Title: ANUBIS – A Probe-Class UVO Space Observatory (AstroNomical Uv proBe Imager & Spectrograph)

Type of Activity: Space Based Project

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Overview

We propose a next generation Probe-class UV-optical (UVO) observatory called *ANUBIS* that is capable of conducting wide-field imaging and far-ultraviolet (FUV) spectroscopic surveys to address critical topics in modern astrophysics and planetary science. High-resolution, wide-field UVO imaging surveys combined with time domain coverage will examine the formation and survival of star and planet forming environments, map motions and evolution of dynamic environments such as jets and accretion flows, and identify sources of ionizing radiation across the low-redshift universe – all providing a vital complement to NASA's *Wide Field Infrared Survey Telescope (WFIRST)*. FUV spectroscopy with the wavelength coverage and spectral resolution necessary to reach and resolve the forest of diagnostic emission and absorption lines necessary to 1) study the interface between galaxies and the intergalactic medium (IGM), 2) probe the structure and dynamics of the interstellar medium (ISM) in all its phases (locally and in extragalactic systems), 3) characterize the environment around protostellar systems and the conditions within which new planets form, 4) constrain the star-planet interaction in more mature systems, and 5) observe upper-atmospheric processes in solar system targets.

ANUBIS combines a true discovery survey camera with orders of magnitude better AΩ than the *Hubble Space Telescope (HST)*, and larger collecting area and higher resolution (spatial=30 mas per pixel; spectral=30,000) than *GALEX*. The concept leverages modern advances in UVO mirror coating and detector technologies to maximize its scientific impact within the specified Probe-class price point range. The baseline *ANUBIS* design combines a wide-field UVO imager with a FUV spectrograph fed by a 1.5 meter telescope. We will explore the option of a public-private partnership to allow additional instrumentation and possibly a larger aperture that could enhance the scientific return while limiting costs to NASA. We seek to build on the legacy of *HST*, while complementing the new capabilities provided by the *James Webb Space Telescope (JWST)* and *WFIRST*.

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1. Key Science Goals and Objectives

The *ANUBIS* mission concept is designed to carry out a wide range of compelling science investigations: Solar system, protoplanetary disk formation, exoplanets, ISM, Star formation, the CGM, galaxies and stellar populations, and early Universe studies.

1.1 Solar System Science

Solar system science enabled by *ANUBIS* includes critical studies of the Jovian system, (time domain) dynamics in the solar system, small bodies and active moons. In the Jupiter system, *ANUBIS* observations will complement prior or contemporaneous *in situ* investigations (e.g., *Juno*, *JUICE, Europa Clipper*). *ANUBIS's* UV capabilities and long-duration coverage on varying timescales allow studies of numerous aspects of the system, such as aurorae and airglow of Galilean satellites, Io and its plasma torus, Europa and its atmosphere, and the Jovian aurorae. For many giant planet aurorae and atmosphere investigations, UV imaging and spectroscopic capabilities are required. *ANUBIS* is ideal for studying atmospheric dynamics, including storm tracking and photometric studies of horizontal motions and changing cloud cover related to vertical motions. In the Saturn system, the *ANUBIS* wide-field capabilities allow us to observe and monitor Enceladus activity, system OH, and ring-magnetosphere-moon interactions in the post-*Cassini* era. Titan seasonal variations can be studied via cloud monitoring, haze layer imaging and UV stellar occultations. *ANUBIS* observations will be critical for measuring the temporal variability of UV emissions in icy satellite atmospheres and distinguishing between plumes and atmospheric auroral signals, for example at Europa.

At Mars and Venus, UV imaging and spectroscopic capabilities on *ANUBIS* can be used to study airglow (e.g., faint neutral atomic oxygen, hydrogen in upper atmospheres) and aurorae for paleoclimate studies and mission support in the post-*HST* era. Meanwhile, asteroids, particularly near-Earth objects (NEOs), have been poorly studied thus far in the UV. As potential future targets for human visitation, NEOs should be characterized thoroughly over a wide wavelength range. UV wavelengths are particularly important for studying space weathering effects, where UV spectra can be merged with existing visible spectra to reveal composition and physical structure, which in turn are related to mitigation strategies for the impact hazard at Earth. Another key area of study is the main belt comets.

ANUBIS can be used to determine shapes, sizes of small bodies – and also masses from binary orbits – to measure densities without a spacecraft encounter. *ANUBIS* will replace critical capabilities of *HST* at UV and visible wavelengths inaccessible to *JWST*.

1.2 Protoplanetary Disk Formation and the Diversity of Planets

Thousands of exoplanets discovered in the past twenty years have shown that entirely different types of planets exist throughout the galaxy than what resides in our solar system, including 'hot-Jupiters,' 'super-Earths' and rogue planets. The 'hot-Jupiters' changed the prevailing view of planetary formation from that of a static disk with inner rocky planets and outer gas giants to a dynamic picture where gravitational interactions between protoplanets and the disk cause the young planets to move in and out radially as the disk ages. To understand this remarkable diversity of planetary types and configurations we must trace planets back to their birthplaces, the protostellar disks. Within protostellar disks, a complex interplay of gas, dust, radiation, gravitational accretion, fragmentation, gap formation, shadowing, ablation, winds, and magnetic phenomena combine to make all the planets in our galaxy. It is now possible to directly observe some of these processes. For example, recent high-resolution images of circumstellar disks around young (1-10 Myr) stars reveal remarkable gaps and spiral arms (e.g., *ALMA* Partnership 2015, Wagner et al. 2015, Andrews et al. 2016), a signature of advanced planet formation.

Gas constitutes most of the mass of protostellar disks and largely determines how these systems evolve. Cold atomic gas is often difficult to observe because the strongest absorption and emission lines arise from resonant transitions in the FUV. While *ALMA* can acquire high-resolution images of the dust emission as close as 5-10 AU from the star in nearby star-forming regions, *ALMA* is less sensitive to warm/hot (>100K) gas at terrestrial planet-forming radii. *JWST* may detect molecular emission lines, but will not resolve the terrestrial planet-forming regions of disks in the nearest major star-forming regions. Hence, high spectral-resolution UV molecular observations with a facility such as *ANUBIS* will be critical for interpreting *JWST* observations of H_2, H_2O and other molecules at terrestrial planet-forming distances.

Several recent studies have shown that high spectral resolution FUV observations of protoplanetary environments are the best way to measure the composition, structure, and evolution of the primary zones of rocky and gaseous planet assembly (0.1 – 10 AU) around young stars, essential inputs for any model of planetary formation. The strongest electronic band systems of H_2 and CO in the 100 – 170 nm bandpass probe the inner molecular disk (Herczeg et al. 2002; France et al. 2011), while separate high-resolution observations of H_2 and CO fluorescence can constrain the radial distribution of gas within 10 AU (e.g., Hoadley et al. 2015). Such observations are sensitive to gas surface densities as low as $\Sigma \sim 10^{-6}$ g cm^{-2}. Hence, these data are extremely useful probes of remnant gas at $r < 10$ AU around older (5-20 Myr) pre-main sequence F – M stars undergoing the last phases of disk dissipation and giant planet assembly. In cases where mid-IR CO spectra or traditional accretion diagnostics (e.g., Hα equivalent widths) suggest that the inner gas disk has dissipated, FUV H_2 observations can offer unambiguous evidence for the presence of a remnant molecular disk (Ingleby et al. 2011; France et al. 2012).

1.3 Exoplanet Science

ANUBIS can make important and unique contributions to our understanding of exoplanets. Transit spectroscopy of exoplanets in the UVOIR has been carried out by *HST* (e.g., Sing, et al. 2011; see also Iyer et al. 2016 and references therein), and *ANUBIS* would be able to complement and extend such studies. Exoplanets' astounding diversity includes many examples that are difficult to form any other way than by the loss of the light elements from a primordial atmosphere. UV photons from the host star are the primary way to break apart and ionize atmospheric molecules, driving escape from short-period exoplanets, and surely transforming many other planets' atmospheres chemically. Most of the UV radiation comes in flares for the lower-mass stars where planets are being found with NASA's *Kepler* K2 phase and will be discovered with *TESS*. The flares' UV spectrum is crucial in determining the escape and the atmospheric composition. Time-domain UV spectroscopy of a sample of these stars will tell us how the atmospheres of both hot planets and those in the habitable zone are impacted. Similar observations of stars near the start of their lives will reveal how their UV emission disperses the circumstellar gas to reveal newly-formed planetary systems. The recent detection of absorption in Ly alpha due to the expanding exosphere of HD209458b by Vidal-Madjar et al. 2003 is an example of the kinds of work that can be done in the UV in exoplanetary systems. There are also exocomets that have been seen in Ca II and Na I that are observable in the UV absorption lines of the more abundant elements C, Si and Fe (Jones et al 2018).

Regarding direct imaging of exoplanets, *ANUBIS* in an L2 orbit would provide a scientifically interesting aperture size if it were paired with a starshade, which could become available if one were deployed for use with, e.g., *WFIRST*. *ANUBIS* would explore shorter wavelengths than

WFIRST, where modeling suggests that both resolution and contrast improve. We will explore the options for making *ANUBIS* "starshade ready," similar to the approach being taken with *WFIRST*, as well as (perhaps) a longer-term large UVO mission concept such as *HabEx*.

1.4 ISM Science

ANUBIS will map highly-ionized and molecular gas within galaxies, providing direct measurements of the energetics associated with star formation. Highly ionized gas fills most of the volume within galaxies, and governs the dynamics of many astrophysical phenomena. On large scales, powerful winds from supernovae and starbursts power energetic outflows that create large cavities and at the same time compress material at the edges of the cavities. At smaller scales, bipolar flows from protostellar accretion disks provide the primary means of feedback from young stars to their nascent clouds. Spectroscopy with *ANUBIS* will be especially important for studying all of these systems, because highly-ionized gases often move supersonically and their absorption and emission lines are typically the only way to measure temperatures, densities, and velocities. The FUV contains nearly all the strong diagnostic lines for gas between $3{\times}10^4$ K and 10^6 K, and effectively bridges the optical forbidden-line tracers that dominate at 10^4 K with X-ray line and continuum observations at coronal temperatures. In addition, fluorescence in the UV provides a direct way to study homopolar molecules such as H_2 that lack strong infrared dipole lines.

- **Galaxy Halos -** *ANUBIS* will be able to detect FUV diagnostic lines to characterize fountains in many external galaxies. Hot halos are important indicators of the process of galaxy formation by accretion or by mergers, and also play a central role in the spread of metals and energy from supernova explosions through a galaxy. Since O VI is much more difficult to produce by photoionization because of the higher photon energies needed, it is a better tracer of hot gas at temperatures of 0.2 to 1.5 million Kelvin. O VI lines are detected in absorption along many lines of sight through the Milky Way halo. Our goal is for *ANUBIS* to be sufficiently sensitive to detect O VI and other key lines.
- **Fermi Bubbles, AGN feedback -** Winds from the massive black holes in active galactic nuclei (AGN: quasars, Seyfert galaxies and liners) provide feedback during the process of galaxy formation by limiting the amount of gas that eventually falls into the black hole and by reducing the amount of gas that forms stars in the galactic disk. AGN UV emission lines are efficiently excited at temperatures of around 100,000 K, so they are an excellent indicator of shock excitation. O VI absorption can be used to study the interface between gamma-ray emitting gas and the normal galactic halo (Keeney et al. 2006), and *ANUBIS* would make a systematic study possible.
- **Accretion Processes -** Accretion onto compact objects such as white dwarfs, neutron stars and black holes in close binary systems produces X-ray emission very close to the surface of the compact object, and farther out it produces several kinds of UV emission: a strong UV continuum arises from the disk from the energy liberated locally by viscosity in the disk. These accreting stars also produce strong ultraviolet emission lines from neutral atoms and from ions up to five times ionized (O I through O VI). The profiles of these lines contain information about accretion disk structure and the physical processes such as magnetic instabilities, X-ray illumination and winds that affect the accretion rate.
- **Nebulae -** An exciting prospect offered by *ANUBIS* would be observing face-on shock waves near the centers of SNRs in the Galaxy and the Large Magellanic Cloud. Supernovae drive shock waves at tens to thousands of km/s that can induce star formation, but at the same time they drive gas away and reduce the amount of gas that collapses into stars. The flows generate

turbulence that supports the interstellar gas in the Galactic disk against vertical collapse, the shocks destroy dust grains, and also accelerate some particles to become cosmic rays. SNRs also dominate the destruction of interstellar dust grains in the ISM, and they therefore determine the dust fraction.

1.5 Massive Star Forming Regions and CGM Feedback

ANUBIS' near-UV (NUV) and optical imaging capability will probe the cycles of star formation and feedback in a variety of environments, such as Galactic star-forming regions, the Magellanic Clouds, and the local group. We will use an array of broadband and narrowband emission-line filters to target stars, diffuse gas, and dust at every phase in the life cycle of massive stars. *ANUBIS* also has the potential to study massive star-formation in cluster galaxies as a function of the cooling flow environment. To understand star formation as a global *system*, we need to design and engage in a systematic program of imaging that covers a large number and variety of Galactic star forming regions. To understand star birth in the early Universe, galaxy formation and evolution, the origin of the stellar mass spectrum, the formation of planets, and feedback and how it scales with stellar populations, we must treat star birth as an integrated systemic process. *ANUBIS* will observe star forming complexes in their entirety, tracing the interactions between gas and stars, between stars and stars, and between protostellar disks and their environments. To make progress, we must spatially resolve disks, multiple stars, and star clusters, measure stellar motions, and perform relative photometry with sufficient precision to age-date young stars.

- **Massive Star-formation in the Milky Way -** *ANUBIS* observations will be used to better understand the influences of feedback from massive stars on the physical and morphological characteristics of their natal clouds and interstellar (and ultimately, intergalactic) environments. *ANUBIS* observations of Galactic star-forming regions will address the details of the multi-phase structure of star-forming regions and their impact on the local interstellar environment, providing an improved observational basis for theories of star-formation in galactic disks (e.g., Ostriker, McKee, & Leroy 2010). *ANUBIS* will combine the sensitivity, spatial resolution, and filter set to characterize precisely the physical conditions in massive star-forming regions on spatial scales of degrees.
- **Massive Star Feedback in the Magellanic Clouds -** *ANUBIS* will study mechanical feedback processes, from the main-sequence lives of O and B stars, through their dusty dense winds as red supergiants and luminous blue variables, and on to their energy deposition into their environments during their deaths as supernovae. In the Magellanic Clouds, our observations will probe massive star feedback in a low-metallicity environment and offer an opportunity to study in detail the properties of massive star-forming regions and their influence upon the structure of their host galaxy. Cataloging the NUV properties of the hot stars in the Magellanic Clouds will enable studies of how stellar photons are reprocessed on a galactic scale, from the O and B stars studied by *ANUBIS* to PAH emission features to the thermal-IR and atomic fine-structure emission such as [O I] 63 μm and [C II] 158 μm.

1.6 Beyond the Tip of the Iceberg: Studies of the CGM

The circumgalactic medium (CGM) — the gaseous envelope of a galaxy extending to the virial radius and beyond — mediates many crucial processes that profoundly affect galaxy evolution. On the one hand, it has been clear for decades that galaxies must be resupplied with gas throughout their lifetimes to explain their prolonged star-formation histories, but theoretical understanding of how galaxies accrete gas fails in a variety of ways (e.g., Maller & Bullock 2004). Gas accretion occurs through the CGM, and many physical processes can significantly complicate this seemingly straightforward aspect of galaxy evolution, e.g., the gas can be shocked, heated, and ablated as it falls into a galaxy, and somehow cooling and angular momentum redistribution must occur before infalling matter can truly fuel star formation in the regions where stars are observed. In addition to these internal processes, galaxies interact with their broader surroundings through mechanisms such as ram-pressure stripping, tidal interactions, major and minor mergers etc., and gas physics plays crucial roles in these interactions as well (e.g., Weinberg 2014). In many ways, stars are only the tip of the galactic iceberg, and a complete understanding of galaxies can only be attained by observing the vast and complex reservoirs of gas and plasma in the CGM and the broader intergalactic medium.

However, CGM and IGM physical conditions make such observations very challenging. During much of the "baryon cycle" of matter flowing into and out of galaxies, the gas has very low densities, which makes emission difficult to detect. Moreover, CGM temperatures often exceed 10^5 K, and consequently, detailed and diagnostic studies can only be done with rest-frame ultraviolet and/or X-ray observations in many cases. Currently, the most effective and practical technique for probing the low-density CGM is to study the absorption lines that the CGM and IGM imprint on the spectra of background continuum sources such as quasars. The CGM has a complex, multiphase nature including cool, low-ionization material as well as highly ionized plasma (e.g., Tripp et al. 2011; Meiring et al. 2013; Werk et al. 2016; Rupke et al. 2005; Weiner et al. 2009), so high spectral resolution ($R \geq 30000$) is required to reliably measure the physical conditions in gas containing ions ranging from Na I, Mg I, Mg II, etc., up to O VI and Ne VIII. Ultraviolet spectrographs can easily provide such high spectral resolution with excellent sensitivity while X-ray spectrographs cannot, and there are vastly more targets available to UV instruments than X-ray spectrographs (i.e., there is only a small sample of known extragalactic X-ray sources bright enough for this purpose).

The high-resolution UV spectrograph on *ANUBIS* will be a powerful facility for CGM studies. *ANUBIS* will not only fill the glaring hole in our post-*HST* capabilities, but it will provide a greater capability for CGM studies than *HST*. Our design pushes further into the FUV than *HST* (with a baseline capability of observing to wavelengths as short as 1000 Å and a stretch capability of extending to 912 Å), and we envision long-slit and/or multi-object modes so that UV emission from the CGM can be mapped using bright resonance lines of species such as O VI, C IV, C III, C II, and H I, which is critical for characterizing the energy exchange between galaxies and their CGM. The highly successful *FUSE* mission demonstrated that CGM science can be effectively pursued with a modest aperture using absorption and emission spectroscopy; *ANUBIS* will be a "super-*FUSE*," with substantially improved sensitivity and resolution.

1.7 Galaxies, Stellar Populations and Galactic Archaeology

ANUBIS will build on the legacy of *HST* by aiming to complete the census of nearby galaxies and to characterize their stellar population and ionized gas in high angular resolution panchromatic wide-field images and associated far- and near-UV spectra. The resulting data are expected to reveal low surface brightness galaxies and fossil star streams from accreted and disrupted satellites (Ibata et al. 2001, Mihos et al. 2005, Martínez-Delgado et al. 2008, 2010, Laine et al. 2016), enable UV studies of iconic nearby galaxies with unprecedented coverage and detail, and leverage complementary data in the widely anticipated visible and IR surveys planned for the 2020s.

Low-surface-brightness galaxies challenge galaxy evolution theory because of the enormous total mass that must have accumulated in the absence of major merger events (Kasparova et al. 2014). Dwarf galaxies and large low-surface-brightness galaxies (Hagen et al. 2016) are predicted to far outnumber their more luminous counterparts, but most remain undetected. For example, numerous faint galaxies are expected to reside in galaxy clusters, making Virgo and Coma high-priority targets for *ANUBIS* (Ferrarese et al. 2016; Allen 2016). These cluster-focused UV imaging and spectroscopic data sets will put new constraints on cluster luminosity functions, dynamics, kinematics, structure, as well as galaxy morphology, star formation, galaxy-galaxy interactions and galaxy intra-cluster medium interactions: all rich areas of on-going research (Boselli et al. 2016) that inform ΛCDM and WDM galaxy evolution models.

ANUBIS will further enable detailed studies of individual nearby galaxies, such as the Magellanic Clouds (Besla et al. 2016), the enigmatic Sombrero galaxy, the Messier galaxies M 33, M101, and M81 as well as the low-surface-brightness galaxy Malin-1 (Mapelli et al. 2008). The high spatial resolution will allow *ANUBIS* to separate the individual stars producing the UV emission seen by *GALEX*, providing sensitive probes of star formation timescales, UV output at low star formation intensity, and extended star-forming structures (Jansen et al. 2009, Marino et al. 2016). Furthermore, at low redshift, *ANUBIS* Far-UV spectroscopy of highly ionized metals diagnose shocks in SNe and galactic winds, and will reveal the multi-phase intergalactic and circumgalactic medium, which contains ~80% of the baryonic matter in the local universe (Danforth et al. 2016). The interplay between matter and energy cycling between galaxies and this surrounding medium, driven by outflows powered by supernovae and active galactic nuclei, is complex requiring sensitive UV observations to understand. Such observations will inform chemical evolution models and provide insight into the era of re-ionization in the early universe.

Finally, *ANUBIS* observations will leverage important photometric redshifts for distant galaxies detected in the widely anticipated *Euclid*, *WFIRST* and *LSST* surveys that aim to measure the nature and origin of cosmological acceleration. *JWST* will yield a vast archive of faint near–mid-IR sources for which *ANUBIS* will provide the wider UV context. The stability and long visibility periods afforded by an L2 orbit also is extremely attractive for time-domain studies, which will be a focus of *JWST* and *LSST*. *ANUBIS* will be able to contribute by providing improved statistics on SNe Ia progenitors plus enable follow-up UV observations of new transients coordinated with *LSST* alerts and gravitational wave detections. In short, *ANUBIS* will enable high angular resolution (67 mas at 400nm) wide-field visible surveys of nearby galaxies and their environments with supporting UV spectroscopy. These capabilities will provide constraints on cosmology and galaxy evolution, as well as crucial complementary data for the large optical and IR surveys of the coming decade.

1.8 Reionization & the Dark Ages

Reionization heralded the end of the dark ages when the energy from the first stars and galaxies ionized the IGM, representing the first time luminous sources impacted the structure of the universe. While it is believed that high-energy UV photons (>13.6 eV) from early galaxies were responsible for the ionizing budget, such a scenario depends on the existence of galaxies well below the limit of even Hubble's deepest images, and knowing the fraction of ionizing photons which escape the galaxies and are thus available to ionize the IGM. While the Hubble Frontier Fields lensing studies have now directly observed galaxies intrinsically 100× fainter than the previous blank-field limits (e.g., Atek et al. 2015; Livermore et al. 2016), the escape fraction is still largely unknown.

This uncertainty is not for a lack of substantial observational efforts. Dozens of nights of ground-based observing, and hundreds of hours of *Hubble* integration have been dedicated to directly detecting escaping ionizing radiation, at $z < 4$ where the ionized IGM is transparent enough to make this measurement. The vast majority of studies have yielded either non-detections (e.g., Siana et al. 2010), or detections later found to be dominated by interloping galaxies (e.g., Nestor et al. 2011; Vanzella et al. 2012). Lately there have begun to be some successes, as a few galaxies have been directly detected (e.g., Izotov et al. 2016 in the nearby universe, and Vanzella et al. 2016 at z~3), and a faint detection has also been realized by stacking z~2-3 galaxies (Smith et al. 2016). However, the sparse observational data do not allow us to constrain the nature of the ionizing sources at high-redshift, as these dwarf galaxies (log M* = 6-8) are much smaller than the majority of the targeted (and detected) galaxies. The majority of recent theoretical studies predict that these dwarf galaxies dominate reionization not just due to their large numbers, but that they preferentially have higher escape fractions.

The excellent UV sensitivity of *ANUBIS* will allow direct detection of Lyman continuum radiation for dwarf star-forming galaxies at z=0.1-1, true nearby analogs to the likely dominant sources of reionization. In particular, the large field of view coupled with a multi-object spectrograph will allow an extremely sensitive measurement of the average escape fraction via stacking (to levels of $f_{esc} < 0.01$), as well as sensitivity to individual galaxies with modest escape fractions ($f_{esc} > 0.1$).

2. Technical Implementation and Design

While the heart of the design for *ANUBIS* will be defined and refined using the science drivers discussed above, we already have some notional ideas concerning the capabilities that *ANUBIS* will need to deliver to allow this science to be possible. These capabilities include a wide field (tens of arcminutes FOV) diffraction-limited NUV-visible-NIR camera, and a high resolution (R>40,000) FUV (100-250nm) spectrograph.

2.1 *ANUBIS* Camera – FUV, UV and UVOIR Imaging Detectors

To address the UV/optical/NIR spectral response requirements of *ANUBIS*, we baseline the use of silicon-based imagers. While high quality, large format HgCdTe focal plane arrays (FPAs) are available to cover $\lambda > 1$ µm, and have sensitivity in the optical (after substrate removal), the comparatively lower cost of silicon arrays remains a major disincentive for use of HgCdTe FPAs. The maturity of silicon imagers, their high performance, and developments to extend their spectral range to longer and shorter wavelengths makes them the detectors of choice for UV/optical/NIR instruments. Silicon imagers typically use CCDs or CMOS detectors. CMOS devices use a direct readout scheme that converts the charge to voltage in each pixel and then transfers that voltage to an output amplifier, and they generally have high degree of integration (e.g. on-chip bias, timing, control and many parallel readouts). Because the detection layer and readout layer are separated in CMOS devices, they can accommodate a variety of detector architectures (e.g. PIN diodes, or avalanche photodiodes) and novel manufacturing processes (e.g. silicon on insulator). Innovations in the detector layer are rapidly developing, such as in the “QIS” (Quanta Image Sensor) design which could have transformational effects.

To achieve the highest performance in quantum efficiency (QE), spectral range, fill factor, and dark current (surface-generated), silicon imagers need to be back illuminated with processes such as JPL-invented delta doping and superlattice doping (generally and from here on called 2-D doping) technologies. Delta doping has been demonstrated to provide stable, uniform, 100% internal QE with bare p-channel, n-channel CCDs (Nikzad 2017), electron multiplying CCDs (EMCCDs), CMOS imaging arrays, and hybrid arrays. P-channel arrays have higher radiation tolerance than n-channel devices by nearly an order of magnitude and will be considered as an option during the trade study. JPL’s end-to-end, post fabrication processing also includes advanced custom coatings using atomic layer deposition (ALD) and other techniques for antireflection (AR) coatings and detector-integrated out-of-band-rejection filters. High in-band efficiency and out of band rejection in 3-4 orders of magnitude have been demonstrated in avalanche photodiodes, EMCCDs, and other silicon arrays. These tailorable custom coatings have demonstrated with external QE of up to 80% in the UV and near 100% in the optical spectral region. As part of this study we will determine the optimum basic detector design. CMOS imagers and hybrid imagers that combine CMOS readout technology with PIN diode array detectors that can be depleted are two of the alternatives.

In addition to the image-tube based ultraviolet detector technology that has been the workhorse of UV instrumentation for several decades, solid-state options have been developed over the last two decades that form a viable and superior alternative to these state of the art detectors. These include 2-D doped EMCCDs, Single Photon Counting Avalanche Diode (SPAD) arrays, and Geiger mode Avalanche Photodiode (G-mode APD) arrays. Tailored antireflection coatings have been shown in combination with delta doping, to increase the response (external QE) from 50-80% in the 100-400 nm both for narrow band and broadband applications (Nikzad 2016, 2017, 2019).

2.2 *ANUBIS* Spectrograph – FUV Detectors

Microchannel plate (MCP) detectors have been a detector of choice for many UV astronomy missions successfully operated over the last two decades, such as *EUVE*, *FUSE*, *GALEX*, *HST-STIS* and *COS* (Siegmund et al. 1997; Vallerga et al. 2001; P. N. Jelinsky et al. 2003; Green et al. 2006). They are also being provided to the soon to be launched NASA *ICON* Small Explorer (Immel et al. 2013) and *GOLD* Mission of Opportunity (Eastes et al. 2007), and are widely used on NASA's UV sub-orbital sounding rocket investigations. MCP detector technology has been developed and now combines high spatial resolution (<20 µm FWHM), photon counting (noiseless) imaging in a robust, radiation-hard package that is scalable to very large formats (>100 mm and >8k × 8k pixels; Hussey et al. 2013) and can provide large curved focal planes. Standard operation is at room temperature, with very low dark count rate and extreme radiation hardness. Sealed vacuum tube configurations are commonly used for wavelengths above 115 nm and provide sensitivity up to >400nm; open face designs are sensitive down to 30nm. MCP detector longevity has been proven in a wide variety of mission implementations from LEO to Pluto. Performance enhancements to accommodate higher signal to noise measurements, to reduce fixed pattern distortions, lower the event background rate and increase detection efficiency are being addressed with new MCP fabrication techniques and anode readout technologies. These allow operation at MCP gain factors of ~20 lower than before, 5× reduction in background rate, and photon counting event rates >6 MHz, and increases in the quantum detection efficiency.

Specific technologies for the *ANUBIS* spectrometer detector include microchannel plates using atomic layer deposition (ALD) techniques [in formats up to 200 × 200mm] that have been shown (Siegmund et al. 2015) to increase the MCP lifetime by an order of magnitude, lower the intrinsic background to 0.03 cts s^{-1} cm^{-2}, reduce gamma ray background sensitivity by factors of ~2×, and increase the QE by increasing the open area ratio of the MCP input pores (Ertley et al. 2015, Siegmund et al. 2014). Cross strip readouts currently provide the best spatial resolution (<15 µm), size formats (100mm) and events rates (>5MHz). Existing NASA Strategic Astrophysics Technology (SAT) programs have developed a 50 × 50 mm MCP detector design with a cross strip readout, and a 100×100mm detector is in construction. Conventional photocathodes with high TRL, such as CsI, CsTe and UV optimized bi-alkalis with QE's between 50% and 25% in sealed tube devices can cover the bandpass from 115nm to 450nm. However, photocathodes such as GaN with 50% QE (100nm – 300nm) need more study to elevate their TRL. These are adaptable technologies can be very economically scaled to the detector required for the readout of the FUV spectrometer for *ANUBIS*.

3. Technology Drivers

3.1 Mirror Technology

The primary and secondary mirror elements in *ANUBIS* will be closed back designs using TRL-9 Low Temperature Fusion (LTF) manufacturing methods. The LTF starts with carefully selected boules of Corning ULE® glass that have a matching Coefficient of Thermal Expansion (CTE) to within 10 parts per billion (PPB) with an overall CTE zero within a few PPB. This sandwich construction creates a very stiff mirror with a first mode around 250Hz. The resulting primary mirror is them very thermally and dynamically stable for both launch and operations.

3.2 UV Coating Development

Over the past 4 years, JPL and GSFC with a combination of internal R&D, ROSES-APRA, and ROSES-SAT projects and industry collaborations have developed the materials and process technology to produce mirror coatings with broadband reflectivity from the FUV to near-IR. Through enhanced conventional coating techniques as well as newly developed Atomic Layer Deposition (ALD) processes with AlF_3 as a protective layer on Al we have advanced the state-of-the-art in order to reach reflectivity >50 % in the 100-200nm spectral range without affecting the rest of the UV, visible and NIR performance (Figure 1). Further advances are feasible with continued development of the processes. Uniformity and stability of mission critical coating performance are also within reach as demonstrated with small coupons. Scaling the process to larger chambers is now essential to further the technology development. In principle, and in practice for other applications, ALD is easily scalable to large areas.

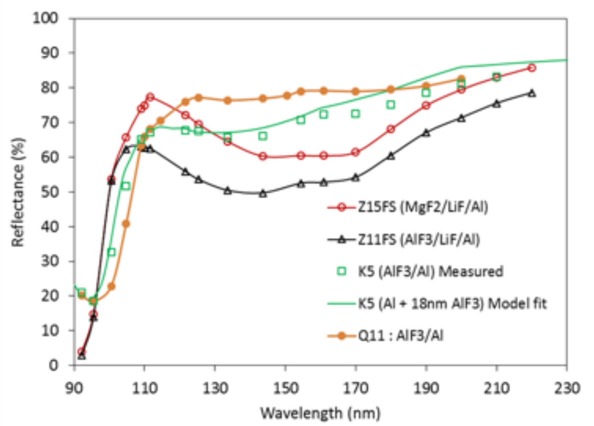

Figure 1. FUV reflectance of tri-layer mirror samples produced by conventional thermal evaporation (samples Z11 & Z15); bi-layer mirror samples produced by e-beam of Al and ALD of AlF_3 (samples K5 & Q11); see Balasubramanian et al. 2015 and Hennessy et al. 2016.

The basic coating processes developed for Al, LiF, MgF_2, and AlF_3 are also applicable to a variety of optical filters with further design and optimization. Research and development at GSFC has experimented with optimizing conventional coating processes as a function of substrate temperatures and coating recipes to produce optical coating performance that is within theoretical prediction. At JPL, we have developed the ALD processes for coating fluorides on Al with proven performance. Our industry collaborators, for example ZeCoat Corp in CA and Surface Optics Corp in San Diego, have been working with us over the past 3 years and have augmented their coating chamber fitted with moving sources and process controls to achieve better uniformity over a meter class mirror. With the combined expertise and capabilities, further work in this area can ensure a successful pathway to reach the goals of *ANUBIS*.

4. Organization, Partnerships and Current Status

We have formed a strong team of scientists and technologists to define a cutting-edge science program and a facility that uses state-of-the-art mirror, coating and detector technologies for the UV/optical passbands. Technical team members reside at Harris, UCB-SSL, CSIC, Aerospace Corp., Northrop Grumman, BATC, as well as NASA's JPL, GSFC, and MSFC. The program has not been formally costed but the team stands ready to propose for a Probe-class mission AO if announced.

5. Schedule

Since the formal study of the mission concept has not been completed, a schedule for the mission is unclear, but we would expect a 4 year developmental period for Phases A-D, and a 3 year mission for Phases E-F.

6. Mission Cost Rationale

The idea of hosting a regular cadence of Probe-class missions within NASA's Astrophysics portfolio goes back almost 15 years. The prime examples in recent years of this class of medium-sized mission with focused capabilities and high science impact include *Kepler* and *Fermi*, each with a mission cost (including launch vehicle) of ~$600M. *Kepler* in particular — with its 1.4m primary mirror, 0.95m Schmidt corrector, ~100 Mega-pixel imaging camera, precision spacecraft pointing, and high-stability Earth-trailing orbit — is a relevant benchmark against which we compare the *ANUBIS* capabilities and architecture. We will take advantage of significant technological progress since *Kepler* was launched in 2009, especially in the areas of large-format detectors and optics, to deploy significantly more capability at similar cost. We have access to parametric cost models, industry inputs, and NASA cost data from previous concept studies (including for Discovery program proposals) in compiling our total *ANUBIS* mission costs.
Table 1 lists the *ANUBIS* initial cost estimates. In particular, we follow the costs of launch vehicles, orbital optical systems, detectors and spacecraft, which are clearly trending down compared to even a few years ago due to expanding commercial demand. We note that the U.S. industrial base has significant experience developing space telescopes with the proposed *ANUBIS* aperture.
Table 1 assumes launch to a libration point orbit in a 4-meter class fairing using, e.g., a Falcon 9, Vulcan, Antares, or other suitable vehicle in the 2020's. It also assumes a full Class B program, *Kepler*-like pointing requirements, full spacecraft redundancy, high-rate Ka-band communications, and a propulsion system for orbit injection, maintenance, and retirement. We will assess the cleanliness and contamination control at the observatory and spacecraft level for this UVO mission, which will depend on the selected coatings, etc. Integration and test does not require facilities beyond those for other Class B payloads and are within standard test facility capabilities.

Table 1: *ANUBIS* Cost Estimates

Component	Cost Estimate ($M)	Cost Basis
Management (PM/SE/MA)	$90	Comparable missions, parametric model
Instrument: Wide-Field Camera	$175	Other missions (*HST*, *Kepler*), concept studies (*HORUS*, SALSO)
Instrument: FUV Spectrograph	$105	Other missions (*HST*, *FUSE*), concept studies (*HORUS*, SALSO)
Telescope (OTA, OBA, PLAIT, etc.)	$110	Other missions (*HST*, *Kepler*), concept studies (*HORUS*, *WFIRST*)
Spacecraft	$120	Other missions (*Spitzer*, *Kepler*, *Fermi*), commercial analogs
30% Reserves	$180	
Launch Services	$75	Other missions (*Kepler*, *TESS*), commercial rates
Total (Phases A-D)	*$855*	
Phase E (MO & DA)	$120	4 Years with Kepler MO ($20/yr) + Chandra DA ($10M/yr)
Lifecycle Total	**$975**	

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