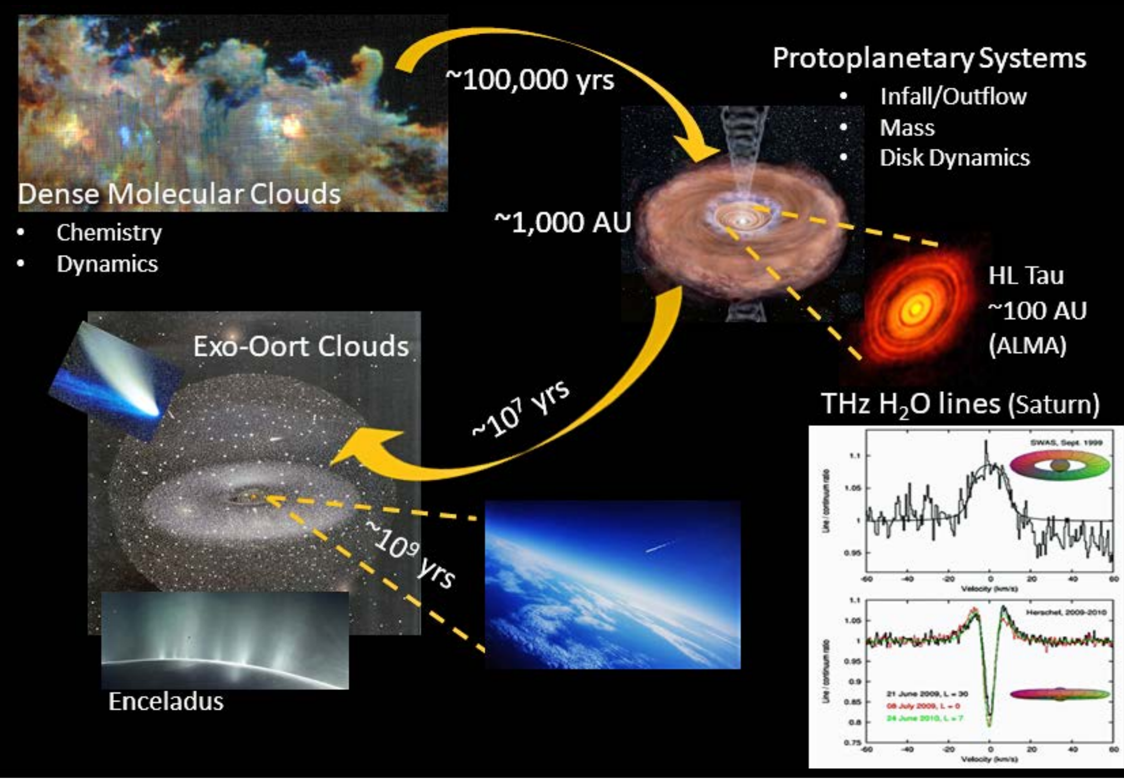
Orbiting Astronomical Satellite for Investigating Stellar Systems (OASIS):

Following Water from the Interstellar Medium to Oceans



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Orbiting Astronomical Satellite for Investigating Stellar Systems (OASIS)

A Pathfinder to Large Space Telescopes

Summary

The Orbiting Astronomical Satellite for Investigating Stellar Systems (OASIS) is a 20 meter class space observatory that will perform high spectral resolution observations at terahertz frequencies (see Figure 1). Over its nominal 2 year mission OASIS will probe conditions and search for biogenic molecules (e.g., water) towards 100's of protoplanatery disks and solar system objects (planets, moons, comets, and asteroids). The telescope consists of an inflatable, reflector secured to a spacecraft via deployable struts. The innovative inflatable structure allows packaging of a large aperture telescope within available launch volumes/masses. At launch the entire telescope fits within a ~1 m^3 volume. The proposed effort directly addresses NASA's Strategic Goal 1.1; Understanding the Sun, Earth, Solar System, and Universe. Realizing large space apertures using traditional approaches has proven difficult and costly. The OASIS concept breaks with tradition and will serve as a pathfinder for a new generation of large space telescopes capable of seeking out harbingers of life within the solar system and beyond.

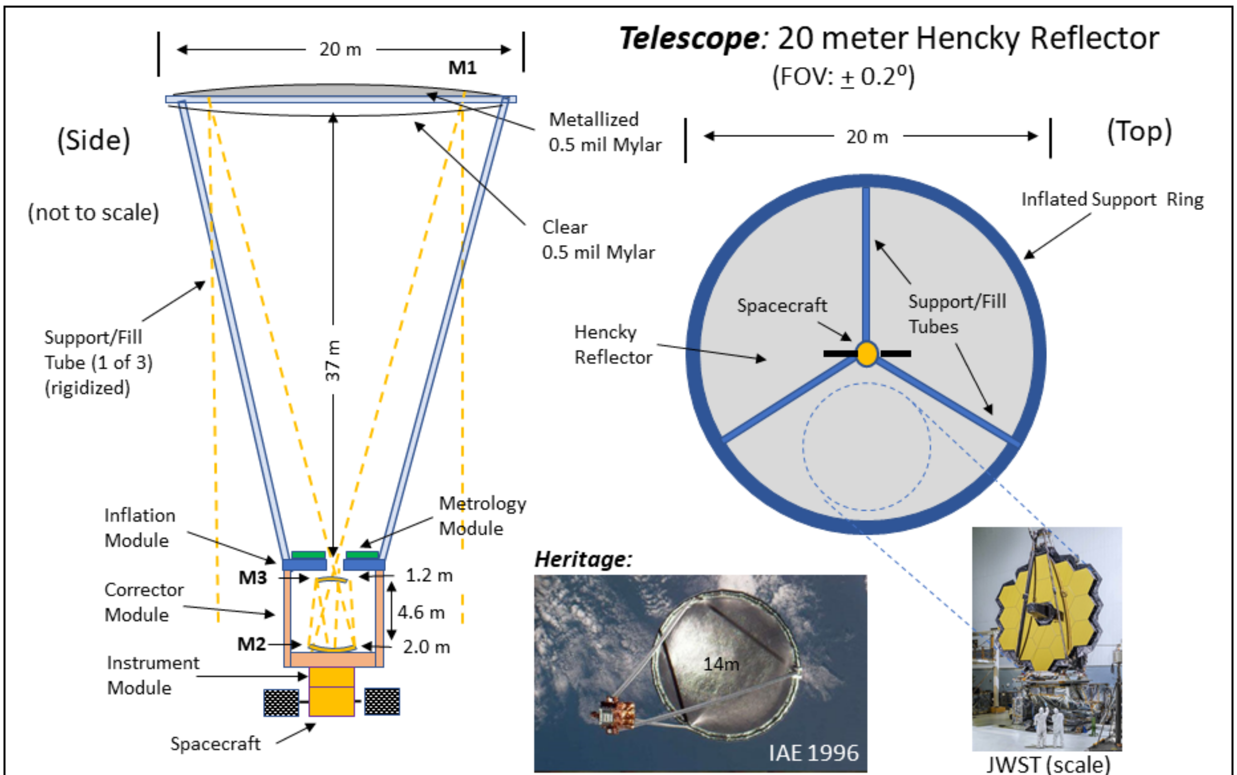

Figure 1. OASIS Concept. The science objectives of OASIS are met by utilizing a 20 meter inflatable aperture with heritage from the Inflatable Aperture Experiment (IAE) mission, which demonstrated in-orbit, deployment of a 14 meter aperture in 1996. OASIS will utilize a Hencky reflector geometry together with proven adaptive optics techniques to yield a wide-field-of-view inflatable aperture that can operate at submillimeter wavelengths (i.e., terahertz frequencies).

Key Science Goals and Objectives

OASIS will have ***~30x the collecting area and ~6x the angular resolution of Herschel*** and complements the short wavelength capabilities of JWST. With its large collecting area and suite of terahertz heterodyne receivers, OASIS will have the sensitivity to explore the role water plays in the formation and evolution of planetary systems and directly measure gas mass. The science goals of OASIS are:

1) Understand the origin of the Earth's oceans[1,2,3].
2) Understand the source and mechanisms by which water outgasses from solar system objects[4].
3) Understand the role gas mass has in the evolution of proto-planetary systems [1,5.]
4) Understand the role water plays in planet formation[1,2,3].
5) Understand the transport of water from the outer to inner solar system[1,2,3,4].

Decadal Science White Papers containing discussions of the importance of the OASIS science goals are listed in the references section.

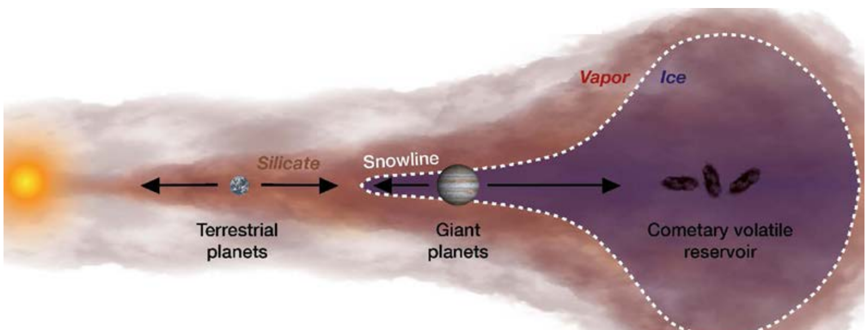

Figure 2. Protoplanetary Disk. Ice bearing planetesimals form beyond the snowline[1].

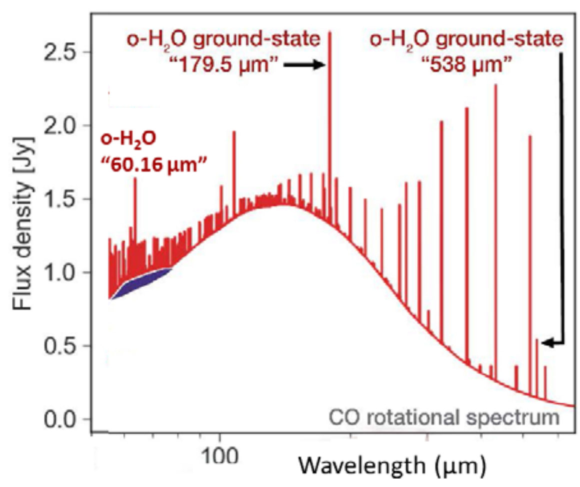

Figure 3. Far-IR spectrum of protoplanetary disk[1]

Figure 2 shows an edge-on view of a protostellar system. Figure 3 is a model of the associated far-infrared spectrum (Pontoppidan[1] et al., 2019). Atop the blackbody emission from dust is a plethora of water lines. In general, water lines at longer wavelengths have lower excitation temperatures and probe the cooler, outer parts of the disk, while shorter wavelength lines sample warmer gas closer to the protostar. By the judicious choice of transitions, it is therefore possible to sample conditions throughout a protostellar system without spatially resolving the object. Where exactly the emission originates in the disk can be inferred via Kepler's law from the Doppler shifted frequency at which the transition is observed (see

Figure 4, adapted from Blevins et al., 2016). The heterodyne receivers to be used on OASIS have superb velocity resolution (~ 1 km/s) making this a straightforward determination.

A candidate list of lines to be targeted by OASIS is provided in Table 1. The list includes the ground state water line at 538µm, which probes the cool, outer regions of a protostellar system (≥100 AU), as well as the 179.32µm and 60.16µm transitions. These shorter wavelength transitions can, depending on conditions, probe regions from less than 1 to ~100 of astronomical units (AU) from a star (Blevins et al. 2016). Also included in the list are deuterated molecules (e.g., HD and HDO) which can be used to both accurately measure the gas mass of protostellar systems and trace the transport of material from interstellar space to planetary surfaces. Over the past ~20 years the D/H ratio of water has been painstakingly measured in interstellar clouds, a handful of comets, meteorites, and the Earth's oceans. From a comparison of these values, it should be possible to deduce how and when the Earth's oceans formed (Lis et al.[2]; 2013). Unfortunately, there is not a sufficient number of observations of the D/H ratio in non-terrestrial objects to reach a meaningful conclusion. The large aperture of OASIS will provide the sensitivity necessary to yield a statistically significant number (100's) of D/H measurements within our solar system and beyond, allowing greater insight into the processes by which oceans are formed.

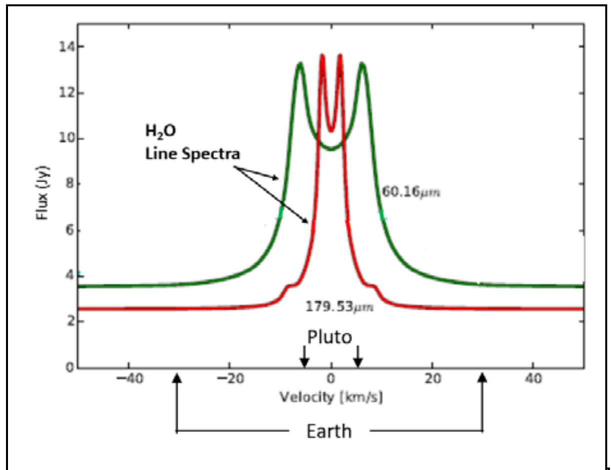

Figure 4. Model Protoplanetary Disk H_2O Spectra of RNO 90 (Blevins, et al. 2016). High resolution spectroscopy combined with Kepler's Law can be used to **resolve a disk** in velocity space, allowing an accurate determination of disk properties as a function of distance from the star. (Orbital velocities of Earth and Pluto are shown for comparison.)

Table 1: OASIS Line List

Transition	Frequency	Wavelength (µm)	Beam (")
HDO $1_{10}\rightarrow 0_{00}$	464.92 GHz	645.27	8
$H_2{}^{18}O$ $1_{10}\rightarrow 1_{01}$	547.676 GHz	547.39	6.8
^{13}CO J= 5→4	550.926 GHz	547.16	6.7
H_2O $1_{10}\rightarrow 1_{01}$	556.936 GHz	538	7
H_2O $3_{21}\rightarrow 3_{12}$	1.163 THz	258	3.2
H_2O $2_{12}\rightarrow 1_{01}$	1.671 THz	179.53	2.3
HD J= 1→0	2.675 THz	112.07	1.4
H_2O $3_{21}\rightarrow 2_{12}$	3.98 THz	75.38	0.9
H_2O $8_{26}\rightarrow 7_{35}$	4.99 THz	60.16	0.7

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Technical Overview

The observational goal of OASIS is to make high spectral (1 km/s) observations of water and deuterated molecules towards large numbers of protostellar and solar system objects. To achieve this goal the OASIS telescope must have a collecting area >10x that of Herschel and carry a suite of sensitive THz heterodyne receivers. To enable the possibility of long, uninterrupted integrations and maintain temperature stability, OASIS will be placed in an L2 or Earth trailing orbit (see Figure 5). A simplified, functional block diagram of OASIS is provided in Figure 6. Table 1 provides a summary of Mission and Instrument Parameters.

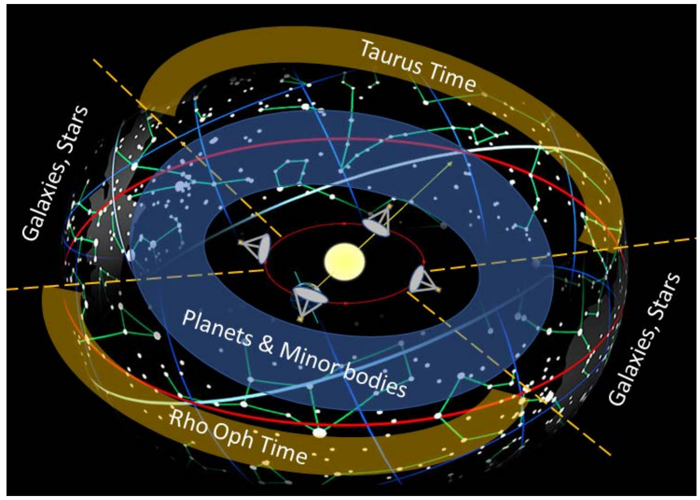

Figure 5. OASIS Orbit. In order to ensure a stable temperature environment and facilitate the possibility of long, uninterrupted integrations, OASIS will be placed in an Earth trailing or L2 orbit. The telescope's large FOV permits many objects within a given molecular cloud (e.g., Taurus or Rho Ophiuchi) to be targeted using a tip/tilt mirror in the focal plane without requiring movement of the entire telescope/spacecraft.

Large telescope apertures can be achieved in space by utilizing inflatable reflector technology. As described by Meinel & Meinel (2000), an inflatable membrane mirror can be formed by using two thin, circular, polymer membranes (one transparent and the other metallized) that are sealed on their periphery, attached to a tensioning ring and inflated to a pressure sufficient to produce the required focal ratio. Examples of thin polymer membrane materials used in space are Mylar and Kapton. Light passes through the transparent, front membrane and reflects off the metallized back membrane (see "M1" in Figure 1). The profile of such a mirror is an oblate spheroid, generally expressed by an even power series termed the Hencky curve (Hencky 1915). The reflected waves come to a focal line at ~1/4 of the reflector's radius of curvature, ~24 meters. A spherical corrector, formed from two aspheric mirrors ("M2" and "M3") then collapses the focal line to a focal point for efficient coupling to the detectors. The wide FOV of a Hencky reflector allows the emergent beam to be redirected through wide angles using a tip-tilt mirror in the focal plane, obviating the need to adjust the attitude of the spacecraft/telescope until large slews are required. A closed-loop adaptive optics system continuously measures the reflector's surface and compensates for non-spherical distortions by utilizing a deformable mirror (Walker et al., 2017; Lesser et. al. 2019).

To achieve the required spectral resolution, OASIS will utilize dual polarization, heterodyne receivers. The receivers downconvert the high-frequency sky signals to microwave frequencies, multiplying the incident sky and local oscillator (LO) beams together across a nonlinearity in the superconducting mixing devices, either SIS or HEB, depending on the frequency (Walker 2015). The product of the multiplication contains sum and difference frequencies. Filtering permits only the difference (i.e., intermediate frequency (IF)), signal to appear at the mixer output. From there, coax conveys the down-converted sky signal to a series of low-noise cryogenic and room-temperature microwave amplifiers. The amplifiers boost signal levels to the point at which they can be digitized and turned into power spectra by autocorrelator spectrometers. ***Much of the OASIS instrument architecture and hardware is based on technologies developed and demonstrated for airborne (SOFIA), balloon-borne (STO & GUSTO), and space-based (Herschel) THz telescopes.***

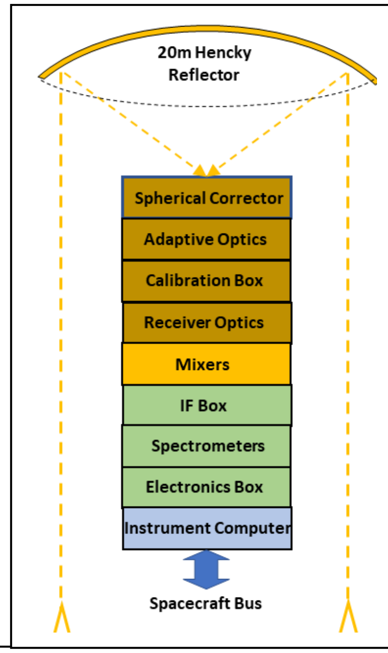

Figure 6. OASIS Block Diagram. Light from the reflector is first corrected for aberrations by utilizing a spherical corrector together with an adaptive optics system. Once brought to a focus, the signal is downconverted by superconducting mixers to microwave frequencies, amplified, digitized, and processed to create spectra.

Table 2: Mission and Instrument Parameters	
Mode	Free Flyer
Duration	2 years
Orbit	Earth Trailing or Sun-Earth L2
Launch	2028
Telescope	20m Hencky reflector; inflated; FOV $\pm 0.2^0$
Instrument	Heterodyne Receivers; SIS & HEB
System Noise Temperature (Tsys)	Tsys $\leq$ 100K; 460 GHz < f < 1.2 THz (SIS) $\leq$ 1,000K; f > 1.2 THz (HEB)
Spectrometers	Autocorrelator (~1 km/s)
Pointing	2 arcsec (with adaptive optics)
Cryogenic System	4K Cryocooler
Payload Mass	~500 kg
Payload Power	~1kW
Data Volume (2 years)	7 Terabits

Technical Drivers

As discussed above, the instrumentation required for OASIS is already at a high Technology Readiness Level (TR6+). Likewise, as indicated by Table 2, the spacecraft requirements are relatively modest and can be accommodated by commercially available buses. Work performed by our team under NASA's NIAC program (as well as other federal agencies) indicate thin membrane technology combined with adaptive optics techniques can be used to realize large, deployable reflectors for operation throughout the far-infrared. Over 50 years ago Project Echo (30.5m; Clemmons 1964) and, more recently, the Inflatable Aperture Experiment (IAE) (14m; Freeland et al., 1996; 1992) provided valuable on-orbit experience into how large inflatable reflectors can be realized in space. Due to being in the hard vacuum of space, the internal pressures required to inflate and maintain such structures are very low (<10^{-4} psi), which makes them resilient against punctures from micrometeorites and space debris. Due to these low pressures, gas only slowly diffuses through punctures. Lifetime calculations have been performed assuming a standard micrometeorite background flux, with the result being that multiyear operation can be achieved by carrying only a modest resupply of inflatant. For example, the nominal 2 year mission lifetime of OASIS can be achieved with ~80 kg of CO_2, which could be carried in liquid form. Due to less surface stress being required to maintain the reflector's shape, larger apertures require *lower* internal pressures, which means less inflatant is needed per unit volume. In this respect, it is *easier* to make larger apertures.

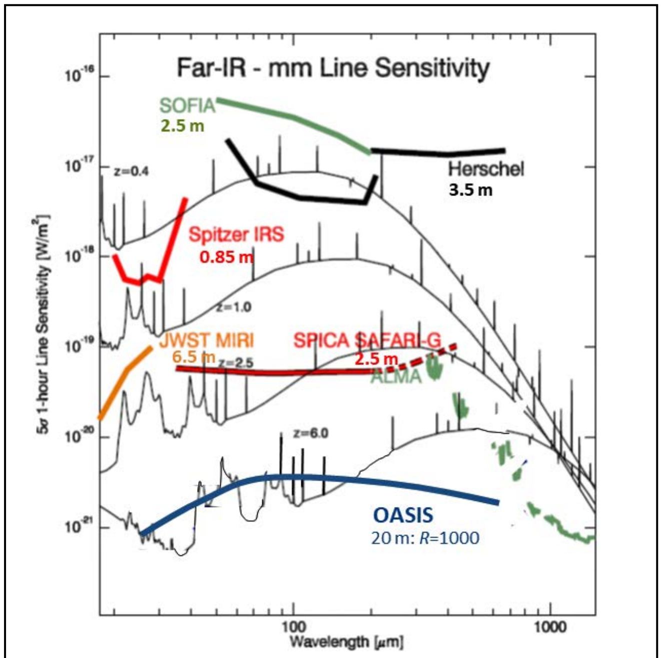

Fig. 7. OASIS telescope sensitivity compared to past, present, and proposed FIR/THz missions. Here the telescope is radiatively cooled to ~63K. The large aperture of OASIS results in major advantages in terms of scientific performance (e.g. higher angular resolution) and simplicity of implementation (SED template from Bradford, FIR Surveyor STDF; Walker 2015 (Fig. 7.11)).

The fundamental limit to the sensitivity of a space-based observatory is set by the photon noise generated by the telescope optics (referred to as NEP_{ph}, Reike (2003); Walker (2015)). This noise depends on the temperature of the optics and the frequency and bandwidth of the detectors being used. It is independent of the telescope size, whereas the number of signal photons scales with collecting area. This means that a desired signal-to-noise ratio can be achieved by either using a smaller telescope cooled to a lower temperature or a larger telescope operating at a higher temperature. The latter case has two significant advantages; 1) a larger aperture provides greater angular resolution that mitigates the possibility of hitting the source confusion limit and 2) since the aperture is warmer, the requirements on detector sensitivity (i.e., NEP_{det}) can be significantly reduced. A plot comparing OASIS sensitivity to past, present, and proposed FIR/THz missions is provided in Figure 7. For the science case presented here, the goals are achieved utilizing cryogenic heterodyne receivers. The receivers have a sufficiently narrow bandwidth (i.e., $R\sim10^6$) that the contribution of noise due to thermal radiation of the telescope is insignificant, even at ambient (~300K) temperatures. Therefore, no cooling (active or passive) of the telescope is required.

The technical driver for achieving large, affordable, space telescopes with more than 10x the collecting area of JWST is a space-based demonstration of the combination of reflector and adaptive optics technology being envisioned for OASIS. The OASIS mission, in itself, will provide fundamental insights into the role water plays in the origin and evolution of planetary systems.

It will also serve as a stepping stone to realizing a new generation of space telescopes that have the potential of revolutionizing our understanding of the cosmos.

Organizations, Partnerships, and Current Status

The OASIS team consists of individuals and organizations with many decades of experience in the areas of expertise required for a successful OASIS mission. These organizations include the University of Arizona (Lead; terahertz astronomy, instrumentation, and optics), Goddard Space Flight Center (instrumentation, mission management and operation), NASA Wallops Flight Facility (inflatable technologies), Southwest Research Institute (inflatable technologies), Ball Aerospace (cryogenics & spacecraft), Raytheon Space and Airborne Systems (spacecraft), and LGarde Aerospace (space inflatables). Currently our team is performing a detailed design study of all aspects of the OASIS mission and using a combination of IRAD and NIAC funding to further mature key technologies in preparation for the next Astrophysics Medium Explorer (MIDEX) Announcement of Opportunity. This work includes building and testing a scale model of the OASIS reflector. Additional team members will be added as the concept matures.

OASIS Schedule

Continued Development	Present - 2020
MIDEX Proposal	2021
MIDEX Phase A Downselect	2022
MIDEX Phase B Downselect	2023
Launch Readiness	2028
Flight Operations*	2028 – 2030
Full Data Release	2030

*Flight operations could be extended 2+ years by carrying additional inflatant.

OASIS Cost Estimates

Since inflatable space telescopes are shaped and maintained by gas pressure, they offer significant advantages over more traditional approaches. These include (Williams et. al. 1999):

a) Low weight and packing volume.
b) Low launch costs due to their extremely high packaging density.
c) Low development and production costs.
d) Simple, robust deployment mechanisms.
e) Enhanced accuracy; gas pressure inherently attempts to perfect bodies of revolution.
f) Not susceptible to launch vibrations and have excellent on-orbit dynamics.

These advantages translate into more than an order of magnitude of cost reduction compared to what can be achieved utilizing traditional approaches. This makes it possible to propose the OASIS mission within the cost cap of a MIDEX mission, ~$250M. **Therefore, for the purposes of the Decadal, OASIS falls within the <u>Small</u> (<$500M) space mission category.**

References

Relevant Decadal Science Papers

[1]"The trail of water and the delivery of volatiles to habitable planets", Klaus M. Pontoppidan
[2]"D/H Ratio in Water and the Origin of Earth's Oceans", Darek Lis
[3]"Deciphering the Protostellar Disk Evolution Recorded by Cometary Deuterated Water", Bj�orn J. R. Davidsson
[4]"Dynamical Processes in the Planet-Forming Environment", Alan Boss
[5]"Measuring Protostar Masses: The Key to Protostellar Evolution", John J. Tobin

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