The *Origins Space Telescope*: A NASA 2020 Decadal Study

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ABSTRACT

The *Origins Space Telescope* is an evolving concept for the Far-Infrared Surveyor mission, and the subject of one of the four science and technology definition studies supported by NASA to prepare for the 2020 Astronomy and Astrophysics Decadal Survey. The *Origins Space Telescope (OST)* will carry out observations in the long infrared wavelengths (5 to 500 μm). At mid-infrared wavelengths (10–30 μm) *OST* will be a factor of 30–100 more sensitive than *Spitzer* and *JWST*, while at far-infrared wavelengths *OST* will offer a factor of 10,000 improvement over *Herschel*, *AKARI* and *SOFIA*.

OST instruments will be capable of tracing our origins from first stars and galaxies when the universe was less than 500 million years old to life today in our galaxy after some 13 billion years. The observations will involve 3D spectroscopic surveys of the distant universe, a transformative study of habitable planetary system formation from the interstellar medium to life-bearing worlds, and the characterization of bio-signatures in extra-solar planets around Milky Way dwarf stars.

Keywords: Infrared Space Missions, galaxy formation, star formation, planetary system formation, exoplanets

1. INTRODUCTION

The *Origins Space Telescope (OST)* is an evolving concept for the Far-Infrared Surveyor mission (NASA 2013 Roadmap)[1], and the subject of one of the four science and technology definition studies supported by NASA to prepare for the 2020 Astronomy and Astrophysics Decadal Survey. The goal of the project is to create a mission concept that is scientifically compelling and executable in the 2030s. The project includes two intertwined components: a scientific case that motivates the design of the observatory, and an engineering study that has enough detail to serve as a proof of principle and allow the derivation of a cost estimate. The scientific case has been driven by a community-based science and technology definition team (STDT) who are the authors of this paper (Meixner et al. 2016). The engineering study, centered at NASA Goddard Space Flight Center (GSFC), includes input from partners NASA Jet Propulsion Laboratory (JPL), NASA Ames Research Center, Japan Aerospace Exploration Agency (JAXA), Centre National d'Etudes Spatiales (CNES), Ball Aerospace, Northrop-Grumman, Harris and Lockheed-Martin. This paper will present the *OST* Mission Concept 1 and the science case that motivated it.

2. MISSION CONCEPT 1

The approach for *OST*'s Mission Concept 1 is to articulate the most exciting science questions and to design an observatory that can address them all. The result is a very ambitious observatory with a large cold telescope and 5 highly

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[1] NASA 2013 Science Roadmap Team (Kouveliotou, C., Chair), "Enduring Quests, Daring Visions: NASA Astrophysics in the Next Three Decades," https://smd-prod.s3.amazonaws.com/science-red/s3fs-public/atoms/files/secure-Astrophysics_Roadmap_2013.pdf

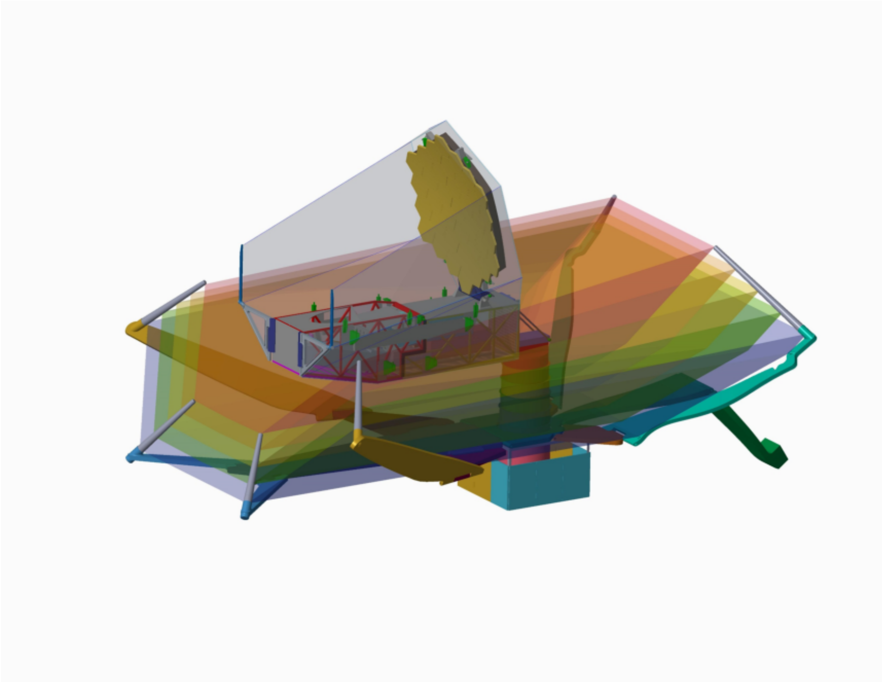

Figure 1. *Origins Space Telescope*: Mission Concept 1, fully deployed.

capable instruments (Tables 1 and 2). The telescope is a 9.1 m off-axis, segmented telescope that is cryogenically cooled to 4 K. A sunshade, baffle and cryocoolers ensure the telescope environment is maintained at 4 K. The primary mirror is deployed and the secondary is fixed inside the instrument accommodation module (Figure 1). The observatory will be outfitted with large Control Momentum Gyroscopes and momentum wheels to enable large scale mapping of the sky at approximately 100 arcseconds per second. The telescope is a three-mirror anastigmat optical configuration, which provides an adequate field of view for all the instruments, and the third mirror is used as a fast steering mirror for the rapid sky measurements needed for the detectors. The flight system comprising of the telescope, instrument accommodation module, sunshield and spacecraft would be launched in an 8.4 m diameter fairing in NASA's Space Launch System, which is currently in development.

Table 1. Origins Space Telescope: Mission Concept 1

primary mirror	9.1 m off-axis
temperature	4 K
wavelengths	5–660 μm
instruments	5 science
launch date	2030s
orbit	Sun-Earth L2
data rate	348 Mb/s
lifetime	5 year, 10+ year goal

The five instruments covering wavelengths from 5 to 660 μm enable a broad range of scientific activity (Table 2). Two instruments, MISC and FIP, have broadband imaging capabilty. The MISC imager will also be used for guiding or pointing information purposes. FIP additionally has capability for differential polarimetric imaging. Four of the instruments, MISC, MRSS, HRS and HERO, have spectroscopic capability with a wide range of spectral resolutions. MISC has a specialized transit spectrometer for transiting exoplanet research and a coronagraph for imaging outer giant planets in other planetary systems. The spectrometers, shown in Figure 2, will have two to four orders of magnitude more sensitivity than Herschel because of the anticipated improvements in detector sensitivity and the large, cold primary mirror.

The motivation for the instrument capabilities were science driven based on more than 32 science proposals from the astronomical community. The MISC has been driven by the transiting exoplanet research needs for molecular transitions of methane (CH_4), ozone (O_3), water (H_2O) and carbon dioxide (CO_2) and extra galactic imaging and spectroscopy. The

FIP has been driven by a plan to search for and characterize trans Neptunian objects (TNOs), study star formation, and resolve the extra-galactic background. The MRSS has been driven by desire for efficient deep spectral surveys that will enable galaxy and blackhole formation and cosmic evolution studies. The HRS has been driven by the need for sensitive measurements of proto-planetary and debris disks that will enable a clearer understanding of planetary system formation and development. The HERO has been driven by interstellar medium studies of Milky Way and nearby galaxies, and kinematic followups of the brighter proto-planetary disks that will provide insight into the distribution of water and the overall mass distribution.

3. SCIENCE MOTIVATION

OST will trace our origins from first stars to life and address three questions from the NASA Astrophysics Roadmap: How does the Universe work? How did we get here? Are we alone? We envision these questions to be addressed primarily through general observer programs with some key programs that require substantial amounts of time. In this paper, we focus on just two exciting science areas that are driving many top level requirements for the *OST* Mission Concept 1.

3.1. The formation and evolution of galaxies and blackholes and the rise of metals and dust

A core science goal of the *OST* mission is to study the cosmological history of star, galaxy, and structure formation into the epoch of reionization (EoR, Figure 3). With MISC and FIP, *OST* will survey the well studied deep fields (e.g. GOODS, or COSMOS), resolve the extragalactic background into individual galaxies through mid-IR imaging and far-IR spectral line surveys, and enable synergistic studies with *HST*, *JWST* and *WFIRST* observations. *OST*/MRSS will survey these deep fields to measure the rest-frame mid-IR lines (e.g., ([Ne II]+[Ne III])/([S III]+[S IV]) in tens of thousands of galaxies across cosmic time. This statistically significant sample will constrain the relative metallicity and chart the rise of metals in the Universe. Moreover, with FIP measurements of the continuum and MRSS spectroscopic measurements of the PAH feature, *OST* will quantify the dust enrichment history of the Universe, uncover its composition and physical conditions, reveal the first cosmic sources of dust, and probe the properties of the earliest star formation. Astrophysical dust comprises

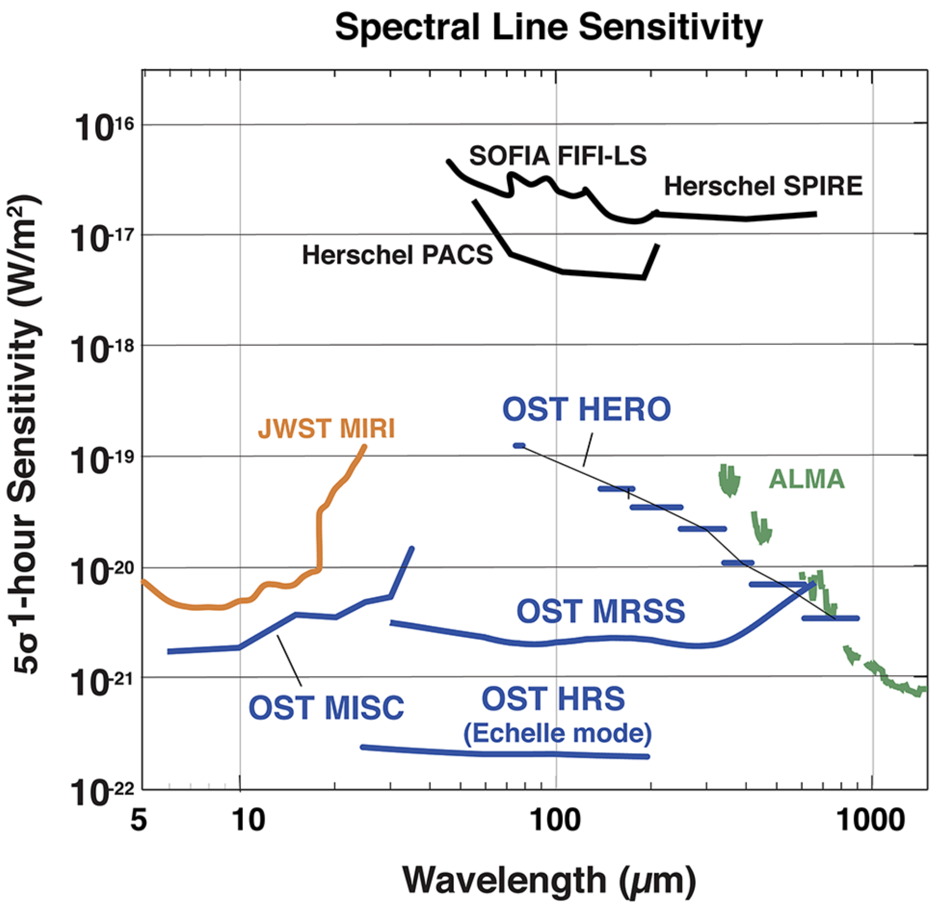

Figure 2. Leveraging improvements in detector technology and a large, cold primary mirror, OST will offer two to four orders of magnitude improvement in sensitivity over Herschel. OST will bring arc-second imaging and unprecedented spectroscopic capabilities to the infrared universe.

Table 2. *OST* Instruments in Mission Concept 1

Instrument	Wavelength (μm)	R ($\frac{\lambda}{\Delta\lambda}$)	Observing Modes
MISC: Mid-Infrared Imager, Spectrometer, Coronagraph	5–38	15, 300, 1200, 2.5×10^4	imaging, spectroscopy Coronagraphy (10^{-6} contrast) transit spectrometer (< 10 ppm stability)
MRSS: Medium Resolution Survey Spectrometer	30–660	500, 4×10^4	Multi-band Spectroscopy survey, pointed
FIP: Far-Infrared Imager and Polarimeter	40, 80, 120, 240	15	broad band imaging Field of view: $2.'5 \times 2.'5$, $7.'5 \times 7.'5$ differential polarimetric imaging
HERO: Heterodyne Receiver for *OST*	63–66, 111–610	10^7	Multi-beam spectroscopy
HRS: High Resolution Spectrometer	25–200	5×10^4, 5×10^5	spectroscopy

less than one-hundredth of one percent of the baryonic mass of the Universe, yet approximately one-half of all energy radiated by stars and accreting black holes over its history has been reprocessed by dust to long wavelengths.

With MRSS, *OST* will probe the birth of galaxies through warm H_2 emission during the cosmic dark ages. The rotational H_2 lines are key to probing turbulence and shocks, and can dominate the cooling of gas even in the presence of metals. For the redshifted universe, the rotational H_2 lines fall squarely in the far IR, and cannot be observed practically by any known current facility. The birth of galaxies could be probed through gravitationally lensed sources found in large

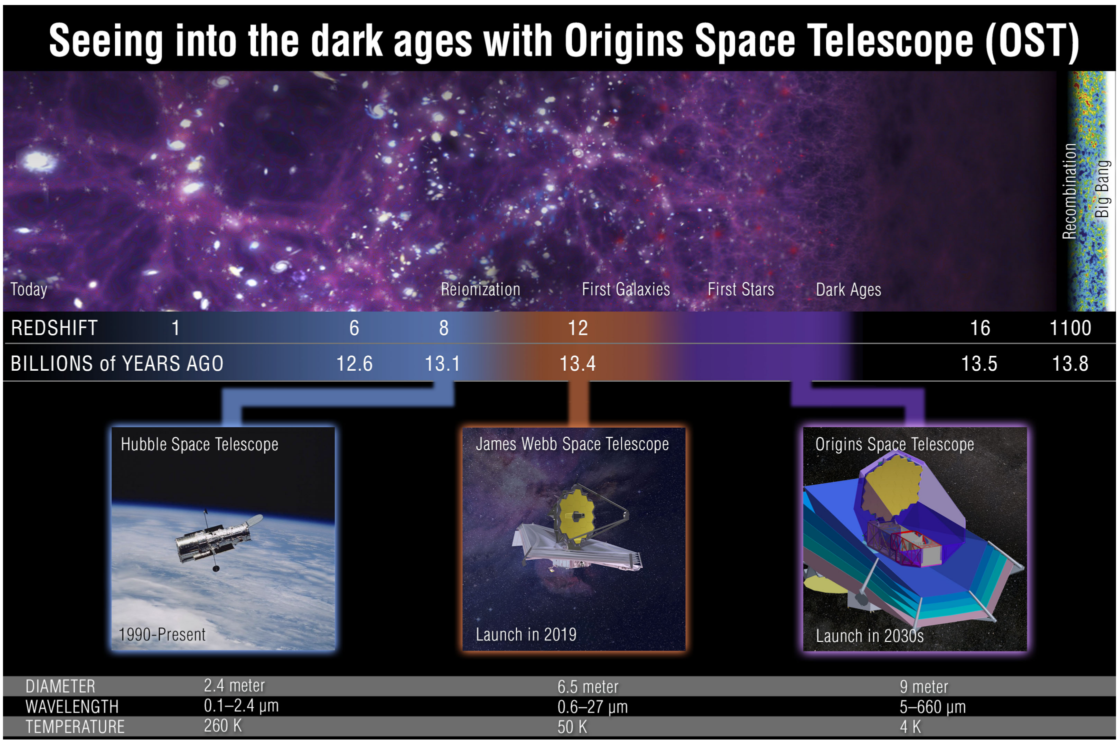

Figure 3. A core science goal of the OST mission is to study the cosmological history of star, galaxy and structure formation into the epoch of reionization.

surveys. To understand the sources and the process of reionization, it is essential to probe the population of low-metallicity, low-luminosity, and low stellar mass galaxies at $z > 6$. Tomographic line intensity mapping with *OST*/MRSS offers a powerful means of observing the dwarf galaxy population during EoR.

A persistent question in galaxy evolution is why and how galaxies and their central supermassive black holes co-evolve. The infrared uniquely probes both of these components of galaxy growth and the interaction between the two. Through large area, deep surveys in the infrared, which have resolved a significant fraction of the cosmic infrared background, it is now clear that the bulk of the star formation in galaxies occurred between redshifts of $z = 1$–3 (e.g., Berta et al. 2010; Magnelli et al. 2013), and that the vast majority of the UV light from young stars was reprocessed by dust into the far-infrared. At these epochs, when the bulk of cosmic star formation is happening, a consensus picture is emerging in which distant galaxies at a fixed stellar mass have larger star formation rates than those in the local Universe. Why is this star formation more efficient than at low redshift? What physics in the ISM determines the star formation efficiency across the bulk of cosmic star formation history? What are the dominant feedback mechanisms that regulate star formation, and how does their relative importance evolve with galaxies at different masses and epochs? Some models suggest that radiative feedback from massive stars regulates star formation and sets the ISM structure. Others invoke kinetic energy input from supernovae, while yet others require the accretion of cold gas from the intergalactic medium to set the turbulent structure in the ISM. Understanding the phase structure of the ISM can dramatically narrow the parameter space of underlying physical phenomena that set galaxy star formation rates/efficiencies at high-z.

3.2. **Tracing life ingredients from the ISM to life bearing worlds**

For the first time in human history, our species has the technology needed to answer one of the longest-standing questions: "Are we alone?" Only recently have planet-hunting programs such as TRAPPIST, MEarth, and NASA's *Kepler Space Observatory* confirmed the first Earth analogues, Earth-size planets orbiting within the habitable zones of their host stars. However, only once these planets' atmospheres have been characterized with sensitive astronomical spectra will we be able to ascertain their potential for supporting life.

The *Origins Space Telescope (OST)* will have the power to reveal the complete history of the formation, evolution, and potential existence of biospheres by using the many unique tracers of water, organics, and nitrogen-bearing species that dominate the infrared wavelength region (5–600 μm). The vastly-improved infrared sensitivity offered by an actively cooled, 4 K telescope, combined with new infrared detector technology will enable us to improve sensitivity to infrared molecular lines by more than 3 orders of magnitude and determine the atmospheric constituents of up to 20 habitable planets.

The science enabled will trace the ingredients of life during the birth of planetary systems to the planets themselves (Figure 4). Over the lifetime of *OST*, astronomers will:

- Measure biosignatures: By obtaining spectra in transmission, dayside emission, and observing over a full planetary orbit, the *OST* will exploit the information-rich mid-infrared spectrum to make definitive measurements of atmospheric constituents, such as methane, ozone, carbon dioxide, and water. The emission spectra will also provide direct constraints on planetary temperatures. To this end, the *OST* will be equipped with a transit spectrometer optimized to make these observations. *OST* will find conclusive evidence for the presence or absence of the signatures of life within the atmospheres of exoplanets, and will greatly expand the reach of the *James Webb Space Telescope (JWST)* to characterize many exoplanets, enabling comparative exoplanetology.
- Create a census of water in planet-forming disks around stars of all masses: The *OST* will obtain velocity-resolved spectra of water lines tracing – for the first time – the full range of gas temperatures in 1000 planet-forming disks around stars of all masses. This will determine the mass and distribution of water as a function of stellar mass, and will establish the degree to which planets are seeded with water during their formation. The *OST* will thus enable our understanding of planet formation and the development of planetary habitable conditions. How did the Earth get its oceans? Do other planets harbor life? What conditions lead to the formation of habitable planets, and how common are these conditions?
- Determine the total amount of primordial planet-forming gas around all stars: *OST* will use the ground-state HD line at 112 μm to obtain unambiguous and precise measurements of the total gas mass available for the formation of planets around 1000 stars of all masses. This sample is sufficiently comprehensive to fully determine the efficiency of planet formation as a function of stellar mass by comparison to exoplanet demographics.
- Trace the origin of Earth's water and of water in our Solar System: *OST* will determine the D/H ratio in hundreds of comets providing, for the first time, a full statistical sampling of this critical fingerprint for probing the origin of water on our living planet. *OST* will use low-lying lines of H_2O and HDO to determine the D/H ratio with high precision. This sample is large and will set stringent constraints on cometary delivery of Earth's water, and will explore the heterogeneity of D/H within cometary reservoirs (Oort Cloud, Kuiper Belt). These measurements will be transformative in understanding the origin of water in the solar system.
- Trace water and other volatiles back to their interstellar origins: To complete the puzzle, the *OST* will follow the water from the interstellar medium to young protoplanetary disks, revealing how planetary systems form.

4. NEW TECHNOLOGY FOR NEW SCIENCE

An important enabling technology for *OST* is large arrays of direct detectors which are sufficiently sensitive to meet the astrophysical photon background, per-pixel sensitivities need to be on order 3×10^{-20} W Hz$^{-1/2}$ for far-infrared spectroscopy (Zmuidzinas 2012). These sensitivities have been obtained with transition-edge-sensor (TES) bolometers (e.g., Staguhn et al. 2016), as well as quantum capacitance detectors (QCDs). However, work is required to create a detector system compatible with formats of up to 1 million pixels. This requires high-density (1000 x) frequency-domain multiplexing as is now employed with the kinetic inductance detectors (KIDs). Mid-infrared detectors, such as those that are part of the mid-infrared instrument on *JWST* (Love et al. 2005), require improvements in stability in order to measure the exoplanet transits. Everything needs to be cold with detectors at ~50 mK and the telescope optics ~4 K. These temperatures can be attained by scaling up existing cryocooler systems, sub-Kelvin coolers, and with careful space observatory thermal design. Instrument technologies such as compact direct-detection spectrometers are also needed to satisfy instrument accommodation constraints.

5. MISSION CONCEPT 2 & SUMMARY

The STDT will be working on a Mission Concept 2 that will be less ambitious than Mission Concept 1 and better optimized for science return per dollar. The telescope size will be comparable to *JWST* and actively cooled to 4 K. To minimize deployments, the second concept will have a Spitzer-like configuration with a wrap-around sunshade and be designed for a vehicle with a 7 m diameter or larger fairing. The instruments will be descoped in capabilities to satisfy accommodation constraints through a science-driven process.

6. SUMMARY

The STDT will be wrapping up its major work in 2018 and finalizing the report for delivery to the Decadal Survey in 2019. If you are interested in contributing to the science or technology case, send email to ost_info@lists.ipac.caltech.edu. Bi-weekly STDT telecons are open to the community (see Events link at https://asd.gsfc.nasa.gov/firs/). For more information about *OST*, see http://origins.ipac.caltech.edu.

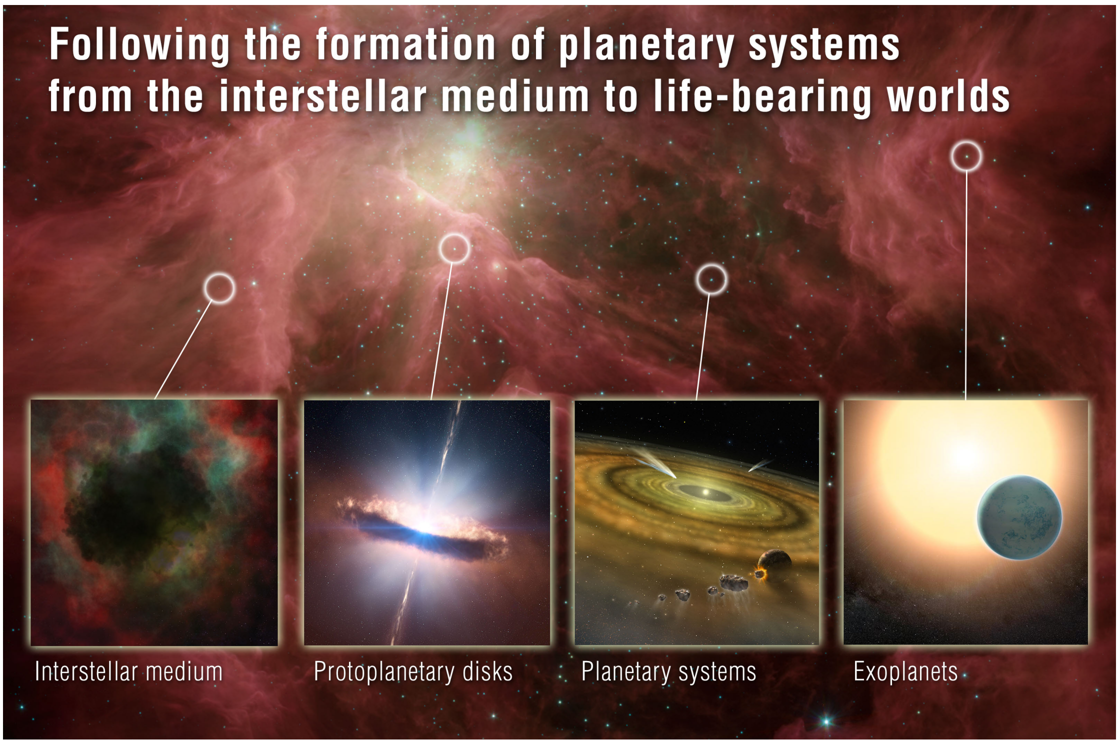

Figure 4. OST will explore the trail of life's ingredients from planetary origins to inhabited worlds.With its wide spectral grasp, OST can detect nearly the entire rotational spectrum of water, including its ground states, to trace the origins of life-fostering water in the cold dense interstellar medium. OST will survey hundreds of planet-forming disks through all evolutionary stages to reveal planetary origins through their total gas mass (with HD) and the location of the water snowline.

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