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Progress Report on the All-UV Probe Mission Concept, CETUS

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ABSTRACT

We report on the status of CETUS, an all-UV, Probe-class mission concept to be evaluated by the Astro2020 Steering Panel. This report expands and updates the scientific uses of CETUS and CETUS technology as described earlier by Kendrick et al. (2019). The major updates derive form technological advances that promise to make CETUS a scientifically more powerful and long-lived space observatory than originally proposed. A long, useful lifetime will be needed to fulfill the future needs of the astronomical and planetary-science community.

Keywords: Ultraviolet, mission concept, spectrograph, multi-object spectrograph, microshutter array, camera

1. INTRODUCTION

After 30 years in orbit and 11years since the last servicing mission, the Hubble Space Telescope is old. Yet every year, Hubble is overloaded with observing proposals. This oversubscription is partly due to Hubble's unique capabilities, one of which is that Hubble gives access to the UV, a spectral region rife with astronomical diagnostics. But at some time, Hubble will end. What will take its place? We describe a NASA Probe-class, all-UV mission concept, called CETUS which should be a worthy successor. We proposed to study CETUS to NASA four years ago and were selected. We find that, except for exquisite imagery, CETUS can do most of the things Hubble does now, yet is enough different from Hubble to provide new kinds of UV observations. Figure 1 summarizes the CETUS instruments and their capabilities.

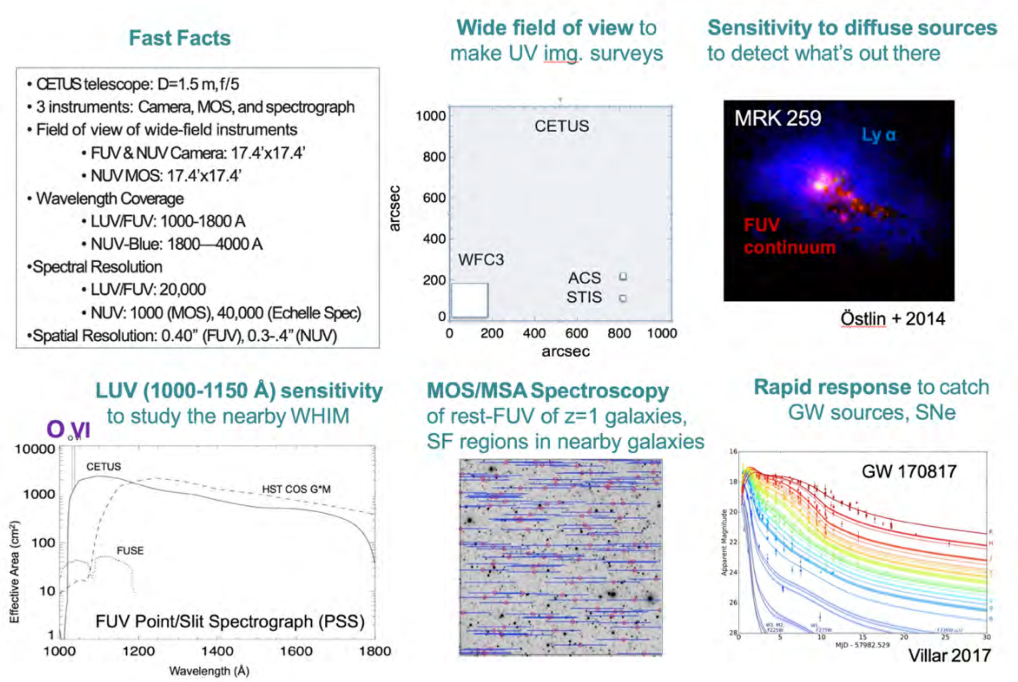

Figure 1. Visual summary of the unique features of the CETUS space telescope.

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In 2016, we proposed a 1.5-m rather fast (*f*/5) telescope with three instruments: a far-UV/near-UV camera like Hubble's ACS or STIS but having a wide field, a far-UV/near-UV spectrograph like Hubble's COS and STIS, and a new instrument: a multi-object spectrograph with a microshutter array like that in JWST's NIRMOS. We were careful to propose only high-heritage components like those already in Hubble and JWST to give credibility to our contention that CETUS could be built on a Probe budget.

Now in 2020, we have the same telescope and instruments but many critical components within these instruments are new and improved. We will describe these improvements in Section 3. In addition, we have witnessed new kinds of astrophysical events like the neutron star binary merger, and we have benefitted from the explosion of ideas expressed in the Astro2020 Science White Papers; the White Paper, "UV-based Science in the Solar System: Advances and Next Steps" submitted by Hendrix et al. (2020) to the Planetary Science and Astrobiology Decadal Survey, 2023-2032; and White Papers submitted to "Voyage to 2050", the next planning cycle of the ESA science program. These papers have had a profound effect, which we describe in Section 2.

Formal study of CETUS ended in March 2019 with submission to NASA of the *CETUS Final Report*, but later, we posted another CETUS Final Report (Heap et al. 2019). Study of the CETUS mission concept by the co-I team has continued to this day. Our partners have continued to develop critical components of CETUS, usually bolstered by funds from NASA's APRA and Strategic Astrophysics Technologies (SAT) programs. The result is a CETUS mission concept that is both scientifically more powerful and long-lived. Section 3 of this report gives the details.

2. EXPANDED SCIENCE CASES FOR CETUS

CETUS will work in concert with other telescopes of the 2020's and 2030's to solve major problems in astrophysics. These other telescopes are generally used to observe astronomical sources at wavelengths other than the UV. (This is not to discount high-resolution UV data from Hubble.) Some of these telescopes are on the ground, and some, in space. Figure 2 shows some examples. Going clockwise from lower left:

- CETUS will observe nearby galaxies imaged by E-ROSITA, which has already completed a first-year survey of the X-ray sky;
- CETUS will follow up on interesting transients discovered by the Rubin telescope (formerly LSST)
- CETUS will add a NUV extension to optical/IR images and spectra obtained by Subaru's Hyper-Suprime Cam and Prime-Focus Spectrograph, Euclid, and Roman (formerly WFIRST) telescopes;
- CETUS will study "100,000 star factories" in 74 nearby galaxies being observed by ALMA in the PHANGS survey of CO (a proxy for H_2) in star-forming galaxies;
- CETUS will join with the SKA and Roman to track the evolution of hydrogen in the universe in all its forms: ionized hydrogen, atomic hydrogen including Lyman-alpha and 21-cm radiation, and molecular hydrogen.

The emphasis on surveys is intentional and deserves some mention. A survey isn't meant just to collect more data; it is to derive *distributions.* What is an astronomical distribution? The Initial Mass Function (IMF) of stars is a distribution. So is the distribution of galaxy colors, and so on. With the distributions in hand, we can then look for correlations among distributions (e.g. galaxy morphology correlates with galaxy color) and identify their physical drivers. This is the best way to unravel multi-parameter processes.

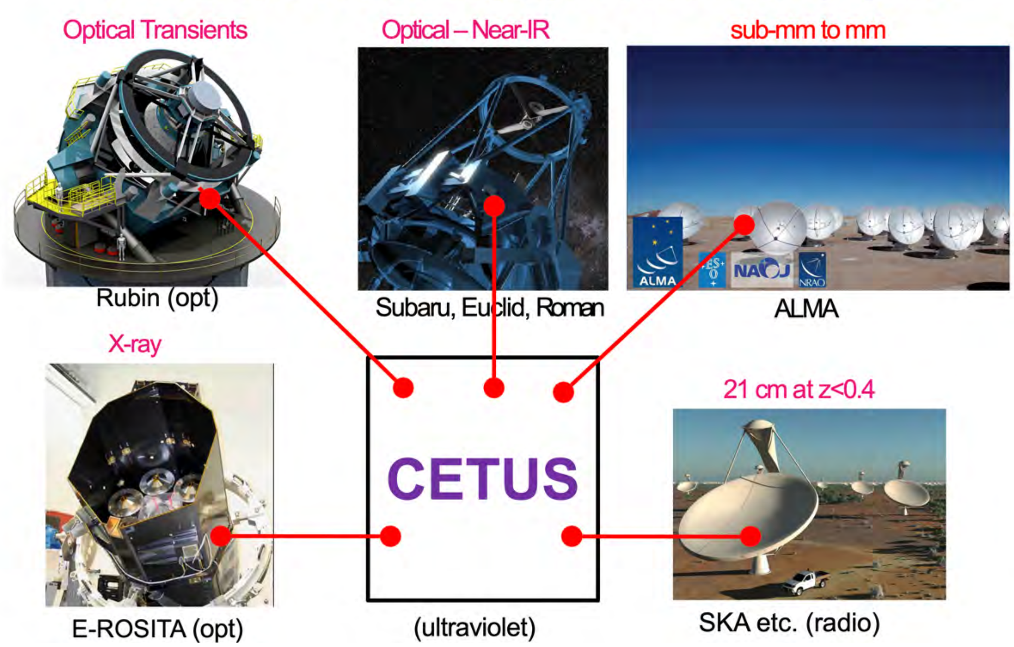

Figure 2. CETUS will work other telescopes of the 2020's and 2030's to solve major problems in astrophysics.

There are *lots* of examples of scientific quests that surveys including CETUS will contribute to – too many to list here, so we describe just 2 examples. One is on the circumgalactic medium where we show how e-ROSITA (X-ray) and CETUS (UV) observations are complementary to one another for solving the problem of the missing baryons. The other example is on star formation, where we show how CETUS will contribute to our understanding of star formation through observations of dust and gas in or near the star-forming region.

2.1 Science Case: The Warm-Hot Circumgalactic Medium (CGM): CETUS and E-ROSITA

In 2018, Brian Fleming and colleagues (Fleming et al. 2018) demonstrated how one could build a relatively large telescope like CETUS that is sensitive at the spectral region of the O VI doublet at 1032, 1038 Å in nearby galaxies (Fig. 1, lower left). The O VI doublet is the only tracer we have of the warm-hot medium ($T \sim 1\text{-}5 \times 10^5$ K). Hubble can't observe it in nearby galaxies because its telescope mirror coatings make it insensitive at wavelengths less than ~1150 Å. FUSE in principle could have done it, but its telescope was too small. The upshot is that CETUS, with its sensitivity extending to 1000 Å, will be the first to observe warm-hot gas surrounding *nearby* galaxies and measure the strength of their O VI lines. According to the *Pairs* Catalog (David Bowen, 2018, priv. comm.) there are about 160 nearby galaxies that can be probed in this way. Such observations less than double the number of galaxies that have already been observed by Hubble's COS. However, COS galaxies are nearly all at redshifts, z=0.15 or more. A redshift of 0.15 doesn't sound like much, but compared to a galaxy at 10 Mpc, that galaxy is 9 mag fainter and only $1/50^{th}$ the size of the nearby galaxy; it's only a smudge even, on a Hubble image. The CETUS sample of nearby galaxies has names like M-this and NGC-that. We *know* these galaxies. Most have been observed over the full electromagnetic spectrum. *They* are the ones that will enable us to relate the properties of the CGM to the properties of the galaxy, and vice versa. That is an important goal of CGM research.

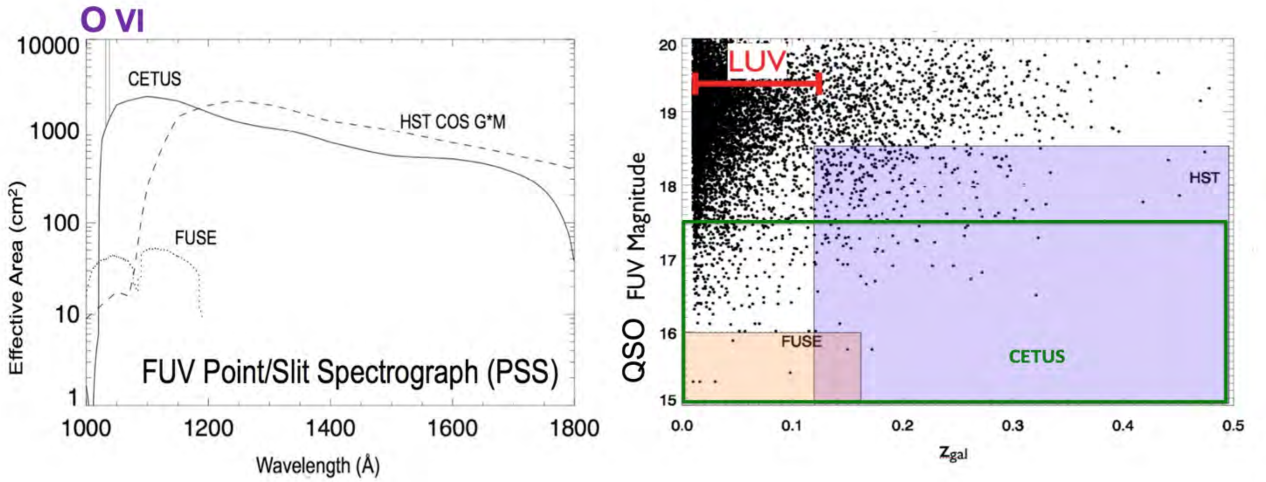

Figure 3. CETUS and X-ray telescopes together will find the missing baryons in the circumgalactic medium around nearby galaxies, and CETUS will relate the properties of the CGM to those of the galaxy. Left: The only diagnostic of warm-hot gas is the OVI doublet at 1032 and 1038 Å. The LUV/FUV spectrograph on CETUS is able to detect and measure the strengths of these two lines. Right: There are 160 nearby galaxies whose background QSO's are brighter than m_{AB}=17.5 for CETUS to observe (green box). They are already well studied galaxies, so it will be possible to look for correlations between the properties of these galaxies and their "halos".

2.2 Science Case: Star Formation: CETUS + ALMA + MUSE

There is an on-going multi-telescope project called PHANGS that aims to "understand the interplay of the small-scale physics of gas and star formation with galactic structure and galaxy evolution" by observing "100,000 star factories" in 74 galaxies. So far, the PHANGS project has observed a good fraction of these galaxies with ALMA (mm) and MUSE (H-alpha). Stars form in cold, dense molecular clouds, and dust is a major player in the star-formation process. Dust promotes the formation of molecular hydrogen in the first place as H_2 can only form from two H atoms on the surface of a dust grain. Dust shields molecules from photo-electric heating of the ambient radiation field, thereby enabling them to cool to the low temperatures required for star formation. After stars have formed, their winds become strong enough to disperse the dust to reveal newly born massive stars in optical light.

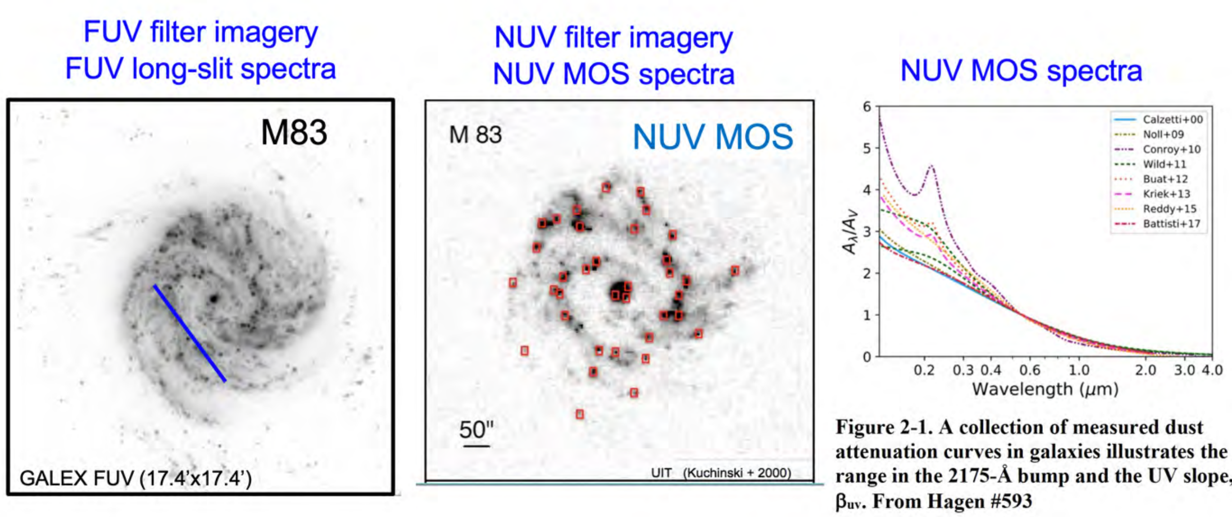

Figure 4. CETUS will play a vital role in elucidating star formation as shown in the example of M 83.

CETUS will make a sensitive and quantitative study of the dust, gas, and young stars in all 100,000 “star factories” observed by PHANGS as illustrated in Figure 4 for the case of M 83. With its wide-field, far-UV and near-UV camera, CETUS will observe the whole extent of each galaxy at a resolution of 0.4”. With its long-slit (6’x1”) on the far-UV spectrograph (blue line in figure at left), it will trace changes in the physical conditions within the galaxy. CETUS will take a further step: it will obtain near-UV MOS spectra of H II regions of M83 (red squares of central figure) that will tell us about the sizes and composition of the dust (right), which in turn tells us about the physical conditions of the star-forming regions and how they relate to the general properties of the galaxy. Coverage of the whole galaxy is essential for relating the properties of dust, gas, and stars with metallicity, which generally decreases with increasing distance from the galactic nucleus.

2.3 CETUS in discovery mode

CETUS will also work continually in discovery mode. Basically, one or both wide-field instruments are always on to obtain deep-sky images or spectra. The scientific goal is to discover “what’s out there” by detecting sources by their emission at Lyman-alpha even if their continuum flux is undetectable. For example, when the near-UV MOS is prime, the CETUS far-UV camera can map Lyman-alpha galaxy halos tens of kpc further out from galaxies than can Hubble (see Fig. 1, top-right). and the CETUS far-UV spectrograph can search for Lyman-alpha emission sources at z<0.4 as shown Figure 5 at left. If the CETUS camera is prime, the CETUS MOS can map Lyman-alpha emission near z~0.7-1.8 galaxies or QSO’s. If the near-UV or LUV/FUV spectrograph is prime, both MOS and Camera can observe in parallel. Both the MOS and Camera have a tip/tilt/focus mechanism that allows these instruments to dither to recover resolution even as the telescope pointing is held steady. This capability ensures that parallel observations can have the same quality as would be obtained if the instrument were prime. The prime instrument only sets the telescope pointing, roll angle, and time on target.

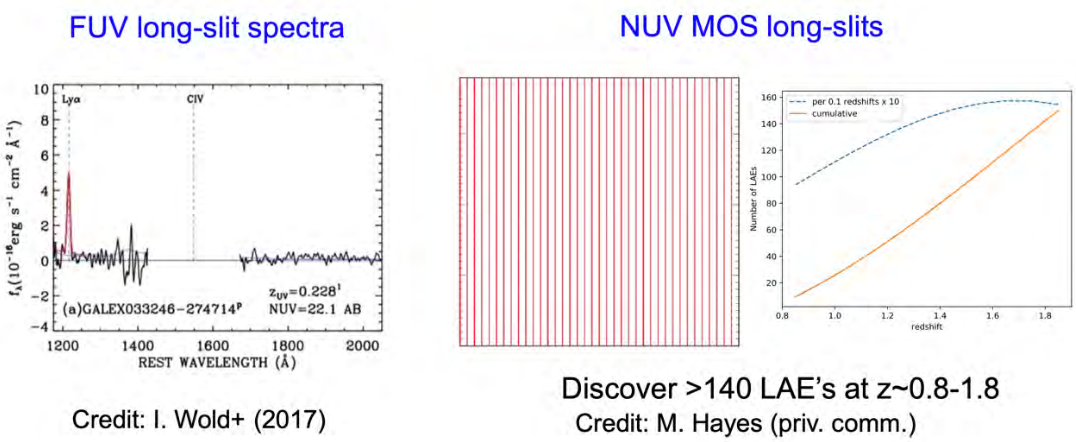

Figure 5. CETUS observations in discovery mode take advantage that each of the three scientific instruments has its own entrance aperture, so all instruments can observe at the same time. Left: detection by the GALEX far-UV spectrograph of Lyman-alpha emission at z=0.228 in sources with undetectable continuum flux. Middle: the CETUS microshutter array can be configured into 38 very long slits (17.4’x2.75”) about a half-arcmin apart. Together, this grid of long slits will be used to search for Lyman-alpha emission (LAE) over an area of 300 sq. arcmin even while the telescope pointing is fixed. Right: Matthew Hayes estimates that over 140 LAE sources at z=0.8-1.8 can be detected in this way.

3. ADVANCES IN TECHNOLOGY BENIFITTING CETUS

3.1 Far-UV instruments (camera and spectrograph)

*Far-UV Detectors***.** CETUS will make far-UV observations utilizing a wide-field far-UV camera and a FUV/LUV spectrograph. The FUV camera on CETUS has no true precursor, as FUV cameras on Hubble's ACS and STIS have very narrow fields of view (Figure 1, top-center), and their FUV detectors were MAMA detectors. The closer antecedent to the CETUS camera is the far-UV camera on GALEX (Martin et al. 2005). Their design choices were like ours: they were constrained by cost to a single detector, and they traded in image resolution for a wide field. Their detector choice was the same as ours: a microchannel plate detector (MCP) with a CsI photocathode made by Berkeley Space Science Labs in California.

The LUV/FUV spectrograph on CETUS has a more recent and direct precursor: the Cosmic Origins Spectrograph (COS) on Hubble, which utilizes a MCP detector also made by Berkeley SSL. While we observers have been delighted by COS far-UV spectra, the far-UV MCP detector has been vastly improved since the COS MCP was made. Table 1 summarizes some of the advances since COS by comparing the properties of the far-UV MCP's for CETUS with those of the COS MCP detector.

Table 1: Comparison of CETUS and HST/COS Far-UV MCP detectors

MCP parameter\/mission	CETUS FUV MCP	HST/COS FUV MCP
Detector type	XS (cross-strip), CsI photocathode	XDL, CsI photocathode
Larger Format	60 mm x 200 mm (spectrograph), 50 mm x 50 mm (camera)	2x85 mm X 12 mm; 9-mm gap ----
Higher Spatial Resolution	20-micron FWHM	35-micron FWHM
Lower Gain	10^6	10^7
High count-rate limit	? >10^6 cnt/s/segment (global)	0.67 cnt/sec/pix (local), 15,000 cnt/sec/segment (global)
Ultra-low background	0.05 events/sec/cm^2 (pre-launch)	<0.5 events/sec/cm^2 (pre-launch)
DQE at 1152, 1334, 1560 Å 1025 Å	58%, 32%, 18% (Siegmund 2019, Fig. 18) 45% at λ=1025 Å	44%, 26%, 12% 42% at λ =1025 Å
Long- λ Limit	~1800 Å (CsI cutoff)	~1800 Å (CsI cutoff)
Long stable lifetime	>4x10^{13} events/cm^2	4 lifetime positions due to gain sag

Background. The far-UV sky is darker than in the near-UV mainly because there is no zodiacal light in the far-UV. In fact, the only significant source of astronomical background in the far-UV is scattering of solar Lyman-alpha by hydrogen atoms in the interplanetary medium, which only contaminates about +/- 5 Å around Lyman-alpha at 1216 Å. The FUV sky will appear even darker in CETUS images, because Berkeley SSL has switched to a borosilicate glass in the MCP having low intrinsic radioactivity. The result is a background that is only a tenth that on COS. The lower background will enable CETUS to detect even fainter astronomical structures at redshifts, z=0.01-0.40.

Longer Lifetime. The limited lifetime of a detector or instrument on Hubble has not been such a critical issue, because Hubble instruments were designed to be replaceable on Hubble servicing missions. This is not the case for CETUS. What is launched stays with CETUS; no servicing is envisioned. There are no plans for another servicing mission to Hubble. In COS's 11 years in space, the spectral format on the detector has had to be moved 3 times to a fresh location in order to avoid "gain sag" at positions that have received heavy doses of radiation. Each move has entailed a totally new recalibration program, and each location is not quite as good as the first.

The CETUS MCP should not have these troubles. It should be long lived, as it will operate at a much lower gain than does Hubble's COS MCP detector. Our expectation, although not a formal requirement, is for the CETUS MCP detectors to last 20 years or forever long it takes until the next UV mission takes its place.

Extension of UV sensitivity into the Lyman-UV. For astronomers, one of the most exciting features about CETUS is the extension of sensitivity of the far-UV spectrograph down to 1000 Å, well into what is called the Lyman UV (900-1200). On Hubble, AstroSat, and other space observatories currently operating, the short-wave limit is ~1150 Å. In that 150-Å segment between 1000 and 1150 Å lie extremely important diagnostics that the FUSE observatory was able to exploit. However, FUSE had a small collecting area and hasn't been operational since 2007. Since then, the science case for LUV observations has grown substantially, so a 1.5-m aperture telescope with LUV sensitivity is most welcome. Probably, the biggest use of the far-UV spectrograph will be spectroscopy of AGN's or QSO's whose line of sight pierces the circumgalactic medium of nearby galaxies, which leave their imprint in the form of O VI absorption lines at 1032, 1038 Å (Section 2.1). O VI is the only diagnostic of the warm-hot circumgalactic medium, which is where arguably the bulk of baryons in the modern universe lies. CETUS observations of the O VI doublet in the CGM of nearby galaxies will double the total number of lines of sight investigated, but its main value is that they will tell us about the CGM around *nearby* galaxies. Nearby galaxies are generally well observed and their properties well determined. Hence, observations of nearby galaxies mean that an inquiry into the relationship between a galaxy and its CGM can begin in earnest.

The far-UV spectrograph in our original 2016 proposal to NASA did not have LUV sensitivity. Instead, it was a conventional far-UV spectrograph with mirrors coated with Al and MgF_2, like all Hubble far-UV spectrographs. Indeed, that was the only option, because both the Hubble telescope primary and secondary mirrors were coated with Al/MgF_2. Our 2016 CETUS proposal followed the Hubble recipe because Al overcoated with LiF, which *is* sensitive down to 1000 Å, requires extraordinary measures to prevent degradation in humidity that would surely occur sometime before the launch of CETUS. That presumption was upended by Fleming et al. (2018), who showed that overcoating LiF with an Atomic Layer Deposition (ALD) coating of MgF_2 or AlF_3 would prevent degradation in conditions up to 50% humidity. A 10 to 20-A overcoating is thick enough to protect the LiF coating from humidity but thin enough to be essentially non-absorbent.

Since learning of this technique, we have adopted the Fleming prescription and contacted both L3Harris (Rochester) and Danbury Mission Solutions. We found that either company could coat the CETUS 155-cm telescope primary mirror substrate providing a clear aperture diameter of 150 cm. Other mirrors on CETUS are small enough (<50 cm) that JPL could apply the ALD coatings.

3.2 Near-UV instruments (camera, spectrograph, and MOS)

Near-UV Detectors. CETUS has 3 near-UV scientific instruments: a spectrograph, a multi-object spectrograph (MOS), and a camera. All 3 instruments in our 2016 proposal to NASA were to employ the same 4K x 4K CCD from Teledyne-e2V, which was ready, off-the-shelf. At that time, Teledyne-e2v also produced an EMCCD but only in a 1Kx2K version. This EMCCD has been flight-tested in the joint NASA/CNES balloon experiment, FIREBALL-2 (Hamden et al. 2020), the pioneering experiment in UV detection of faint, extended sources in the CGM. Recently, Teledyne-e2v announced the 4K x 4K EMCCD, and NüVü has announced a new version of CCD packaging and control electronics for photon-counting for this size EMCCD. We are in the process of adopting EMCCD, CCD packaging, and control electronics by NüVü for all three near-UV instruments on CETUS.

The obvious advantage of EMCCD is no read-noise, a capability that should enable us to detect ever fainter UV sources. While there remain other sources of noise even with photon-counting, such as clock-induced charge and "excess noise factor", they should add up to less than 1 e^- effective read noise.

There are other important advantages of EMCCD's as well. CETUS's ambitions call for a long useful lifetime – something that has been problematic for CCD's on Hubble. Cosmic rays damage a CCD leading to a loss of its charge-transfer efficiency (CTE). On Hubble, the solution has been in-orbit replacement. Hence, we've had three generations of cameras on Hubble: WF/PC, WFPC2, and WFC3 (and would welcome a fourth if it became available!). In-orbit replacement is not possible for CETUS because it will orbit the sun-earth L2 point ~0.01 AU away. And worse: cosmic rays will be more plentiful at L2 and have an admixture of heavy ions. The NüVü CCD Control electronics for Counting Photons (CCCP) produces photo-electron multiplying gains of up to 5000 for detecting individual photons. This sizable gain has the effect of enhancing CTE, thereby extending the useful lifetime of near-UV detectors and CETUS in general.

CETUS is geared for detecting faint diffuse sources. Although the CETUS telescope is smaller than Hubble's, that is of no consequence: a large aperture provides no benefit as the observed surface brightness scales as $(f/D)^{-2}$. The small f-ratio of CETUS, $f/D=5$, makes it 23 times more sensitive to extended sources than is Hubble whose f/D=24. However, detecting very faint surface-brightness sources requires a low instrumental background, e.g. low dark current, while maintaining a high CTE. Experience with balancing all the operating parameters provided by NüVü's CCCP will be needed to optimize the Teledyne-e2v EMCCD. Testing and calibration of the T-e2V NUV detector by NASA/CNES FIREBALL-2 team (Picouet et al. 2020) and the optical EMCCD by the Roman team will be helpful to all of us following them.

The Near-UV camera. The Sloan Digital Sky Survey (SDSS) has set the gold standard in filter photometry by devising a scheme of filters, *u*, *g*, *r*, *i*, *z* that overlap one another at the half-power point. This set of filters enables very low-resolution spectrophotometry with full assurance that strong emission lines within the wavelength range of the camera would be detected at one or two filters. Nearly all optical surveys since then have adopted the SDSS filter set. Our plan is to extend the SDSS system into the UV. The filter wheel can accommodate 6 spectral filters. We plan on 5 overlapping filters covering the wavelength region, 2000-4000 Å. The filters have roughly similar bandwidth except for a filter centered on the 2175-A dust extinction bump, which is somewhat narrower.

Such a filter setup would be unthinkable were it not for advances in sensitizing CCD's in the UV. As shown in Figure 6, Nikzad et al. (2012) has shown how an AR-coated, delta-doped CCD can provide 50% or more QE in both the far-UV and near-UV. Their techniques have been further refined since then (Nikzad et al. 2017). We plan to work with Nikzad and colleagues at JPL to customize the near-UV EMCCD's for CETUS.

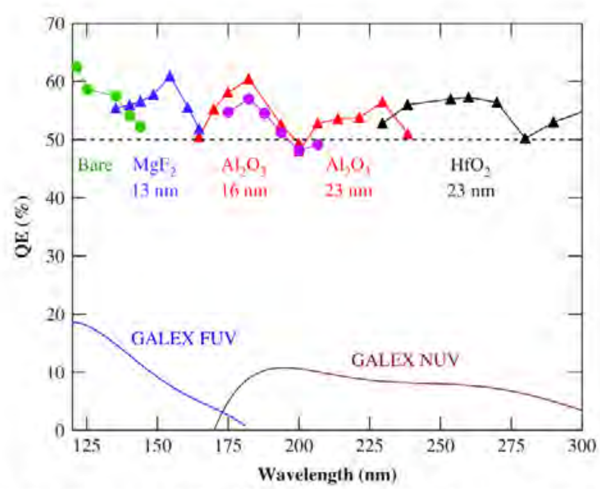

Figure 6. UV response of an AR-coated, delta-doped CCD, showing 50% or greater QE.
(Credit: Nikzad et al. 2012)

The near-UV multi-object spectrograph (MOS). CETUS was designed around the requirements for a multi-object spectrograph with a micro-shutter array (MSA) serving as a programmable slit mask. The MSA was developed by Goddard (Moseley et al. 2004) and incorporated in JWST's NIRspec instrument about 10 years ago. We selected this MSA for use in CETUS' near-UV multi-object spectrograph in 2016, and in 2017, Robert Woodruff designed the MOS for CETUS (as well as the telescope and other two science instruments). Since then, a new and better version of the MSA has been developed by Goddard with funding from NASA's APRA and SAT programs. This next-generation MSA activates the shutters by electrostatic action rather than by a large magnet sweeping over the array. It should be more efficient and reliable as well as larger. A goal of the current SAT program is to produce a single 240x480 NGMSA, which is more than adequate for CETUS, which will use only a 190x380-shutter portion of it. At the time of this writing, we expect that at the end of 2021, a single 240x480 MSA should become available for testing. In the meantime, a small-scale version of the NGMSA, 64x128 array, has been flown successfully in a rocket experiment in October 2020 (McCandliss, priv. comm.), so at least the small version NGMSA is at TRL 5-6.

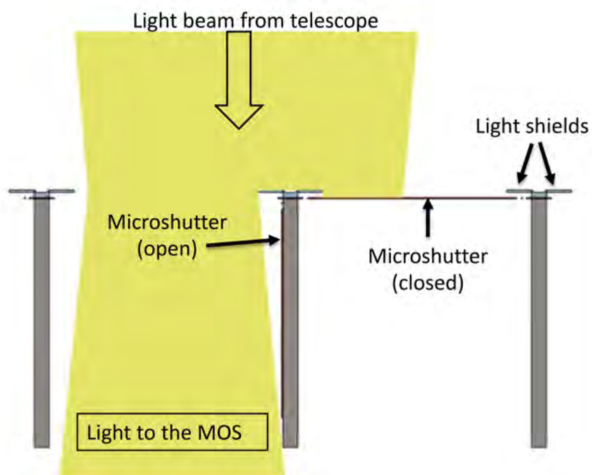

Figure 7. How the MSA works. The figure shows a schematic showing a cross-section of two adjacent shutters, each 100 x 200 microns, or 2.75" x 5.55" for the f/5 telescope of CETUS. The filling factor of the MSA is about 70%. The shutter at left is open to the sky; the shutter at right is closed. Light from the telescope comes to a focus at the plane of the shutter light shields (blue), which keep light from grazing the shutter walls (gray) thereby forming scattered light. In this schematic, light from a ~3.5"-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. No light is transmitted by the right shutter. (As the galaxy image straddles two microshutters, it probably would not be selected for observation.) (Credit: Alexander Kutyrev)

*Near-UV high-resolution spectrograph***.** A near-UV echelle spectrograph has been a staple of Hubble's GHRS and STIS instruments. In both cases, however, the near-UV spectrograms are marred by scattering by the echelle grating. This scattering has the effect of lowering the intensity of the signal in the echelle orders and raising the inter-order background. Recently, R. McEntaffer and group at Penn State University have been successful in producing efficient echelle gratings with order peaks at 70%. They view making the CETUS echelle grating as specified by the CETUS optical design (R. Woodruff) as straightforward.

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