Source - A Space Mission to Probe the Trail of Water

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***Abstract*— Water is critical for determining the habitability of planets, and understanding how the Earth became wet is essential for determining the occurrence of ocean worlds. Water is believed to have been accreted onto the Earth well after its formation, plausibly from impacts of comets or asteroids formed during the evolution of the protoplanetary disk. This disk itself collapsed from a dense core in a molecular cloud. The water transferred from core to disk was formed in the dense interstellar medium, so that tracing the trail of water is an overarching goal for both astronomy and planetary science. Tracing the inheritance of water requires observation of the submillimeter rotational lines of water and of its isotopologues $H_2^{18}O$, $H_2^{17}O$, and HDO. The most favorable transitions lie at 500 GHz to 1200 GHz. To observe a statistically meaningful sample of sources in a 3-year mission requires a 3.2 to 4.2 m telescope equipped with highest sensitivity SIS receivers and digital spectrometers. We discuss here the science and mission design of our proposed mission, Source.**

I. INTRODUCTION

Water is a critically important biological molecule, but is also of astronomical importance as it is one of the key coolants of interstellar material gravitationally contracting to form new stars and planetary systems. Observations of water at far-infrared/submillimeter wavelengths are almost impossible from the Earth's surface due to absorption by water molecules in the atmosphere. Much of the submillimeter wavelength range can be observed from airborne platforms such as SOFIA [1] but atmospheric absorption at the frequency of water lines is still significant from aircraft altitudes. Consequently, water observations have been carried out with a variety of space missions including SWAS [2], which showed that that water was widespread in interstellar clouds but much less abundant than predicted by gas-phase chemistry molecules [3]. More recently the improved sensitivity and angular resolution of the *Herschel* Space Observatory [4] allowed probing water in dense cores contracting to form a new star [5] and protostellar disks [6], along with imaging a wide variety of other sources in the interstellar medium. Herschel observations also measured the D/H ratio in comets, revealing a surprising range for this ratio based on measurements of HDO/$H_2^{18}O$. In at least two comets the ratio is consistent with that on the Earth, supporting the hypothesis of cometary delivery of water to the Earth [7].

The surprising results for water in the interstellar medium and the tantalizing results for disks and comets have encouraged thinking for how to gain a better understanding of all phases of the water trail. The timing is important, as observations of water ice, which may contain the majority of water but in which measurement of isotopic ratios is extremely difficut, will become feasible in the next few years with the launch of JWST. The main challenge is to observe a statistically significant sample of interstellar clouds and cores, protostellar disks, and comets and other solar system bodies to understand with much-increased confidence how much water is delivered to forming planets in different environments. Studying the water trail is a key goal of the Origins Space Telescope (OST), a Flagship-class mission being studied by NASA for consideration by the 2020 Astronomy Decadal Survey. The earliest launch date for OST is 2035, so a relevant question is whether significant progress can be made sooner with a much less expensive mission.

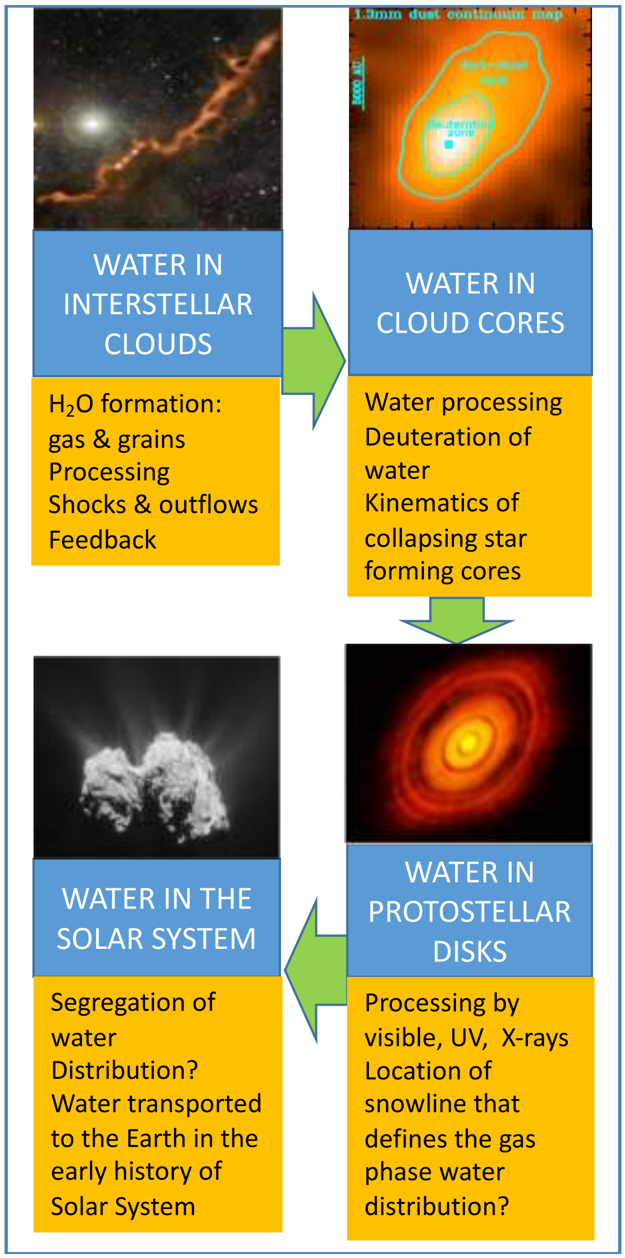

Fig. 1. Schematic of different phases of the water trail from interstellar clouds to habitable planets.

II. Requirements for the Mission

A. Frequency Coverage

A critical aspect of studying the trail of water is that much of this species is in relatively cold regions, with temperature well below 100 K. This means that only relatively low-lying rotational transitions are going to be sufficiently excited to be visible in emission. Table 1 gives information on the transitions for all of the water isotopologues that we need to observe in order to determine the inheritance of water.

Table 1. Frequencies and lower level energies of transition from low-lying energy levels of water and isotopologues

TRANSITIONS FROM LOW-LYING ENERGY LEVELS OF WATER ISOTOPOLOGUES				
SPECIES	TRANSITION	FREQUENCY (GHz)	E_l (K)	Notes
HDO	1(0, 1) - 0(0, 0)	464.925	00.00	
HDO	1(1, 0) - 1(0, 1)	509.292	22.31	
$H_2{}^{18}O$	1(1, 0) - 1(0, 1)	547.676	34.18	ortho
$H_2{}^{17}O$	1(1, 0) - 1(0, 1)	552.021	34.21	ortho
$H_2{}^{16}O$	1(1, 0) - 1(0, 1)	556.936	34.24	ortho
HDO	1(1, 1) - 0(0, 0)	893.639	00.00	
$H_2{}^{18}O$	1(1, 1) - 0(0, 0)	1101.698	00.00	para
$H_2{}^{17}O$	1(1, 1) - 0(0, 0)	1107.167	00.00	para
$H_2{}^{16}O$	1(1, 1) - 0(0, 0)	1113.343	00.00	para
$H_2{}^{18}O$	2(1, 2) - 1(0, 1)	1655.867	34.18	ortho
$H_2{}^{17}O$	2(1, 2) - 1(0, 1)	1662.464	34.21	ortho
$H_2{}^{16}O$	2(1, 2) - 1(0, 1)	1669.905	34.24	ortho

The minimum frequency range must include transitions of both ortho-H_2O and para-H_2O, and thus extends to ~1200 GHz. Going to higher frequencies is advantageous in terms of having a smaller beam, but the mixer technology becomes rapidly much more challenging as materials from which to fabricate very low noise Superconductor-Insulator-Superconductor mixers remain problematic. We are currently adopting 1200 GHz as the upper frequency limit.

B. Aperture Size

As indicated in Fig. 1, we wish to observe water in a variety of sources. Detections of water in each have previously been made, primarily using Herschel, so we have an idea of the line intensities expected. The impact of the *Source* mission discussed here will be to increase from one or two disks and handful of comets to meaningful statistical samples. Within the phase of dense cloud cores, we want to study separately low-mass, intermediate-mass, and high-mass prestellar cores to understand how the abundance of water depends on cloud mass, and in the case of protostellar cores, to see how it depends on the mass of the young star. Similarly, for disks, we have different stellar masses, and age. Going through all of the different phases, and wanting a minimum of 10 detected sources in each category, we end up requiring detections of 30 clouds, 60 dense cores, 80 disks, and 50 comets.

Of these, the disks are the most demanding in terms of telescope size, as they are all point like with signal strength varying as the square of the aperture diameter; D^2. The other phases are somewhat extended relative to reasonable anticipated beam sizes. We model the emission based on Herschel observations [6], scaled by ALMA measurements of disk properties. Assuming receiver parameters discussed in the following section, we find that with a 3.5m diameter telescope we can anticipate detecting 60 disks in H_2O 557 GHz in 6000 hours of observations, whichis not sufficient. Going to a 4.2m diameter increases this to 76 detections, very close to our requirement. Given the level of precision of the calculation, we have adopted a nominal 4.2m telescope diameter. The dense core program will take an additional 2100 hours. The comets and interstellar clouds require somewhat less time, and are much less sensitive to telescope diameter. With a 4.2m telescope we thus can achieve all science goals within a 3 year baseline mission, allowing for reasonable observing efficiency.

C. Receiver Design and Performance

The above discussion indicates that achieving the science goals is challenging, and doing so within an allowed mission lifetime requires the very best receiver performance. We show the receiver layout schematically in Fig. 2. The most stringent requirements come from the observations in the 500 GHz – 560 GHz frequency range. The HIFI instrument already had very high-performance SIS mixers in this frequency range [8], and recent developments at JPL have improved the earlier results by a factor of 2. We also assume that we have a dual polarization system with two equally-good noise temperatures. We also envision using a two-pixel receiver with a chopper, meaning that we are observing the source 100% of the time, even while carrying out standard switching between the beams/receivers to cancel any system instabilities. Finally, we will use frequency duplexing to observe in the low-frequency (500 GHz – 560 GHz) and high-frequency (~900 – 1200 GHz) bands simultaneously. The combination of these improvements means that for the same telescope size and assuming 10 times longer integration times, we will be 12.5 times more sensitive than *Herschel*

The SIS receivers will be cooled to ~ 4K by a closed-cycle refrigerator. There will thus be no consumable cryogens, and a heavy vacuum dewar and cryostat are eliminated. We anticipate launching the mission warm, and initiating cooldown only after having stabilized on orbit. This approach has many practical advantages, as it greatly simplifies assembly and testing of the receiver system.

D. Spectrometer

With 2 beams, 2 polarizations, and 2 bands operating simultaneously, *Source* requires 8 spectrometers. Observing a single line with each is not very demanding in terms of bandwidth since the water lines are relatively narrow. A frequency coverage equivalent to velocity coverage of 300 kms^{-1} is 1.2 GHz at the upper end of our frequency range. The velocity resolution required is 0.1 kms^{-1}, which means that 3000 spectral channels are necessary. 4 GHz bandwidth is required if we wish to observe $H_2{}^{17}O$ and $H_2{}^{18}O$ simultaneously. These requirements can be met relatively easily by currently available ASIC CMOS Spectrometers, e.g. [9]. Such units require less than 2W DC power, so that the total power for the spectrometer subsystem will be < 16 W. This is a huge improvement compared to systems used on e.g. *Herschel*, and dramatically reduces the challenge of providing and dissipating the several hundred watts of power that would be required by older technological approaches.

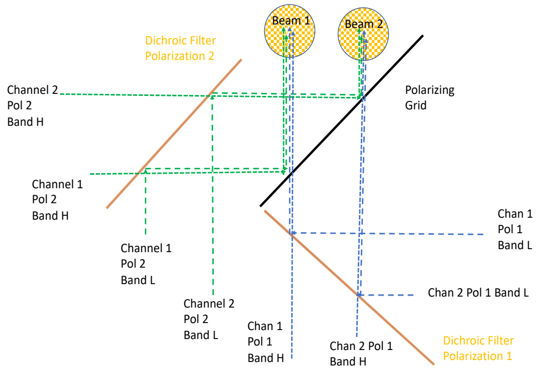

Fig. 2. Schematic layout of the receiver. There are two beams, one of which is on the target being observed and one is observing a nearby reference position. The two polarizations are separated by a polarizing grid, and the two bands by dichroic filters.

E. Telescope Requirements and Construction

There are rotational lines of water throughout the millimeter and submillimeter range, but as indicated in Table 1, the key lines to enable *Source* to follow the water trail are at frequencies below 1200 GHz, and thus $\lambda > 250$ μm. Assuming random errors for the aggregate of the primary and secondary reflectors, $\varepsilon = 12.5$ μm rms provides a Ruze efficiency of 0. 67, while $\varepsilon = 10$ μm increases this to 0.78. These are both significant improvements compared to the standard requirement of $\lambda/16 = 15.6$ μm rms which yields an efficiency = 0.54. We have thus adopted a nominal requirement for the aggregate surface accuracy of $\varepsilon = 12.5$ μm with a goal of $\varepsilon = 12.5$ μm.

A variety of technologies are available for constructing submillimeter telescopes. Herschel employed a SiC primary reflector which was a monolithic structure made from brazed segments. This material has good thermal characteristics and can be polished to a surface accuracy better than our requirement. Ground-based submillimeter telescopes are generally made from individual panels, typically < 1m in size, supported on a backstructure by 3 or more adjustors per panel. One example is the ALMA telescopes which have surface panel accuracy better than 8 μm rms [10]. Carbon fiber structures have also been successfully employed. We are in the process of contacting various suppliers to develop a variety of approaches that can provide this performance over expected temperature variations.

The panelized approaches require metrology to perform the alignment of the surface panels, while even a monolithic surface would need to be verified. This verification is a challenge for a telescope of this size. On-orbit measurement of the surface is difficult at submillimeter wavelengths due to the lack of strong point sources such as stars available at shorter and longer wavelengths. Self-contained metrology systems are expensive and relatively unproven for astronomy space missions. The optimum route would appear to be assembly, measurement, and alignment on the ground with confidence that launch and thermal environment change will not degrade the overall surface accuracy.

An approach being studied at JPL is on-orbit assembly of a panelized surface. One challenge here is the accuracy of the assembled surface, and a major question is whether on-orbit measurement and adjustment will be required. Fig. 3 shows a concept for a submillimeter space telescope assembled robotically from panels. Whether this or a different approach is utilized, this likely gives a reasonable impression of the appearance of *Source*.

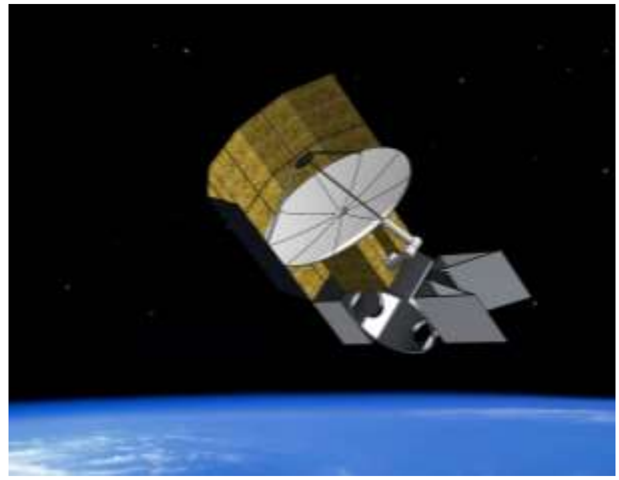

Fig. 3. Conceptual view of *Source.*

III. Summary

We have very briefly described the science goals and the technical approach for *Source*, a space mission to study the trail of water from the interstellar medium to habitable planets. The project is still in a relatively early phase but we hope to submit this concept to NASA in approximately 2 years from now. This research was carried out at the Jet Propulsion Laboratory, which is operated for NASA by the California Institute of Technology.

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