Origins Space Telescope

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Published in:
Astro2020

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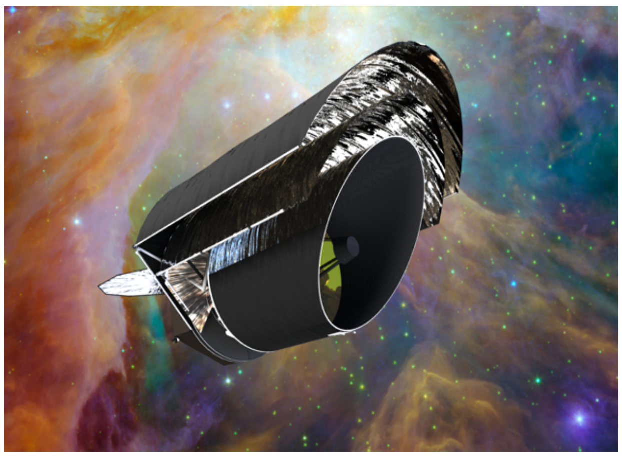

ORIGINS SPACE TELESCOPE

From First Light to Life

A submission to the 2020 Decadal Survey

Theme: Large Class Space Missions
(study supported by NASA and the Goddard Space Flight Center)

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EXECUTIVE SUMMARY

The Origins Space Telescope (*Origins*) traces our cosmic history, from the formation of the first galaxies and the rise of metals and dust to the development of habitable worlds and present-day life. *Origins does this through exquisite sensitivity to infrared radiation from ions, atoms, molecules, dust, water vapor and ice, and extra-solar planetary atmospheres. Origins* operates in the wavelength range of 2.8 to 588 µm and is 1000 times more sensitive than its predecessors due to its large, cold (4.5 K) telescope and state-of-the-art instruments.

Origins investigates the creation and dispersal of elements essential to life, the formation of planetary systems, the transport of water to habitable worlds, and the atmospheres of exoplanets around nearby M-dwarfs to identify potentially habitable worlds. These science themes are motivated by their profound significance, as well as expected advances from, and limitations of, current and next-generation observatories (JWST, WFIRST, ALMA, and LSST). The nine key *Origins* scientific objectives (Table 1) address NASA's three major astrophysics science goals: *How does the universe work?, How did we get here,* and *Are we alone?* These nine aims also drive the instrumental requirements summarized in Table 2. The *Origins* design is powerful and versatile, and the infrared radiation it detects is information-rich. *Origins* will enable astronomers in the 2030s to ask new questions not yet imagined, and provide a far-infrared window complementary to planned, next-generation observatories (e.g., Athena, LISA, and ground-based ELTs).

1. Key Science Goals and Objectives

How do galaxies form stars, make metals, and grow their central supermassive black holes from reionization to today? *Origins* is designed to answer this fundamental question in galaxy formation and evolution through wide area spectral mapping surveys in the far infrared wavelengths. *Origins* is capable of carrying out 3D infrared spectral mapping surveys resulting in spectroscopic data on millions of galaxies spanning the redshift rangge of z=0 to z > 6. These statistics are at a level comparable to the Sloan Digitial Sky Survey (SDSS), but will be attained by *Origins* in a 2000 hours survey, instead of ~5 years from the ground in the optical that took to complete SDSS.

Table 1: Scientific objectives for the *Origins* Space Telescope

NASA Goal	How does the Universe work?	How did we get here?	Are we alone?
***Origins* Science Goals**	 **How do galaxies form stars, make metals, and grow their central supermassive black holes from reionization to today?**	 **How do the conditions for habitability develop during the process of planet formation?**	 **Do planets orbiting M-dwarf stars support life?**
***Origins* Scientific Capabilities**	*Origins* will spectroscopically 3D map wide extragalactic fields to simultaneously measure properties of growing supermassive black holes and their galaxy hosts across cosmic time.	With sensitive, high-resolution spectroscopy, *Origins* maps the water trail from protoplanetary disks to habitable worlds.	By obtaining precise mid-infrared transmission and emission spectra, *Origins* will assess the habitability of nearby exoplanets and search for signs of life.
***Origins* Scientific Objectives**	1) How does the relative growth of stars and supermassive black holes in galaxies evolve with time? 2) How do galaxies make metals, dust, and organic molecules? 3) How do the relative energetics from supernovae and quasars influence the interstellar medium of galaxies?	1) What role does water play in the formation and evolution of habitable planets? 2) How and when do planets form? 3) How were water and life's ingredients delivered to Earth and to exoplanets?	1) What fraction of terrestrial planets around K- and M-dwarf stars has tenuous, clear, or cloudy atmospheres? 2) What fraction of terrestrial M-dwarf planets is temperate? 3) What types of temperate, terrestrial, M-dwarf planets support life?

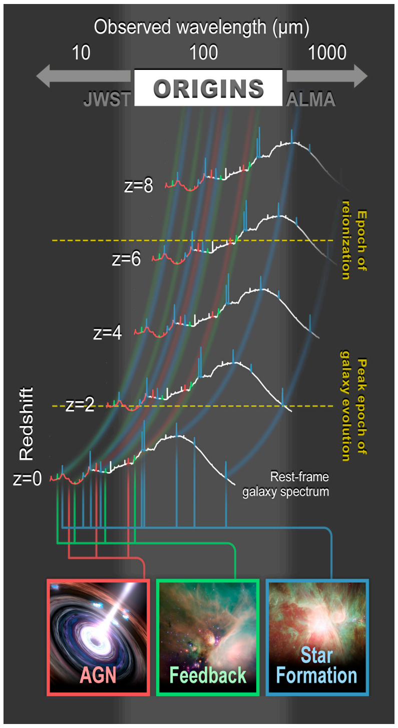

Figure 1. ***Origins*** **complements JWST mid-IR and ALMA sub-mm/mm-wave capabilities.** With *Origins* the community will have access to spectral line diagnostics indicative of AGN (red), star formation (blue), and feedback (green) over a wide range in redshifts, filling in a largely untapped region of wavelength and discovery space between JWST and ALMA.

A complete understanding of the astrophysical processes responsible for the formation and evolution of galaxies is one of the key scientific goals of modern-day astrophysics. While we have made significant strides, there are still huge gaps in our understanding of galaxy formation and evolution, especially the detailed astrophysical processes that grew and shaped galaxies over cosmic time. While small targeted surveys are capable of solving some key problems, uncertainties related to our models of galaxy formation are still strongly tied to small number statistics of galaxies at high redshifts and biases coming from galaxy selections at various wavelengths that are either sensitive to older stellar populations, such as in the near-IR, or active galactic nuclei (AGN) activity, such as in the X-rays. At far-IR wavelengths, spectral lines trace all key ingredients of galaxies providing multifaceted probe of internal processes in play in galaxies (Figure 1). *Origins*' wavelength range will not be explored by JWST, which is poised to provide the most detailed look yet at the distant universe. Furthermore, with a sensitivity that is a factor of 1000 improvement over *Spitzer* and *Herschel*, *Origins* capability moves beyond simply detecting dusty, starbursting galaxies above the stellar mass vs. star-formation rate main sequence to studying dust, gas and AGN in galaxies on the main sequence. Finally, with 3D spectral mapping surveys, *Origins* overcomes issues related to source confusion that impacted previous continuum mapping surveys with *Herschel*.

How do the stars and supermassive black holes in galaxies evolve with time? *Origins* allows us to peer through the obscuring dust, probe the physics of star-formation through atomic and molecular gas, study the buildup of metals from dying stars, and establish the role of supermassive black holes (SMBH) as they accrete and drive energetic outflows into the surrounding interstellar medium (Figure 2). Key spectral signatures from the physical processes that sculpt galaxies are prominent in the infrared, where emission and absorption lines trace complex molecules, small and

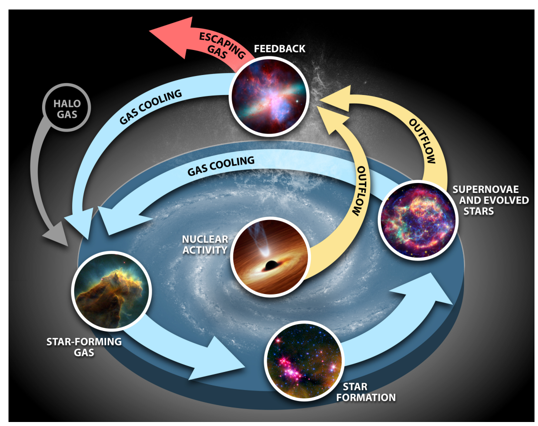

Figure 2: ***Origins*** **studies the baryon cycle in galaxies.** Energetic processes that shape galaxies and the circumgalactic medium together define the galactic ecosystem. Through its ability to measure the energetics and dynamics of the atomic and molecular gas and dust in and around galaxies that are actively star-forming or have AGN activity, *Origins* can probe nearly all aspects of the galactic ecosystem: star formation and AGN growth; stellar death; AGN- and starburst-driven outflows; and gas cooling along with accretion. These measurements will provide a complete picture of the lifecycle of galaxies.

large dust grains, and atoms that are sensitive to changes in ionization and density (Pope et al. 2019).

How do galaxies make metals, dust, and organic molecules? Galaxies are the metal factories of the Universe, and *Origins* studies how metals and dust are made and dispersed throughout the cosmic web over the past 12 billion years. Sensitive metallicity indicators in the infrared can be used to track the growth history of elements via nucleosynthesis, even in the densest optically-obscured regions inside galaxies (metals: Smith et al. 2019; dust: Sadavoy et al. 2019).

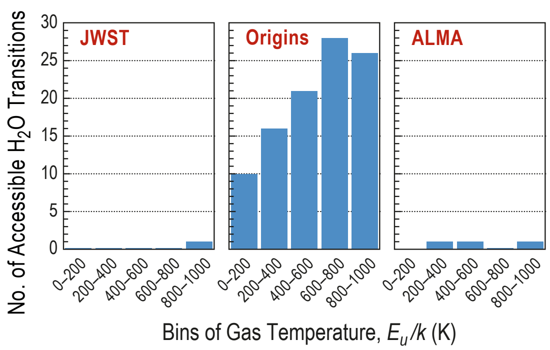

Figure 3: Origins is capable of studying more than 100 transitions of water vapor, compared to one and three with JWST and ALMA, respectively. This plot shows the number of $H_2{}^{16}O$ transitions observable by JWST, *Origins*, and ALMA as a function of the gas temperature, with energies above the ground state below 1000 K. ALMA is limited by atmospheric absorption in its ability to observe water lines from the Galaxy.

How do the relative energetics from supernovae and quasars influence the interstellar medium of galaxies? Galaxies are made of billions of stars, yet star formation is extremely inefficient on all scales, from single molecular clouds to galaxy clusters. *Origins* has the power to study the role of feedback processes at play in galaxies over a wide range of environments and redshifts (Figure 2). *Origins* can study the processes that drive powerful outflows and map the demographics of galactic feedback (Bolatto et al. 2019 White Paper).

How do the conditions for habitability develop during the process of planet formation? Water is essential to all life on our planet. Water provides the liquid medium for life's chemistry and plays an essential biochemical role. The broad wavelength coverage offered by *Origins* includes a large number of unique water vapor lines unavailable to any other telescope, including ALMA or JWST. The water lines accessible to *Origins* trace the entire range of temperatures found in protoplanetary disks, from the cold snowline to the hot steamline in disks (Figure 3). *Origins* can survey all reservoirs of water in more than 1000 planet-forming disks around stars of all masses, including the most common, but faint, M-dwarfs that are likely hosting most planets in the Galaxy.

What role does water play in the formation and evolution of habitable planets? With its unprecedented sensitivity to weak emission from all forms of water (ice and gas), *Origins* provides the measurement capability needed to decipher water's role in all planetary formation evolutionary phases (Figure 4; Pontoppidan et al. 2019).

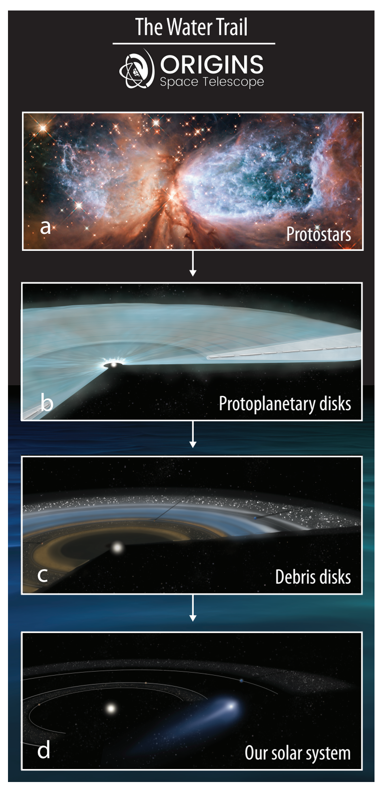

Figure 4: *Origins* will trace water and gas during all phases of the formation of a planetary system. The trail begins in the "pre-stellar" phase, where a cloud of gas collapses (a) into a still-forming star, surrounded by a disk nearly the size of our Solar System, and a collapsing envelope of material (b). Over time, the envelope dissipates, leaving behind a young star and a disk with nascent planets (c), eventually revealing a new planetary system (d). *Origins* will solve key puzzels in planet formation.

How and when do planets form? Another puzzle in planetary formation is the role of hydrogen gas in protoplanetary disks. This gas is the reservoir from which gas giants and planetesimals emerge, and the latter are the building blocks of rocky planets. Despite decades of effort, the hydrogen gas mass of protoplanetary disks is essentially unknown. This is because molecular hydrogen, being a symmetric molecule, is largely invisible at the low temperatures of planet-forming gas. While CO has been used, the conversion to gas mass is uncertain by factors of 10—100 due to the unknown concentration of CO relative to hydrogen (Oberg et al. 2019).

Origins is uniquely able to use the HD 112 μm line as a powerful tool to measure the gas mass of protoplanetary disks, throughout their evolution, to within a factor of 2—3. This is one to two orders of magnitude more precise than alternative tracers and is needed to distinguish between competing models of planet formation. *Origins'* will provide calibrations for all proto-planetary disks observations, including those using ALMA (Bergin et al. 2019).

How were water and life's ingredients delivered to Earth and to exoplanets? The snowline – the distance from the young star where water transitions from a gas to a solid – holds a prominent place in planet formation theories, as it is believed that the Earth and its precursor materials formed inside our Solar System's snowline. It is theorized that water was delivered to the early Earth via impacts from objects that formed beyond the snowline. The evidence for this comes from the relatively high deuterium content of Earth's oceans, which could only have been developed when water formed at a temperature of 10—20 K. In our Solar System, comets and asteroids also carry this signature. Only a handful of comets have been measured to date, all hinting subtle D/H variations. *Origins*' exquisite sensitivity enables precise D/H measurements of about 200 comets, allowing statistics to study the role of comets as the source of Earth's water (Lis et al. 2019).

Do planets orbiting M-dwarf stars support life? Humankind has long pondered the question, *Are we alone?* Only now are scientists and engineers designing instruments that are dedicated to answering this question. Our quest to search for life on extra-solar planets relies on our ability to measure the chemical composition of their atmospheres. *Origins* expands upon the legacy of *Hubble* and *Spitzer* – and soon JWST – with a mid-infrared instrument specifically designed for transmission and emission spectroscopy measurements. In its search for signs of life, *Origins* employs a multi-tiered strategy, beginning with a sample of planets with well-determined masses and radii that are transiting nearby K & M dwarfs, the most abundant stars in the Galaxy. With its broad, simultaneous wavelength coverage and unprecendented stability, *Origins* is uniquely capable of detecting atmospheric biosignatures (Figure 5).

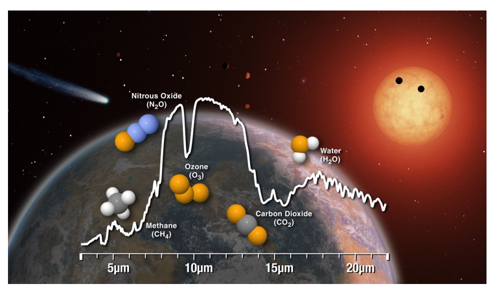

Figure 5: *Origins* is designed to search for atmospheric biosignatures of exoplanets that transit K- & M-dwarf stars. By leveraging the mid-infrared wavelength capabilities with a dedicated state-of-the-art instrument for exoplanet transit and eclipse studies, *Origins* will study the exoplanet atmospheres for gases that are the most important signatures of life.

What fraction of terrestrial K- and M-dwarf planets has tenuous, clear, or cloudy atmospheres? In the first tier of its exoplanet survey, *Origins* will obtain transmission spectra over the 2.8–20 μm wavelength range for temperate, terrestrial planets spanning a broad range of planet sizes, equilibrium temperatures, and orbital distances, in order to distinguish between tenuous, clear, and cloudy atmospheres. Because CO_2 absorption features are so large, this tier can include terrestrial planets orbiting stars from late-M to late-K, giving *Origins* a broader perspective in the search for life than JWST.

Table 2 Science drives *Origins* key design parameters (Scientific Traceability Matrix (STM) provided in the full report)

Origins science driver		Technical or instrument parameter			
Scientific goal	Observable	Parameter	Requirement	Design	Rationale
How do galaxies form stars, make metals, and grow their central SMBHs?	Mid- and far-IR rest-frame spectral lines.	Telescope Size	3.0—5.0 m	5.9 m	5.0 m aperture is driven by the sensitivity to detect z > 6 galaxies; >3.0 m based on the sensitivity needed to detect z > 2 galaxies.
		Telescope Temperature	< 6 K	4.5 K	Sufficiently cold temperature to meet the sensitivity requirements at the longest wavelengths; T_{tel} >6 K imapcts spectral line sensitivity at λ >350 μm.
How do the conditions for habitability develop during the process of planet formation?	$H_2{}^{18}O$ ground state 547.4 μm	λ_{max}	> 550 μm	588 μm	$H_2{}^{18}O$ ground state line and the need to measure continuum around it; λ < 500 μm impacts extragalactic sciences.
	$H_2{}^{18}O$ 179.5-μm line	$R=\lambda/\Delta\lambda$	200,000	203,000	Spectral resolving power is needed for Doppler tomography to connect water emission lines to disk location.
	HD 112-μm line	Spectral line sensitivity	10^{-20} W m^{-2} (1 hr; 5σ)	5x10^{-21} W m^{-2} (1 hr; 5σ)	This sensitivity is required to measure disk gas masses and obtain a useful sample of the population of disks at the distance of Orion.
		$R=\lambda/\Delta\lambda$	40,000	43,000	The spectral resolving power needed for accurate gas mass measurements.
Do planets orbiting K- & M-dwarf stars support life?	CH_4 (3.3, 7.4 μm), N_2O (4.5, 7.8 μm), O_3 (9.7 μm), CO_2 (4.3, 15 μm), $H_2{}^{18}O$ (6.3,17+ μm)	λ_{min}	< 3 μm	2.8 μm	CO_2 at 4.3 μm is the strongest of all features; λ_{min} >5 μm reduces the exoplanet case to surface temperature only.
		Aperture Size	5.3 m	5.9 m	Aperture size determines the sensitivity to detect faint CH_4 and N_2O lines, crucial for a biosignature detection in exoplanet transits over a 5-year mission.

What fraction of terrestrial M-dwarf planets is temperate? For a subset of planets with the clearest atmospheres, *Origins* will measure their thermal emission to determine the temperature structure of their atmospheres. This measurement is critical to assessing climate because it yields an understanding of how incoming stellar and outgoing thermal radiation dictate the heating and cooling of the atmosphere. *Origins* can then determine whether these atmospheric conditions could support liquid water near the surface (Line et al. 2019).

Table 3: *Origins* observatory-level parameters

Mission Parameter	Value
Telescope: Aperture Diameter/Area	5.9 m/25 m^2
Telescope Temperature	4.5 K
Wavelength Coverage	2.8—588 μm
Maximum Scanning Speed	60″ per second
Mass: Dry/Wet (with margin)	12000 kg/13000 kg
Power (with margin)	4800 W
Launch Year	2035
Launch Vehicle	SLS Block IB or Space-X BFR
Orbit	Sun-Earth L2
Propellant ifetime	10 years, serviceable, limied by station-keeping propellant

What types of temperate, terrestrial M-dwarf planets support life? *Origins* will be the first observatory with the necessary spectroscopic precision to not only measure habitability indicators (H_2O and CO_2), but also crucial biosignatures (O_3 coupled with N_2O or CH_4), which are definitive fingerprints of life on habitable-zone planets. In this observational third tier, *Origins* will obtain additional transit observations for the highest-ranked targets to search for and detect biosignatures with high confidence. The wavelength range afforded by *Origins* will provide access to multiple spectral lines for each molecular species. This will increase the detection significance and prevent potential degeneracies due to overlapping features, thus averting false-positive scenarios. This framework robustly detects a variety of potentially habitable planet atmospheres, including the life-bearing Archaean Earth. The entire era of exoplanetary science has shown that Nature's imagination trumps our own and *Origins'* broad wavelength coverage and precise measurements are guaranteed to give us views into the new and unexpected in the domain of life elsewhere in the Galaxy (Kataria et al. 2019).

Origins: A Mission for the Astronomical Community

With more than three orders of magnitude improvement in sensitivity over *Herschel* and access to a spectral range spanning nearly 8 octaves, *Origins* vastly expands discovery space available to the community. While the mission is designed to achieve a specific set of objectives, the science program is intended to be illustrative only. *Origins* is a community observatory, driven by science proposals selected through the usual peer-review process, as with existing NASA observatories.

Unanticipated, yet transformative, discovery space: The impressive *Origins*-enabled scientific advances discussed above are extensions of known phenomena. However, history has shown that order-of-magnitude leaps in sensitivity lead to discoveries of unanticipated phenomena. For example, the sensitivity of IRAS over balloon and airborne infrared telescopes allowed the discovery of debris disks, protostars embedded within dark globules, Galactic infrared cirrus, and IR-bright galaxies, none of which were expected at the time of launch. Likewise, no study anticipated that *Spitzer* can study $z > 6$ galaxies, measure winds transporting energy in exoplanet atmospheres, and detect the dust around white dwarfs produced by shredded asteroids.

Origins' sensitivity exceeds that of its predecessor missions by a factor of 1000. Jumps of this magnitude are very rare in astronomy, and have always revolutionized our understanding of the Universe in unforeseen ways. Thus, it is essentially guaranteed that the most transformative discoveries of *Origins* are not even anticipated today.

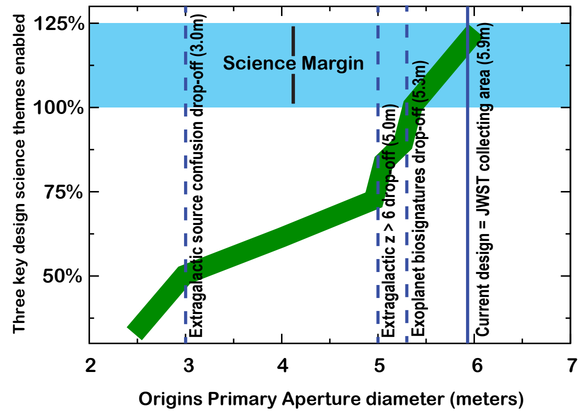

Figure 6: *Origins'* key science program requires a cold telescope with a primary aperture diameter of 5.3 m. This requirement comes primarily from the exoplanet science case to detect biosignatures in a 5-year mission, given that transit durations are fixed and sensitivity cannot be recovered with a longer single-epoch integration. If the mid-infrared exoplanet science case is descoped, the extragalactic study places an aperture size requirement of >5 m based on the need to detect a statistically significant sample of galaxies at z > 6. The minimum primary aperture diameter is 3 m to enable an effective extragalactic and Galactic science program, where source confusion compromise the telescope's ability to conduct spectroscopic studies of galaxies and the sensitivity is not too poor to study water and gas in proto-planetary disks.

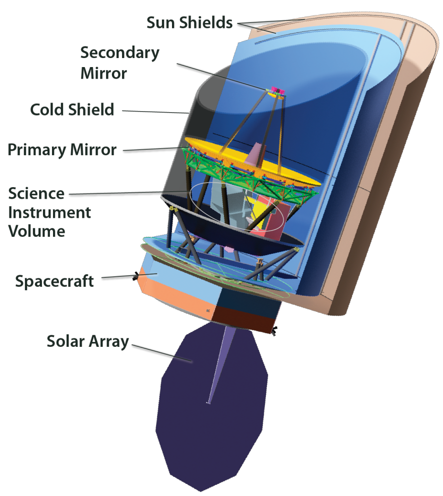

Figure 7: *Origins* builds on substantial heritage from *Spitzer* to minimize schedule risks during assembly, integration and testing, and deployment risks in space. A cutaway view shows the locations of *Origins* instruments and major elements of the flight system. *Origins*, with an aperture diameter of 5.9 m and a suite of powerful instruments, operates with spectral resolving power from 3 to 3×10^5 over the wavelength range from 2.8 to 588 μm. *Origins* has the agility to survey wide areas, the pointing stabiity required to observe transiting exoplanets, and operates with >80% observing efficiency, in line with the approximately 90% efficiency achieved with *Herschel* and *Spitzer*.

Table 4: Instrument capabilities summary				
Instrument/ observing mode	**Wavelength coverage (μm)**	**Field of view (FOV)**	**Spectral resolving power (R=λ/Δλ)**	**Representative sensitivity 5σ in 1 hr**
Origins Survey Spectrometer (OSS)				
Grating	25—590 μm simultaneously	6 slits for 6 bands: 2.7′ × 1.4″ to 14′ × 20″	300	3.7 × 10^{-21} W m^{-2} at 200 μm
High Resolution	25—590 μm with FTS	Slit: 20″ × [2.7″ to 20″]	43,000 × [112 μm/λ]	7.4 × 10^{-21} W m^{-2} at 200 μm
Ultra-High Resolution	100—200 μm	One beam: 6.7″	325,000 × [112 μm/λ]	2.8 × 10^{-19} W m^{-2} at 200 μm
Far-IR Imager Polarimeter (FIP)				
Pointed	50 or 250 μm (selectable)	50 μm: 3.6′× 2.5′ 250 μm: 13.5′× 9′ (107×75 pixels)	3.3	50/250 μm: 0.9/2.5 μJy Confusion limit at 50/250 μm: 120 nJy/1.1 mJy
Survey mapping	50 or 250 μm (selectable)	60″ per second scan rate, with above FOVs	3.3	Same as above, confusion limit reached at 50/250 μm: 1.9 hours/2 msec
Polarimetry	50 or 250 μm (selectable)	50 μm: 3.6′× 2.5′ 250 μm: 13.5′× 9′	3.3	0.1% in linear and circular polarization, ±1° in pol. angle
Mid-Infrared Spectrometer Camera Transit Spectrometer (MISC-T)				
Ultra-Stable Transit Spectroscopy	2.8—20 μm in 3 bands simultaneously	2.8—10.5 μm: 2.5″ radius 10.5—20 μm: 1.7″ radius	2.8—10.5 μm: 50-100 10.5—20 μm: 165-295	For K=10.8 mag M-type star, R=50: SNR/(t/hr)$^{1/2}$ > 12,900 at 3.3 μm with stability 5 ppm co-adding 60 transits

2. Technical Overview

***Origins* is >1000 times more sensitive than prior far-infrared missions and the design avoids complicated deployments to reduce mission risk.** The scientific objectives summarized in Table 1 are achievable with the low-risk *Origins* design. *Origins* has a *Spitzer*-like architecture (Figure 7) and requires only a few simple deployments to transform from launch to operational configuration. With the attributes shown in Table 3, the current design carries significant margin between science-driven measurement requirements and estimated performance (Table 2), leaving room for modest descopes.

Origins provides a thousand-fold improvement in the far-infrared sensitivity relative to *Herschel* (Figure 8). While *Origins* has a 2.8x *Herschel*'s collecting area, cryocooling is the dominant factor affecting enabling its extraordinary sensitivity gain. To achieve the same sensitivity gain at optical wavelengths, the light-collecting area would have to increase a thousand-fold. A far-IR telescope limited in sensitivity by the astronomical background is essential to achieving the *Origins* science goals. Earth's warm atmosphere limits SOFIA's sensitivity and *Herschel* was limited by a relatively-warm telescope (70 K). The cryo-thermal system design of *Origins* leverages *Spitzer* experience and technology developed for JWST. Four current-state-of-the-art cryocoolers cools the telescope to 4.5 K, with 100% margin in heat-lift capacity at each stage. The science requirements can be met with a telescope temperature below 6 K.

The telescope is diffraction limited at 30 μm. All of the telescope's mirrors and mirror segments can be diamond turned and rough polished to the required precision in existing facilities. The JWST primary mirror segment actuator design is reused, to allow the *Origins* primary mirror segments to be adjusted in space in three degrees of freedom (tip, tilt, and piston), enabling final alignment during commissioning. The telescope is used as a light bucket at wavelengths between 2.8 and 20 μm to perform transit spectroscopy for exoplanet biosignatures since spatial resolution is not a technical driver for that scientific objective.

The *Origins* design minimizes complexity. The optical system launches in its operational configuration, requiring no mirror, barrel, or baffle deployments after launch, but the design allows for mirror segment alignment on orbit to optimize performance. The two-layer sunshield

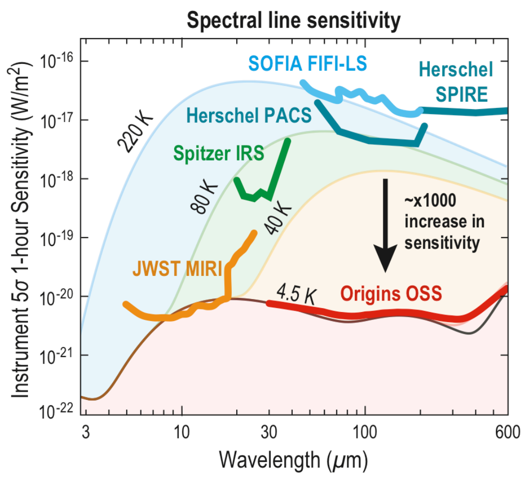

Figure 8: *Origins* taps into a vast, unexplored scientific discovery space, defined by a three-orders-of-magnitude improvement in sensitivity relative to all previously-flown far-infrared observatories. With a temperature of 4.5 K, *Origins'* sensitivity is limited by astronomical background photon noise (lower black curve). SOFIA (220 K), *Herschel* (80 K), and JWST (40 K) are shown for comparison with *Origins* (4.5 K). *Origins'* sensitivity extends JWST/MIRI sensitivity in mid-IR to the far-IR wavelengths.

deployment is simple and low risk and other deployment mechanisms - communication antenna, solar array, telescope cover - have extensive heritage. This departure from the JWST deployment approach is enabled by the new launch vehicles, which are expected to be fully operational in the mid-2030s. The design is compatible with at least two, and possibly three such launch vehicles. The fully-integrated cryogenic payload assembly comprising the telescope, instruments, and cold shield can be tested cryogenically in Chamber A at NASA's Johnson Space Center, following NASA's favored "test-like-you-fly" approach.

The next generation of launch vehicles, including NASA's SLS, SpaceX's BFR, and Blue Origin's 7-m New Glenn, have much larger payload fairings than the 5-m diameter ones available today, enabling the launch of a large-diameter telescope that does not need to be folded and deployed. *Origins* operates in a quasi-halo orbit around the Sun-Earth L2 point. The observatory is robotically serviceable, enabling future instrument upgrades and propellant replenishment to extend the mission life beyond the 5-year design lifetime.

Three science instruments spanning the wavelength range 2.8 to 588 μm provide the powerful, new spectroscopic and imaging capabilities required to achieve the scientific objectives outlined in Section 1 (Table 4). The Origins Survey Spectrometer (OSS) uses six gratings to take multi-beam spectra simultaneously across the 25 to 588 μm window through long slits. When needed, a Fourier transform spectrometer (FTS) and an etalon provide high (10^4) and ultra-high (10^5) spectral resolving powers, respectively, especially for studies of water and HD emission lines.

The Far-IR Imager/Polarimeter (FIP) provides imaging and polarimetric measurement capabilities at 50 and 250 μm. Its efficient mapping can support fast follow-up measurements for time-domain studies, and allow efficient time-monitoring campaigns. FIP surveys take advantage of *Origins'* agility; Similar to *Herschel, Origins* can scan-map the sky at 60″ per second, which is essential, since the FIP 250-μm channel reaches the extragalactic source confusion limit in a few milliseconds. FIP can perform wide area (≥1000 deg^2) photometric sky surveys, such as those targeted by LSST and WFIRST in 1000 to 2000 hours to a flux density below confusion limit at 250 μm.

The Mid-Infrared Spectrometer and Camera Transit Spectrometer (MISC-T) measures *R*~50 to 300 spectra between 2.8 and 20 μm band, with three bands that operate simultaneously. MISC-T provides exquisite stability and precision for exoplanet transits. It employs pupil densification to mitigate observatory jitter and relies on an improvement in detector stability. *Origins*/MISC-T builds on the amazing discoveries anticipated from JWST. JWST is required to deliver extraordinary sensitivity, but transiting exoplanet spectroscopy was not a major design driver. The *Origins* team, however, prioritized exoplanet biosignature detection in the important

2.8 to 10 μm wavelength range, and accordingly established 5 ppm as the required system-level stability for MISC-T. The *Origins* Technology Development Plan calls for investment in ultra-stable mid-IR detectors and offers multiple parallel development paths to reduce risk.

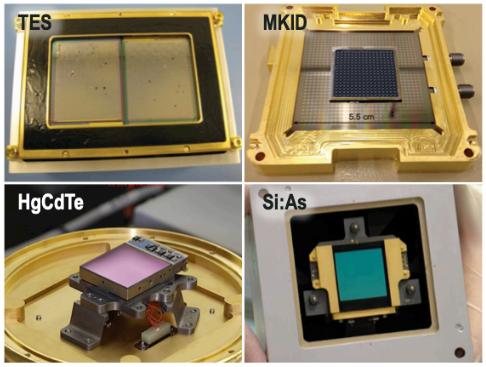

Figure 9: The robust Origins Technology Development Plan recommends parallel maturation of multiple promising detector technologies (clock-wise from top-left): TES bolometers (HAWC+ array); KIDS (432-pixel device); HgCdTe arrays (JWST/NIRCam); and Si:As (JWST/MIRI).

The *Origins* mission concept study team worked on a wider set of instrument options than presented in the baseline concept. These represent possible upscopes which, if adopted, would enhance the mission's scientific capability. These options include: the Heterodyne Receiver for Origins (HERO); the MISC Camera; expanded FOVs for OSS and FIP; and additional FIP bands (100 & 500 μm). The HERO upscope would provide nine-beam spectral measurements of selectable lines between 110 and 620 μm bands, up to very high spectral resolving power around 10^7. The MISC Camera would enable mid-infrared imaging and spectroscopy (R=300) between 5 and 28 μm. In addition to instrument modes, descopes include decreasing the aperture diameter, which impacts to the observatory's science capabilities (Figure 6).

3. Key Technologies

Detectors, ancillary detection system components and cryocoolers are the only *Origins* enabling technologies currently below Technology Readiness Level (TRL) 5. The *Origins* Technology Development Plam outlines a path leading to TRL 5 by Phase A start in 2025.

At far-infrared wavelengths, reaching the fundamental sensitivity limits set by the astronomical background (Figure 8) requires a cold telescope equipped with sensitive detectors. The noise equivalent power (NEP) required for FIP imaging is 3 x 10^{-19} W $Hz^{-1/2}$, whereas the NEP needed for OSS for R=300 spectroscopy is 3 x 10^{-20} W $Hz^{-1/2}$. Transition edge sensor (TES) bolometers and kinetic inductance detectors (KIDs) both show great promise, and we recommend maturation of both technologies to TRL 5 and downselection to a single technology at the beginning of Phase A. While the noise requirements for MISC-T's mid-IR detectors are not particularly challenging, 5 ppm stability over several hours must be demonstrated to meet *Origins* requirement. The Technology Development Plan Plan mitigates risk by recommending the parallel maturation of HgCdTe arrays, Si:As arrays, and TES bolometers (Figure 9).

Mechanical cryocoolers that can reach temperatures of 4.5 K have already flown on *Hitomi* (2016). These coolers, developed by Sumitomo Heavy Industries, had a required lifetime of 5 years compared to *Origins'* 10 years, but meet its performance requirements. Replacing the compressors' suspension system with a flex spring, a relatively straightforward change, will extend the lifetime. Several US companies have also produced TRL-5 cryocoolers or cryocooler components with a projected 10-year lifetime. The TRL 7 JWST/MIRI cryocooler, for example, has a 6 K operating temperature. Sub-Kelvin coolers operating at 50 mK, as needed for the OSS and FIP detectors, were also flown on *Hitomi*. A Continuous Adiabatic Demagnetization Refrigerator (CADR) with a much higher cooling power (6 μW vs. 0.4 μW for *Hitomi*), suitable for *Origins,* is currently being developed to TRL 6 under a Strategic Astrophysics Technology (SAT) grant. This new SAT CADR will also demonstrate self-shielding of magnetic fields to 1

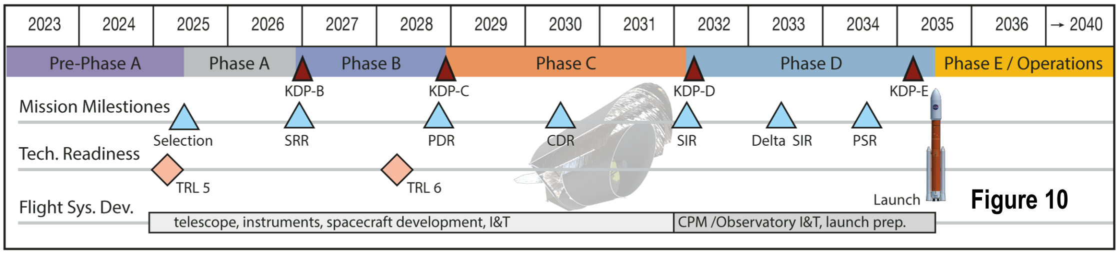

Figure 10

µT, making it compatible with superconducting detectors that demand an ambient field of <30 µT. A straightforward extension of this ADR technology allows operations at even lower temperatures (35 mK), with similar cooling power. Lowering the operating temperature is a simple way to improve TES detector sensitivity, should that become necessary during mission formulation.

4. Schedule and Cost

The *Origins* team developed a mission design concept, technical approach, technology maturation plan, risk management approach, budget, and a master schedule compatible with NASA guidelines for the Decadal Study and grounded in NASA and industry experience from previous successful large Class A missions.

Origins is a NASA-led mission, managed by a NASA Center, and includes domestic and international partners. JAXA, and a CNES-led European consortium were active participants in the mission concept study, with each contributing an instrument design. Domestic participants included GSFC, Ames, MSFC, JPL, and industry (Ball Aerospace, Northrop Grumman, Lockheed Martin, and Harris).

Figure 10 shows the *Origins* Phase A through E schedule. Scheduled milestones and key decision points are consistent with formulation and development for Class A missions. The schedule supports an April 2035 launch, and includes 10 months of funded reserve. Much of the design and development work progresses through parallel efforts, with OSS as the critical path.

NASA Goddard Space Flight Center's Cost Estimating and Modeling Analysis (CEMA) office developed a cost estimate using the industry standard PRICE-H parametric cost modeling tool. The CEMA cost estimate is based on a detailed master equipment list (MEL) and the Integrated Master Schedule (IMS) shown in figure 10 for the *Origins* baseline design. The MEL assigns an appropriate Technology Readiness Level (TRL) to each component. The CEMA cost model assumes that all components have matured to at least TRL 5 by the start of Phase A in 2025, and to at least TRL 6 by mission PDR. A separate *Origins Space Telescope Technology Development Plan* describes the maturation of all mission-enabling technologies on this timeline and reports the cost of technology maturation. The study team's mission cost estimate includes mission definition and development, the flight segment, the ground segment, and mission and science operations for 5 years. The launch cost ($500M for the SLS launch vehicle, as advised by NASA Headquarters) is also included. Working independently, Goddard's Resource Analysis Office (RAO) estimated the mission cost using a top-down parametric model. RAO and CEMA are firewalled from each other, but they both referred to the same MEL and IMS. The RAO and CEMA cost estimates agree to within 24%.

Origins is a "large" (>$1.5B) mission. The NASA Headquarters-appointed Large Mission Concept Independent Assessment Team (LCIT) is tasked with validating the cost estimates supplied by each of the four large missions studied with NASA support. The study teams have decided to wait for feedback from the LCIT before publishing detailed cost information. The *Origins* Final Study Report will provide an LCIT-validated mission cost estimate.

The *Origins* mission design has not been optimized, and optimization may lead to cost savings. Optimization is planned as a Phase A activity. Japan and several ESA member nations have significant relevant expertise and have demonstrated interest in the *Origins* mission. Foreign contributions are expected to reduce NASA's share of the mission cost.

Origins Space Telescope Further Information

Origins website:
https://origins.ipac.caltech.edu/

Origins study center document repository:
https://asd.gsfc.nasa.gov/firs/

Origins Space Telescope Final Study Report and Technology Development Plan will be submitted to NASA HQ on August 23, 2019.

References cited in this APC paper (see also Table 5):

Bergin, E. et al. 2019, The Disk Gas Mass and the Far-IR Revolution, BAAS, 51, 222

Bolatto, A. et al. 2019, Cold Gas Outflows, Feedback, and the Shaping of Galaxies, arxiv:1904.02120

Kataria, T. et al. 2019, The Mid-Infrared Search for Biosignatures on Temperate M-Dwarf Planets, White paper no 462

Lis, D. et al. 2019, D/H Ratio in Water and the Origin of Earth's Oceans, BAAS, 51, 111

Line, M. et al. 2019, The Importance of Thermal Emission Spectroscopy for Understanding Terrestrial Exoplanets, BAAS, 51, 271

Oberg, K. et al. 2019, Astrochemical Origins of Planetary Systems, BAAS, 51, 165

Pontoppidan, K. et al. 2019, The trail of water and the delivery of volatiles to habitable planets, BAAS, 51, 229

Pope, A. et al. 2019, Simultaneous Measurements of Star Formation and Supermassive BlaHole Growth in Galaxies, arxiv:1903.05110

Sadavoy, S. et al. 2019, The Life Cycle of Dust, BAAS, 51, 66

Smith, J. D. et al. 2019, The Chemical Enrichment History of the Universe, BAAS, 51, 400

Table 5: Science white papers to Astro2020 that are specific to *Origins*		
Authors	**White paper title**	**Connection to *Origins***
Alex Pope et al.	Simultaneous Measurements of Star Formation and Supermassive Black Hole Growth in Galaxies	*Origins* Theme 1 (Extragalactic), Objective #1
J. D. Smith et al.	The Chemical Enrichment History of the Universe	*Origins* Theme 1 (Extragalactic), Objective #2
Alberto Bolatto et al.	Cold Gas Outflows, Feedback, and the Shaping of Galaxies	*Origins* Theme 1 (Extragalactic), Objective #3
Klaus Pontoppidan et al.	The trail of water and the delivery of volatiles to habitable planets	*Origins* Theme 2 (Water), Objective #1
Ted Bergin et al.	The Disk Gas Mass and the Far-IR Revolution	*Origins* Theme 2 (Water), Objective #2
Derek Lis et al.	D/H Ratio in Water and the Origin of Earth's Oceans	*Origins* Theme 2 (Water), Objective #3
Luca Matra et al.	Exocometary Science	*Origins* Theme 2 (Water), Objective #3
Tiffany Kataria et al.	The Mid-Infrared Search for Biosignatures on Temperate M-Dwarf Planets	*Origins* Theme 3 (Biosignatures), Objective #1 & #3
Michael Line et al.	The Importance of Thermal Emission Spectroscopy for Understanding Terrestrial Exoplanets	*Origins* Theme 3 (Biosignatures), Objective #2
Asantha Cooray et al.	Cosmic Dawn and Reionization: Astrophysics in the Final Frontier	*Origins* as a probe of reionization, tracing early production of dust and metals, and tracer of gas.
Fabian Walter et al.	The evolution of the cosmic molecular gas density	*Origins* complements molecular gas measurements from ALMA and ngVLA with atomic line diagnostics
Eric Murphy et al.	Robustly Mapping the Distribution of Star Formation in High-z Galaxies	ngVLA maps of free-free emission of galaxies to be combined with [OIII] and other oxygen lines from *Origins* for absolute unbiased abundance measurements.

Christopher Clark et al.	Unleashing the Potential of Dust Emission as a Window onto Galaxy Evolution	Direct measurements of galactic dust and dust properties with *Origins*
Philip N. Appleton et al.	Warm H2 as a probe of massive accretion and feedback through shocks and turbulence across cosmic time	Rest-frame Mid-IR Rotational emission lines of H2 molecules cooling galaxy shocks, across the cosmic history from galaxy groups today to cosmic dawn can be studied by *Origins*.
Susanne Aalto et al.	Extremely obscured galaxy nuclei hidden AGNs and extreme starbursts	Understanding the evolution of galaxies and galaxy nuclei requires studying the extremely obscured activity that has recently been uncovered using submm facilities.
Sarah Sadavoy et al.	The Life Cycle of Dust	Dust physics properties with *Origins* and the connection to the baryon cycle
Margaret Meixner et al.	Infrared Stellar Populations: Probing the Beginning and the End	Use high resolution and sensitive measurements with *Origins* to make measurements of young stellar objects and dying evolved stars and supernovae
Laura Fissel et al.	Studying Magnetic Fields in Star Formation and the Turbulent Interstellar Medium	*Origins is* critical for enabling revolutionary steps forward in our understanding of the magnetized turbulence from which stars are formed.
Mark Heyer et al.	Far Infrared Spectroscopic Imaging of the Neutral Interstellar Medium in Galaxies	*Origins* allowedvelocity-resolved far-infrared emission lines to investigate the thermodynamics of the neutral ISM, the assembly of giant molecular clouds, interstellar turbulence, and radiative feedback.
Mikako Matsuura et al.	Dust in supernovae: --- Do supernovae produce the first dust in the Universe? Are supernovae the key dust producers of galaxies?	This White Paper debates whether supernovae produce the first dust in the Universe, and how this debate will be tested with *Origins.*
Adam Ginsburg et al.	Galactic center star formation & feedback: key questions	The closest galaxy center is a powerful laboratory for studying the secular processes that shape galaxies across cosmic time. Large-scale, high-resolution studies of this section of the Galaxy will connect Galactic star formation studies to extragalactic.
Karin Oberg et al.	Astrochemical Origins of Planetary Systems	White paper outlines the chemical processes that regulate and affect the outcome of planet formation, and makes recommendations on future observatories and laboratory and theory support needed to address outstanding questions.
Kate Su et al.	Probing Unseen Planet Populations with Resolved Debris Disk Structures	Resolving debris structures in thermal emission with *Origins* that is applicable to a large unbiased sample to study unseen planet populations

Christine Chen et al.	Debris Disk Composition: A Diagnostic for Planet Formation and Migration	Using sensitive *Origins* observations to study dust compositions in debris disks to do comparison study with materials in our Solar System
William Fischer et al.	Time-Domain Photometry of Protostars at Far-Infrared and Submillimeter Wavelengths	The majority of the main-sequence mass of a star is assembled in the protostellar phase, where a forming star is embedded in an infalling envelope and encircled by a protoplanetary disk. *Origins* enabls far-infrared programs to probe protostellar accretion variability in the nearest kiloparsec.
Roberta Paladini et al.	On the Origins of the Initial Mass Function	In order to establish if the IMF and CMF are Universal, it is necessary to: 1) perform multi-wavelength large-scale imaging and spectroscopic surveys; 2) require an angular resolution of <0.1" in the optical/near-IR and <5"in the far-IR; 3) achieve far-IR sensitivities to probe 0.1 Msun cores at 2-3kpc.
Elvire De Beck et al.	The fundamentals of outflows from evolved stars	Chemical evolution of the ISM and galaxies depends critically on stellar mass loss. We describe current efforts and future needs and opportunities to characterize AGB outflows: driving mechanisms, outflow rates, underlying fundamental physical and chemical processes such as dust grain formation, and dependency of these on metallicity.