FUV spectroscopic observations of blue straggler stars in the globular cluster M10.

With its 420x840 shutters, the NGMSA will be larger than what CETUS requires (190x380 shutters), (Figure 6-1) but the CETUS MOS can accommodate the larger NGMSA without alteration of the optical design, and an entrance aperture to the NGMSA can be used to isolate the 38mmX38mm active area that CETUS will use. Regardless of whether CETUS uses the JWST MSA or the larger NGMSA, anti-stiction coatings on the shutters will be used for greater reliability. And regardless of which MSA CETUS uses, the light shields protecting against light grazing off the shutter walls, will be customized for the fast f/5 beam from the telescope (Figure 6-3).

The primary areas of the NGMSA development are: 1) fully electrostatic actuation (compared to the JWST microshutters which require magnetic actuation), 2) modularity of the integrated array unit, 3) higher voltage electrical insulation, 4) thinner microshutter blades, 5) improved antistiction, 6) larger format arrays, and 7) simplified electronics design.



**Figure 6-2:** A pilot design NGM-SA array with 128x64 shutters on a PC board with integrated drivers has been fabricated.



**Figure 6-3** With its microshutter array (MSA), the CETUS MOS will observe selected extended sources such as galaxies at  $z\sim1$ . This schematic shows a cross-section of two shutters, each 100 microns, or 2.75" across. The shutter at left (black) is open to the sky; the shutter at right is closed. Each shutter has light shields (blue) that keep light from grazing the shutter walls (gray), forming scattered light. In this schematic, light from the telescope of a  $\sim3.5$ "-diameter galaxy comes to a focus in the plane of the light shields. The light transmitted by the left shutter goes on to the MOS. (As the galaxy straddles two microshutters, it probably would not be selected for observation.) (Figure credit: Alexander Kutyrev)



#### **6.2 Micro-Channel Plate Sensors**

**MCP Sensors:** Imaging detectors that are sensitive to FUV radiation but robust against particle radiation in an L2 orbit are essential to the success of a CETUS mission. MCP detectors incorporating lead silicate plates coated with a variety of photocathodes with double delay line or crossed delay line for readouts are very mature devices (TRL >7) that have flown on a number of NASA missions. The microchannel plate stacks can be shaped to match curved focal-surfaces as was done for the Far UV Spectroscopic Explorer (FUSE) and the Cosmic Origins Spectrograph (COS) on Hubble. Large-area coverage is very feasible where devices with active areas up to 200 mm X 200 mm having been flown on NASA sounding rockets (McCandliss, et al., 2016).

Recent innovations in MCP detector technology currently at TRL level ~ 4 will offer vast improvements in performance. (1) Atomic layer deposition activated borosilicate MCPs (Ertley, Siegmund, et al., 2015) will offer higher gain at lower bias voltage and longer lifetime, uniformity stability, and increased quantum efficiency. (2) Cross-strip MCP detector systems (Vallerga, et al., 2014) with ASIC-based readout is currently supported by NA-SA's Strategic Astrophysical Technologies (SAT) program.

The study of FUV micro-channel plate-based detectors (MCP) will be led by Spectrograph Systems Scientist, Stephan McCandliss (JHU), in consultation with John Vallerga and Ossy Siegmund of Berkeley Space Sciences Laboratory (SSL). The latter two scientists are supported by NASA's SAT program. Dr. McCandliss is PI of a NASA sounding rocket program, which has flown MCP detectors from the Berkeley group incorporating CsI and KBr photocathodes; an additional flight is planned for July 2019. CU has also flown a sounding rocket experiment (DEUCE) in November 2017 with a 200x200 mm MCP and another flight was achieved in December 2018. TRL 6 should be verified by 2021.

#### 6.3 UV Coating Technologies, Straylight Control, Contamination Control

The CETUS telescope optics are baselined to reflect from 100 nm to 1100 nm. The Fine Guidance sensors utilize the longer wavelengths while the UV instruments have coatings for various bands within the 100-400 nm wavelengths. For example, the dielectric optical coatings for the NUV MOS optics will be designed to reflect the in-band UV and transmit the longer wavelengths. The design is based on coatings previously demonstrated by Materion (MacKenty, 2016) on small samples. The cutoff wavelength will be optimized for 350 nm rather than the 320 nm shown in **Figure 6-4**. The long wave cutoff can be shifted as desired.

The baseline coating approach for the telescope optics is LiF over aluminum. Furthermore, the technology for protected LiF coated atomic layer deposited aluminum is being closely monitored for scaleup to the 1.5-m PM.

No element is more critical to the throughput and bandpass of FUV instrumentation than the reflectivity of the mirror coatings, and no single technology has been more historically limiting to instrument design. This paradigm has suddenly shifted in recent years with the advent of enhanced reflectivity lithium fluoride protected aluminum (eLiF; Quijada et al., 2014, Fleming et al., 2018). These coatings have been demonstrated to exceed 85% reflectivity at 110 nm and 80% at H I Lyβ, approximately 400% more per reflection at these wavelengths than the MgF<sub>2</sub> used on HST, and 30% more than the conventional LiF+Al used on FUSE (Figure 6-5). An ultrathin capping layer of MgF<sub>2</sub> applied over the LiF, which is a hygroscopic salt, provides protection from moisture exposure and vastly reduces the environmental risk historically associated with LiF-based coatings. Protected eLiF coatings enable multi-passed FUV optical designs without crippling throughput losses and onerous environmental procedures. This coating is currently baselined for LU-VOIR-LUMOS, which requires four telescope and three internal reflections to achieve high angular and spectral resolution across its wide-field, multi-object FOV (France et al., 2017). The CETUS probe



**Figure 6-4:** The coatings are designed to sharply reduce reflectance of light longer than 320nm. (Reflectance data adapted from MacKenty, J., 2016)





**Figure 6-5:** The theoretical reflectivity of LiF+Al coatings (red) relative to the best realized conventional coating (Blue). eLiF mirror coatings improve LiF+Al reflectivity to closer to the theoretical limit.

concept requires such a coating to achieve sensitivity to the Lyman ultraviolet.

There are numerous on-going NASA funded efforts to qualify these coatings to TRL 7 by the early 2020 timeframe. The University of Colorado SISTINE sounding rocket program (PI: K. France, Fleming et al., 2016) recently successfully coated a 0.5 meter diameter parabola with eLiF in the 2-m coating chamber at NASA GSFC (results to be published in Proceedings of SPIE in 2019, author: N. Nell). The SISTINE secondary mirror was then overcoated with a protective capping layer at NASA JPL with no appreciable change in total reflectivity despite the limited MgF<sub>2</sub> transmission in the LUV. The JPL facilities are not currently sized to handle optics larger than 20 cm, however studies are on-going to scale up the process. SISTINE is currently in the I&T phase and will launch in summer 2019, advancing unprotected eLiF to TRL 7.

The Supernova remnant/Proxies for Reionization/ Integrated Testbed Experiment (SPRITE) CubeSat was funded by NASA in 2019 as a technology testbed for LUVOIR-enabling technologies, including advanced mirror coatings (Fleming et al., 2019). SPRITE will demonstrate the robustness of protected eLiF coatings to the relatively unprotected environment associated with a CubeSat, where the instrument must sit at ambient humidity for nearly 1 month after delivery to the launch provider. The successful launch of SPRITE in 2022 will bring to TRL 7 the protective overcoat technique necessary for LiF-based coatings to be employed on large missions where environmental restrictions can drive cost and risk.

For protected eLiF coatings to be feasible for CETUS, both the physical vapor deposition (PVD)

method developed at GSFC and the atomic layer deposition (ALD) developed at JPL will need to be scaled up to handle 2-m class optics by 2023. This will require some technology investment, however both PVD and ALD are commonly employed in large deposition chambers. Adapting the GSFC and JPL techniques to larger chambers is feasible within the CETUS timeframe.

Exceptional stray light control of out-of-band radiation can be accomplished by directing the light to highly absorptive light traps comprised of carbon nanotubes (Hagopian, et al., 2010; Butler, et al., 2010). In addition, contamination control during the entire assembly and integration process will be essential to minimize molecular contamination of the optics. Heaters will be incorporated near optical surfaces to allow on-orbit reduction of volatile condensable materials. Also, the telescope has a reusable protective cover that will be closed during launch and any sensitive maneuvers where contamination might be generated.

### 7 - ORGANIZATION, PARTNERSHIPS, AND CURRENT STATUS

The CETUS Probe Study Team consists of scientists and engineers from a range of institutions as presented in the List of Participants preceding **Section 1**. A comparable NASA/university/industry team would 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 is in consideration process for offering to provide the PSS.)

**Figure 7-1** shows the projected schedule for the CETUS Mission development assuming a Phase A start in October 2023 and a launch in October 2030. Operations are planned for a 5-year mission, but consumables are planned to allow a 10-year mission. The continued technology development of the three areas discussed in **Section 6** prior to 2023 are fundamental. Should there be additional break-throughs in areas such as UV coatings (e.g., ALD protected LiF/Al coatings), CETUS will consider incorporating the extended UV range and sensitivity those technologies could offer.

While CETUS Implementation may be accomplished by NASA in several ways, even with diverse laboratories or companies producing assemblies and instruments, and even with foreign contribution of one or more instruments, for the purpose of this study we have evaluated/costed/scheduled an implementation based on input from the industrial/ University/NASA Center study team.



|                 | FY24 |        |     | FY25      |              |     | FY26 |            |        |      | FY27 |         |         |       | FY28 |        |          |          | FY29    |       |       | FY30   |            |    | FY31 |             |        |       |        |      |
|-----------------|------|--------|-----|-----------|--------------|-----|------|------------|--------|------|------|---------|---------|-------|------|--------|----------|----------|---------|-------|-------|--------|------------|----|------|-------------|--------|-------|--------|------|
|                 | 1    | 2 3    | 4   | 1         | 2            | 3   | 4    | 1          | 2      | 3    | 4    | 1       | 2       | 3     | 4    | 1      | 2        | 3        | 4       | 1     | 2     | 3      | 4          | 1  | 2    | 3           | 4      | 1     | 2      | 3 4  |
| Mission Phases  | Pl   | nase A | ۱.  | Ph        | ase          | В   |      |            |        |      | Pl   | nase    | e C     |       |      |        |          |          |         |       |       | Ph     | ase        | D  |      |             |        |       | Pha    | se E |
| Reviews         |      |        | SRR | 1         |              | PDR | /    |            | CE     | DR 🔻 |      |         |         |       |      |        | SIR      | V        |         |       |       | PEF    | R <b>V</b> |    |      | PSR         | /      | Laur  | ch     |      |
| ΟΤΑ             |      |        |     | Pro       | elim<br>sign |     | Fir  | nal Design |        | V    | Ha   | ırdware | Build   | 1     | Int  | Env M  | argi [   | Delive   | r to P, | L I&T |       |        |            |    |      |             |        |       |        |      |
| Camera          |      |        |     | Pre<br>De | elim<br>sign |     | Fina | I Design   | CDP    |      | Hard | ware Bu | uild    | Int   | En   | v Marg | De       | liver t  | o P/L   | &т    |       |        |            |    |      |             |        |       |        |      |
| PSS             |      |        |     | Pre<br>De | elim<br>sign |     | Fina | l Design   | CDR    |      | Hard | ware Bu | uild    | Int   | En   | v Marg | De       | eliver t | o P/L   | 1&T   |       |        |            |    |      |             |        |       |        |      |
| MOS             |      |        |     | Pre<br>De | elim<br>sign |     | Fina | l Design   | V      |      | Hard | ware Bu | uild    | Int   | En   | v Marg | De       | eliver   | to P/L  | 1&T   |       |        |            |    |      |             |        |       |        |      |
| Payload I&T     |      |        |     |           |              |     |      |            |        |      |      |         |         |       |      |        | Int      | egrate   | Env     | Margi | Deliv | ver to | OBS        | &т |      |             |        |       |        |      |
| Spacecraft      |      |        |     | Pre       | lim Des      | ign |      | Final      | Design | V    |      | Ha      | ardware | Build |      | Marg   | in Integ | grate    | Env T   | est   | Deliv | er to  | Obs I      | ¢Т |      |             |        |       |        |      |
| Observatory I&T |      |        |     |           |              |     |      |            |        |      |      |         |         |       |      |        |          |          |         |       | Inte  | grate  | Env        |    | Mar  | Deli        | ver to | Launo | h Site |      |
| Launch          |      |        |     |           |              |     |      |            |        |      |      |         |         |       |      |        |          |          |         |       |       |        |            |    |      | Lau<br>Site | nch    | Lau   | nch    |      |

Figure 7-1: The instruments are developed, fabricated, and tested in parallel. Each task also has funded, built-in margin (shown in green).

NASA will have a model for credible implementation, and costs/schedules derived from this approach. The model can be adapted to other scenarios, including distribution of the payload systems, if deemed advisable and cost effective.

#### 8 - COST ESTIMATION

After consulation with and agreement from NASA Headquarters and NASA's Goddard Space Flight Center management, the CETUS Probe Study Team is unable to provide comprehensive cost information on the point design of the mission concept at the present time. Two internal cost estimates were completed with the second being received just a few days prior to the report due date. Initial reviews show vastly (by over a factor of two) different estimates. This is contrary to normal expectations of a roughly 20% differential. Surprisingly, the higher estimate is typically the lower of the two. Furthermore, the team discovered errors in some of the input data tables used in the higher estimate. Given the unusual discrepancies, the team has determined that there is insufficient time remaining to bring them to a resolution before the report is due. The team will provide a public cost estimate table and a description of the methodologies used only after a credible estimate has been secured, approximately a few weeks after submission.



#### 9 - SUMMARY AND CONCLUSIONS

The CETUS mission concept presented in this report is for a 1.5-m wide-field UV telescope with a broad instrumentation suite consisting of a wide-field camera, multi-object spectrograph, and high-resolution echelle spectrographs. CETUS is designed for a five-year mission life in a SEL2 orbit, with enough propellant and other consumables to operate successfully for up to ten years. Its SEL2 orbit provides constant sunlight, thermal stability, constant contact with Earth, the ability to view  $2\pi$  steradians of the sky at any time and  $4\pi$  steradians of the sky every 6 months. This orbit enables efficient surveys and a high probability of being able to quickly observe any transient event.

The above features will allow CETUS to not only maintain equivalent or better observational access to the ultraviolet (UV) after Hubble is gone, but also be a companion to multi-wavelength survey telescopes of the 2020's, a scout for the extremely large ground-based telescopes that will operational starting the mid-to-late 2020s and beyond, and a provider of discoveries that can be pursued by other space telescope concepts, such as HabEx or LUVOIR.

The starting point for defining the capabilities of CETUS was the Astro2010 panel's recommendation for a more capable UV-optical telescope to follow Hubble. The panel did not identify the capabilities or rank them in priority, but they can be inferred from the Key Scientific Questions that they posed, questions that will continue to of great importance to the astronomical community in upcoming years. Nearly half of them, spanning nearly all areas of astrophysics ranging from cosmology to habitable planets, can be addressed by CETUS. Examples of Astro2010 questions that CETUS can address (from **Table 2-1**) include:

- What is dark matter?
- What are the flows of matter and energy in the circum-galactic medium?
- · What controls the mass-energy-chemical cycles within galaxies?
- · How do cosmic structures form and evolve?
- How do black holes grow, radiate, and influence their surroundings?
- Do habitable worlds exist around other stars?

However, the Astro 210 questions were not the ending point for the CETUS design. New capabilities and new observations, such as those summarized in **Table 1-1**, were also designed in. Thus, CETUS not only allows for revolutionary progress on the questions listed above, along with others in **Section 2**, but also for discoveries that we cannot anticipate at this moment in time. Just as Hubble was not specifically designed to discover Dark Energy, it was able to do so because it had a broad instrument suite. Similarly, Hubble was not designed specifically to take some of the first transit spectra of exoplanets around nearby stars, it was able to do so, again because of its broad instrumentation suite. The broad reach of CETUS' instruments will allow it achieve the unexpected.

In summary, if a Probe line of missions is endorsed by the Astro2020 Decadal Survey and is funded by Congress, the CETUS team hopes to fulfill its dream of enabling the upcoming generation of astronomers and astrophysicists to make paradigm-changing discoveries in the late 2020's and the following decade that will inform and inspire the public about the amazing cosmos we live in. By means of its innovative design for a WFOV telescope, three complementary science instruments, wide FoR, and quick reacting spacecraft, as well as minimal needs for new technology, the CETUS study team strongly believes that CETUS can achieve the ambitious science objectives set out for it at low risk while staying within a Probe-class cost cap and schedule.



#### **Public Cost Table**

After consulation with and agreement from NASA Headquarters and NASA's Goddard Space Flight Center management, the CETUS Probe Study Team is unable to provide comprehensive cost information on the point design of the mission concept at the present time. Two internal cost estimates were completed with the second being received just a few days prior to the report due date. Initial reviews show vastly (by over a factor of two) different estimates. This is contrary to normal expectations of a roughly 20% differential. Surprisingly, the higher estimate is typically the lower of the two. Furthermore, the team discovered errors in some of the input data tables used in one of the estimates. Given the unusual discrepancies, the team has determined that there is insufficient time remaining to bring them to a resolution before the report is due. The team will provide a public cost estimate table and a description of the methodologies used only after a credible estimate has been secured, approximately a few weeks after submission.



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### Acronym List

| Acronym | Definition                                   |  |  |  |  |  |  |
|---------|--|--|--|--|--|--|--|
| 4MOST   | 4-meter Multi-Object Spectrograph Telescope  |  |  |  |  |  |  |
| ACS     | Advanced Camera for Surveys                  |  |  |  |  |  |  |
| ACS     | Attitude Control Subsystem                   |  |  |  |  |  |  |
| AGN     | Active Galactic Nucleus                      |  |  |  |  |  |  |
| AI&T    | Alignment, Integration, and Test             |  |  |  |  |  |  |
| ALD     | Atomic Layer Deposition                      |  |  |  |  |  |  |
| AOS     | Arizona Optical Systems                      |  |  |  |  |  |  |
| ATLO    | Assembly, Test, and Launch Operations        |  |  |  |  |  |  |
| BCCG    | Brightest Cluster Galaxies                   |  |  |  |  |  |  |
| BNS     | Binary Neutron Star                          |  |  |  |  |  |  |
| BSG     | Blue Supergiant                              |  |  |  |  |  |  |
| CCD     | Charged-Coupled Devices                      |  |  |  |  |  |  |
| CETUS   | Cosmic Evolution Through UV Spectroscopy     |  |  |  |  |  |  |
| C&DH    | Command & Data Handling                      |  |  |  |  |  |  |
| CDM     | Cold Dark Matter                             |  |  |  |  |  |  |
| CFRP    | Carbon Fiber Reinforced Polymer              |  |  |  |  |  |  |
| CGH     | Computer-generated Hologram                  |  |  |  |  |  |  |
| CGM     | Circumgalactic Medium                        |  |  |  |  |  |  |
| CIM     | Calibration Insert Mirror                    |  |  |  |  |  |  |
| CMM     | Coordinate Measuring Machine                 |  |  |  |  |  |  |
| CNES    | Centre national d'etudes spatiales           |  |  |  |  |  |  |
| Conops  | Concept of Operations                        |  |  |  |  |  |  |
| COS     | Cosmic Origins Spectrograph                  |  |  |  |  |  |  |
| CTE     | Coefficient of Thermal Expansion             |  |  |  |  |  |  |
| DDF     | Deep Drilling Field                          |  |  |  |  |  |  |
| DE      | Dynamic Envelope                             |  |  |  |  |  |  |
| DoF     | Degree of Freedom                            |  |  |  |  |  |  |
| DSN     | Deep Space Network                           |  |  |  |  |  |  |
| EM      | Electromagnetic                              |  |  |  |  |  |  |
| EOL     | End of Life                                  |  |  |  |  |  |  |
| EPS     | Electrical Power System                      |  |  |  |  |  |  |
| EUV     | Extreme Ultraviolet                          |  |  |  |  |  |  |
| FEE     | Front End Electronics                        |  |  |  |  |  |  |
| FEFDAT  | Front End Field Diverse Autocollimation Test |  |  |  |  |  |  |
| FGS     | Fine Guidance Sensor                         |  |  |  |  |  |  |
| FoR     | Field of Regard                              |  |  |  |  |  |  |
| FoV     | Field of View                                |  |  |  |  |  |  |
| FPA     | Focal Plane Assembly                         |  |  |  |  |  |  |
| FSW     | Flight Software                              |  |  |  |  |  |  |
| FUSE    | Far UV Spectroscopic Explorer                |  |  |  |  |  |  |
| FUV     | Far Ultraviolet                              |  |  |  |  |  |  |
| GALEX   | Galaxy Evolution Explorer                    |  |  |  |  |  |  |
| GEO     | Geosynchronous Orbit                         |  |  |  |  |  |  |

| Acronym | Definition   |
|---------|--|
| GHRS    | Goddard High Resolution Spectrograph                         |
| GIANT   | Goddard Image Analysis Navigation Tool                       |
| GO      | General Observer   |
| GRB     | Gamma-ray Burst  |
| GSFC    | Goddard Space Flight Center                                  |
| GW      | Gravitational Wave   |
| HDST    | High-Definition Space Telescope                              |
| HGA     | High Gain Antenna  |
| HSF     | High Spatial Frequency                                       |
| HST     | Hubble Space Telescope                                       |
| HZ      | Habitable Zone   |
| ICD     | Interface Control Document                                   |
| IEM     | Integrated Electronics Module                                |
| IGM     | Inter-Galactic Medium  |
| IR      | Infrared   |
| ISM     | Inter-Stellar Medium   |
| IRSO    | Indian Space Research Organization                           |
| IUE     | International Ultraviolet Explorer                           |
| JATIS   | Journal of Astronomical Telescopes, Instruments, and Systems |
| JHU     | Johns Hopkins University                                     |
| JWST    | James Webb Space Telescope                                   |
| km      | kilometer  |
| LAE     | Lyman alpha emitting   |
| LAMOST  | Large Sky Area Multi-Object Fibre Spectroscopic Telescope    |
| LEO     | Low Earth Orbit  |
| LEV     | L2 Earth Vehicle   |
| LGA     | Low Gain Antenna   |
| LMT     | Large Millimeter Telescope                                   |
| LOS     | Line of Sight  |
| LSF     | Line Spread Function   |
| LSF     | Low Spatial Frequency  |
| LSST    | Large Synoptic Survey Telescope                              |
| LUV     | Long Ultraviolet   |
| LUVOIR  | Large UV/Optical/IR Surveyor                                 |
| LV      | Launch Vehicle   |
| mas     | milli-arcsecond  |
| МСР     | Micro-Channel Plates   |
| MDL     | Mission Design Lab   |
| MEB     | Main Electronics Box   |
| mm      | millimeter   |
| MOS     | Multi-object Spectrograph                                    |
| MSA     | Micro Shutter Array  |
| MSF     | Mid Spatial Frequency  |



| Acronym | Definition                                    |
|---------|---|
| NASA    | National Aeronautics and Space Administration |
| NEN     | Near Earth Network                            |
| NG MSA  | Next Generation Micro Shutter Array           |
| nm      | nanometers                                    |
| NIR     | Near Infrared                                 |
| NGIS    | Northrop Grumman Innovation Systems           |
| NUV     | Near Ultraviolet                              |
| NWNH    | New World New Horizons                        |
| 0A0     | Orbiting Astronomical Observatory             |
| OTA     | Optical Telescope Assembly                    |
| PAF     | Payload Adapter Fitting                       |
| PDU     | Power Distribution Unit                       |
| PFS     | Prime Focus Spectrograph                      |
| PI      | Principal Investigator                        |
| PIE     | Payload Interface Electronics                 |
| PL      | Payload                                       |
| PM      | Primary Mirror                                |
| PSS     | Point/Slit Spectrometer                       |
| QSO     | Quasi-stellar Object                          |
| OSSA    | Outer Sun Shield Assembly                     |
| RSG     | Red Supergiant                                |
| RTOS    | Real Time Operating System                    |
| RWA     | Reaction Wheel Assembly                       |
| SA      | Solar Array                                   |
| SAT     | Strategic Astrophysics Technologies           |
| SC      | Spacecraft                                    |
| SDSS    | Sloan Digital Sky Survey                      |
| SED     | Spectral Energy Distribution                  |
| SI      | Scientific Instrument                         |
| SKA     | Square Kilometer Array                        |
| SM      | Secondary Mirror                              |
| SMBH    | Supermassive Black Hole                       |
| SSL     | Space Science Labs                            |
| STIS    | Space Telescope Imaging Spectrograph          |
| SUIT    | Solar UV Imaging Telescope                    |
| SW      | Software                                      |
| TBD     | To Be Determined                              |
| TBR     | To Be Resolved                                |
| TDE     | Tidal Disruption Event                        |
| TEC     | Thermoelectric Cooler                         |
| TESS    | Transiting Exoplanet Survey Satellite         |
| TM      | Tertiary Mirror                               |
| TMA     | Three Mirror Anasigmatic                      |
| TMT     | Thirty Mirror Telescope                       |
| ToO     | Targets of Opportunity                        |

| Acronym | Definition                           |
|---------|--------------------------------------|
| TRL     | Technology Readiness Level           |
| UV      | Ultraviolet                          |
| UVIT    | Ultraviolet Imaging 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                           |