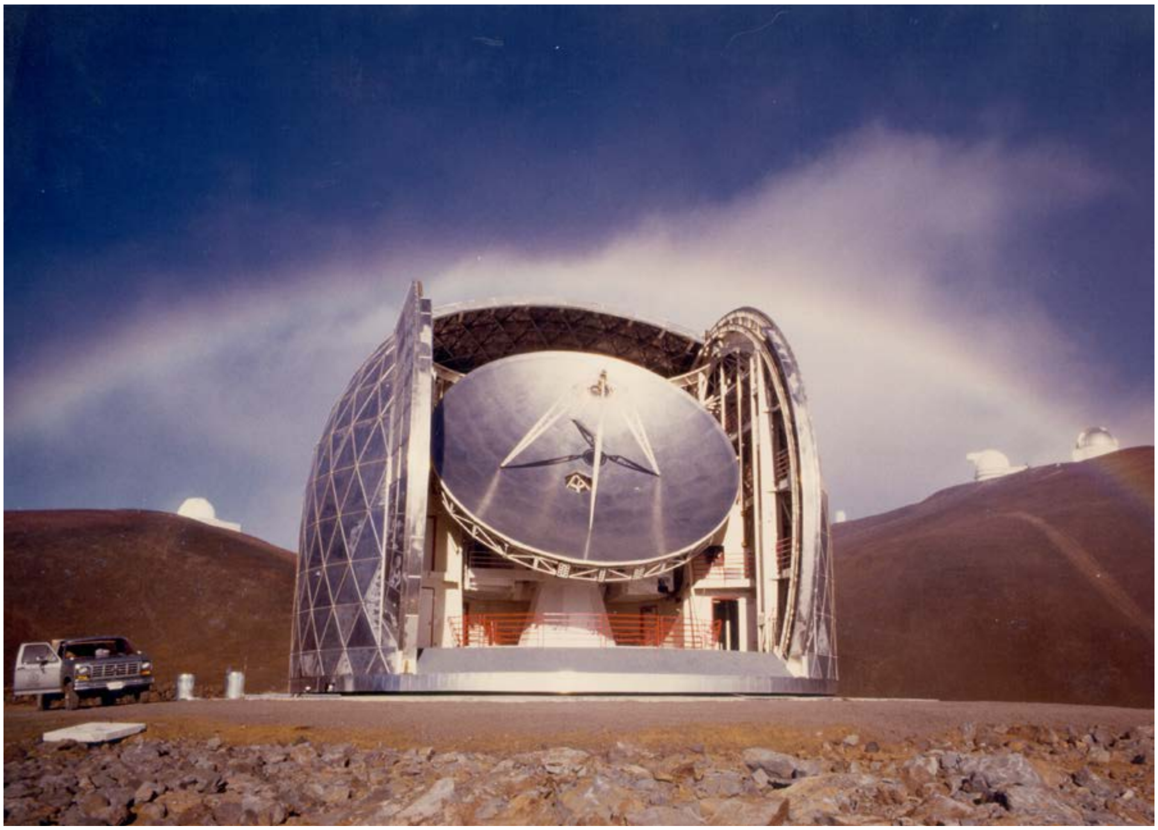
Proposal to Mr. Allen Davis for Sponsorship of the Caltech Submillimeter Observatory



Executive Summary

By revealing aspects of the Universe invisible at other wavelengths, the submillimeter part of the electromagnetic spectrum allows addressing a wide range of science questions at the forefront of contemporary astrophysics: How do stars and planets form? What is the origin of the Earth's oceans? When and how did the first galaxies form?

For over quarter of a century, the Caltech Submillimeter Observatory (CSO) on Mauna Kea, Hawaii, has been a key component of the Caltech suite of astronomical observatories. The CSO has pioneered the submillimeter field and is poised to continue its scientific leadership, leading to the construction of its more powerful successor, the Cerro Chajnantor Atacama Telescope in Chile. However, the CSO facility faces a financial crisis that will force its premature closure within the next year, unless alternate funds are secured.

The California Institute of Technology now seeks sponsorship for the CSO. Benefits of sponsorship include partaking in the intellectual excitement of discovery and access to Institute faculty and students.

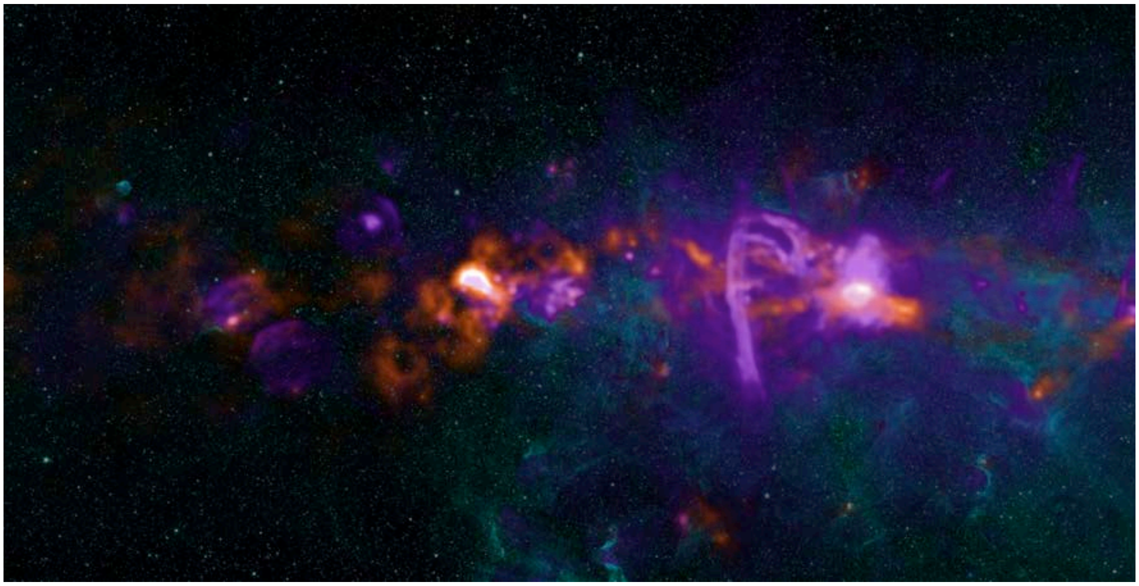


Figure 1—Multi-wavelength image of the Galactic center. CSO observations (red) show cool dense clumps in the interstellar medium associated with star formation. Radio (purple) and infrared (turquoise) observations show hotter material.

Submillimeter Astronomy

How do stars and planets form? When did the first stars form and create galaxies? These unsolved questions are central to contemporary astronomy. The answers remain elusive, because star formation takes place enshrouded in dense interstellar clouds, where molecular gas and dust (fine solid particles) hide the process from the view of optical or infrared telescopes. Submillimeter wavelengths, however, can peer deep into these clouds to reveal the physical conditions and chemical composition of molecular gas at the heart of star formation. Submillimeter observations trace the entire stellar life cycle. Parts of the diffuse interstellar medium collapse into dense clouds and thence into stars and planets. During this phase, submillimeter wavelength molecular lines are the primary mechanism cooling the gas, which in turn allows it to collapse under its own gravity. When stars reach the end stages of their lives, powerful stellar winds eject enriched material back into the interstellar medium. This ejected circumstellar material, rich in complex molecular species, is then incorporated into planet forming bodies in protostellar disks, supplying basic building blocks for the development of life. The processes we see in our Galaxy today have occurred in other galaxies throughout the history of the Universe. Submillimeter observations thus allow us to study the cosmic history of galaxy formation, from the earliest galaxies about 12 billion years ago to the present day.

The Caltech Submillimeter Observatory

For the past quarter century, the Caltech Submillimeter Observatory has pioneered this field. Some recent achievements include: An extensive (220 deg^2) continuum survey of the dust in the Galactic plane has highlighted locations of the dense, cold regions associated with star formation (Figure 1). Spectroscopic surveys (Figure 2) of Galactic nebulae have explored the rich gas-phase and grain-surface chemistry of the interstellar medium and the variety of conditions prevalent in interstellar medium sources. Further spectroscopic observations have established the role of atomic carbon in the interstellar medium, have discovered a wide range of light hydrides, and have probed the stages of cloud collapse and protostar formation. Continuum images of young stars have shown "debris disks" that indicate planet formation. Studies of the isotopic and chemical composition of comets have provided clues to the formation of the Earth's oceans. Continuum images of clusters of galaxies, the most massive bound objects in the Universe, have revealed the hot intracluster gas and the underlying distribution of dark matter. Spectroscopic and continuum observations have revealed galaxies in the early Universe undergoing bursts of star formation many orders of magnitude more intense than anything seen in the present epoch. The bright continuum radiation from the nuclei of these galaxies permits absorption line studies of molecules, such as the tightly bound halide HF, in the surrounding extranuclear interstellar medium.

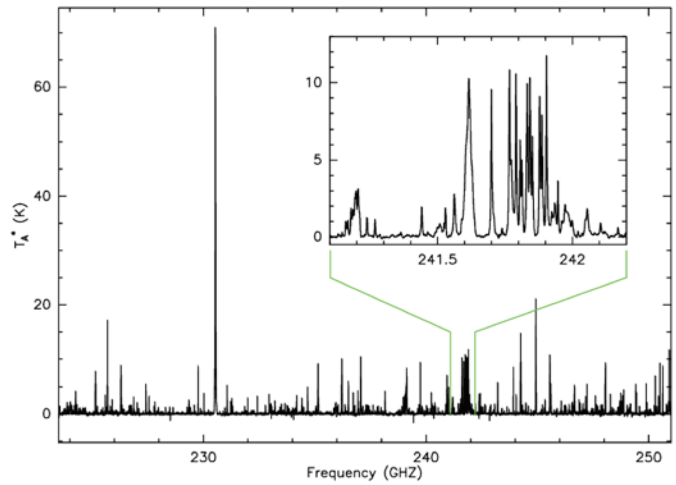


Figure 2—High-resolution spectrum of the Orion nebula observed with the CSO as part of a larger survey. Each emission line indicates an individual rotational transition of a specific interstellar molecule, about 160 of which have been identified to date, illustrating the wealth of information in such observations and the rich chemistry of the interstellar medium.

The CSO remains very much in demand. About 80 observers, many from other institutions, use the telescope each year. Students and young scholars are centrally involved. The CSO is poised to continue its leadership in three major areas: observations of the interstellar medium in the Milky Way and other galaxies to trace star formation throughout the history of the Universe; studies of the physics and chemistry of dense regions in the interstellar medium where stars form, with emphasis on the very early stages of the process when chemical fractionation and enhanced deuteration occur; and imaging the hot intracluster medium in clusters of galaxies.

CSO Research—Comets and the Origin of Earth's Oceans, Debris Disks

Comets are the most primitive bodies left from the planetestimal building stage of the Solar Nebula 4.5 billion years ago. Submillimeter wavelengths are well matched to the cold environments of cometary atmospheres, characterized by temperatures of 40–100 degrees above the absolute zero. Over two-dozen molecular species have now been detected in comets, primarily using submillimeter techniques, many of them at the CSO (Fig. 3). These include some complex organic species, such as methyl formate and ethylene glycol (commonly used as car antifreeze).

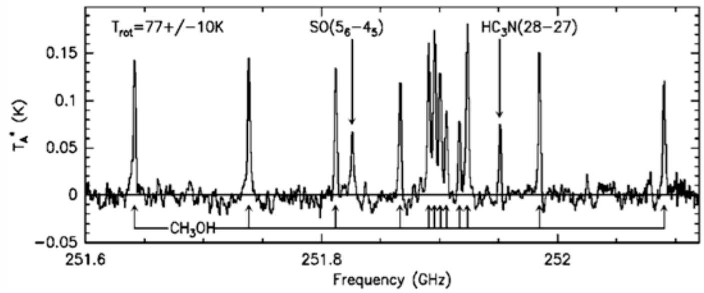


Figure 3—Spectrum of comet Hale-Bopp obtained using the CSO, showing a band of methanol lines that can be used to determine the temperature in the coma. In addition, lines of two molecules identified for the first time in a comet, cyanoacetylene and sulfur *monoxide, can be seen.*

Submillimeter studies of comets provide key clues for understanding the origin of Earth's oceans. Models of the protosolar nebula suggest that the temperature in the terrestrial planet forming zone was too high for the water ice to survive. The so-called "snow line" that separates the dry inner disk from the icy outer disk is located in the middle of the asteroid belt, at about 2.7 astronomical units from the Sun. In this picture, the Earth formed dry and water was likely delivered later, by external sources such as comets or asteroids. Measurements of the hydrogen isotopic ratio—ratio of the heavy to normal hydrogen in cometary water—provide quantitative clues for the origin of Earth's oceans (astronomical equivalent of the forensic fingerprinting).

All heavy hydrogen (deuterium) atoms were produced in the Big Bang and they have been slowly destroyed in stars ever since. The cosmic deuterium abundance is very low (one part in 40,000), but the heavy-to-normal hydrogen ratio can be strongly enhanced in heavy molecules.[1] The CSO provided the first spectroscopic detection of heavy water in a comet (Fig. 4). This measurement, featured in the National Geographic *Birth of the Oceans*, showed that the hydrogen isotopic ratio in long-period, Oort cloud comets is twice as high as that in ocean water, where the ratio is already a factor of 6 higher than the Big Bang value. This suggested that an ice-rich reservoir in the outer asteroid belt was the most probable source of Earth's water.

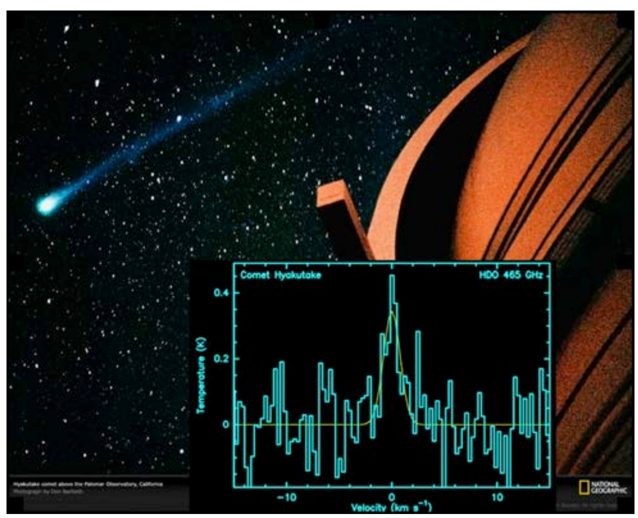


Figure 4—Spectrum of heavy water in comet Hyakutake obtained with the CSO superposed on an optical picture of the comet above the Palomar Observatory (from National *Geographic).*

However, comets have taken again pole position as water bearers following recent observations of comet Hartley 2 using the HIFI instrument on the Herschel Space Observatory. More than 15 years after the CSO observation of comet Hyakutake, HIFI has now detected heavy water in a comet that traces a separate, large reservoir of ice-rich material in the outer solar system—the

[1] In fact, the CSO detected fully deuterated ammonia in the interstellar medium, a molecule in which *all three* hydrogen atoms have been replaced by heavy hydrogen—an interstellar trifecta.

Kuiper belt, beyond the orbit of Neptune. The ratio measured in comet Hartley 2 is exactly the same as in Earth's ocean, suggesting that comets like Hartley 2 might have delivered a much larger fraction, or possibly all ocean water. These comets also might have seeded the early Earth with organics thus providing the starting point for the development of life.

With the Herschel cryogenic mission ending in early 2013, ground-based telescopes, such as the CSO will have to continue these difficult, yet important measurements in the future.

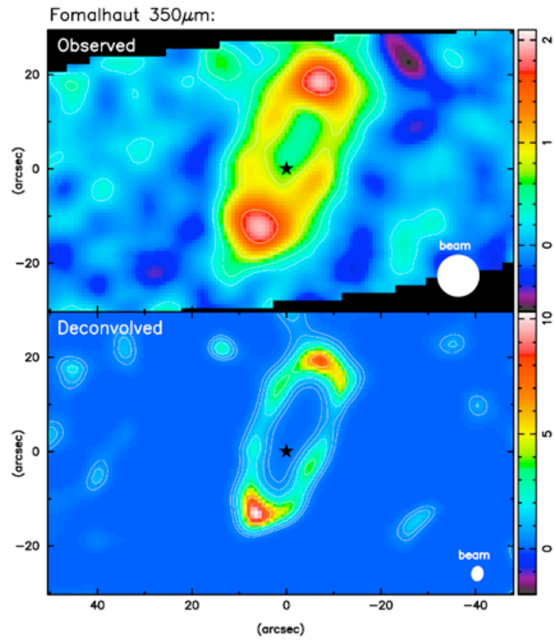


Figure 5—Debris disk around Fomalhaut at 350 μm, imaged with CSO/SHARC II. The upper and lower panels represent the observed and resolution-enhanced images, respectively.

The solar system today consists of the Sun, the four terrestrial planets, the four giant planets, and a large number of small bodies, concentrated mostly in the asteroid belt between Mars and Jupiter, and in the Kuiper belt beyond the orbit of Neptune. But the Sun and planets formed from a giant rotating cloud of gas and dust, which collapsed under its own gravity forming a flattened disk. Such disks can be observed at submillimeter wavelengths around other stars. Young "protostellar" disks are gas-rich and can be studied through spectral line emission of numerous molecular species. In older disks the gas has already been cleared and what is left is dust and larger debris orbiting the central star, which can be studied through their dust continuum emission. Such old "debris disks" are a starting point for planetary system formation. The SHARC II submillimeter camera at the CSO has proven invaluable for clarifying characteristics of debris disks. One example is the disk around Fomalhaut (Fig. 5), a nearby star 25 light years from the Sun. The CSO results confirm the ringlike morphology, but also show that the geometric center is displaced from the star by about 8 astronomical units, due to gravitational perturbation by an unseen planet. The observations of Fomalhaut, Vega and ε Eridani have confirmed the critical importance of the submillimeter in characterizing debris disks—due to the presence of large particles, which are spatially segregated by size, the appearance of disks changes dramatically over wavelength intervals of only a factor of 3. Many additional nearby debris disks can be imaged and spatially resolved using the CSO.

CSO Technology

The scientific success of the CSO has been due to the development and application of advanced technology. The telescope itself, with a 10.4 m diameter segmented primary mirror, was designed and built at Caltech incorporating concepts ahead of its time. A unique active control system maintains the alignment of the mirror segments to better than 15 μm—substantially less than the width of a human hair. This accuracy gives the telescope high gain and efficiency for short wavelength (350 μm) observations. Even today, over 25 years after its construction, the CSO has the best surface accuracy of any radio telescope its size. The telescope is located at 4100 m altitude near the summit of Mauna Kea, above 95% of the atmospheric water vapor that otherwise precludes submillimeter observations. The CSO is outfitted with a suite of advanced technology cameras and spectrometers for observations at 2 mm to 350 μm wavelengths. High-resolution, heterodyne spectrometers employ superconducting tunnel junction mixers with sensitivity approaching fundamental quantum mechanical limits, in conjunction with fast digital signal analyzers. Cameras for continuum imaging incorporate cryogenically cooled detectors with sensitivity limited only by the natural radiative background. Recent developments include larger array sizes, simplified readouts, multicolor pixels, and a new class of devices, superconducting microwave kinetic inductance detectors. Broadband, direct-detection spectrometers offer unequalled sensitivity for moderate spectral resolution observations.

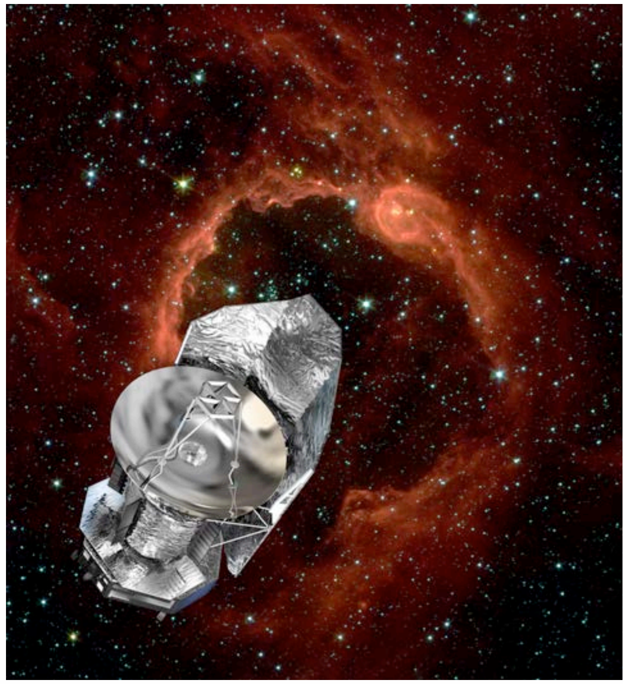


Figure 6—Herschel Space Observatory, where the HIFI instrument is fitted with receivers designed by the CSO staff.

These technologies have been used by other ground-based observatories and space missions, in particular Herschel (Fig. 6), a 3.5 m diameter telescope, orbiting at the L2 point far away from the Earth. Technologies developed and pioneered at the CSO have been widely disseminated. Mixer and instrument designs, software, and other components have been made available to other observatories and laboratories. Beyond astronomy, submillimeter wavelengths have many other technical applications, including short range communications not susceptible to eavesdropping, radio frequency heating in tokamaks, modeling of radar reflections (glints) from scale models of aircraft, and body imaging for security applications. On Mauna Kea, the CSO has supported long term monitoring of stratospheric ClO since 1991 by Stony Brook University (SUNY), a sign of destruction of the ozone layer. Using the CSO facility, Xilinx, Intel and Cypress have exploited the enhanced cosmic ray flux at high altitude for studies of device reliability.

CSO Education

The CSO's greatest legacy is its students. Although Caltech is renown for its research, education is the Institute's primary mission. The CSO is, therefore, a hands-on facility where students learn how to operate the telescope and its instrumentation and, in many cases, develop that instrumentation. Access to the CSO has not been limited to Caltech—most of the observing time has been used by scientists from other US and international institutions. More than 85 students have completed doctoral theses based on their work at the CSO and another 43 students are working on ongoing projects. In addition, over 50 postdoctoral scholars have worked at the CSO and undergraduates participate both on campus and at the telescope. These talented young scientists have gone on to leadership positions both in academia and in industry. Besides astronomy, CSO alumni work in aerospace, device physics, detector and semiconductor development, optics, telecommunications, quantum computing, finance, management consulting, and journalism.

Financial crisis

For the CSO's entire history, the National Science Foundation has funded the observatory. After 25 years, however, the NSF has abruptly ceased its support and the CSO now faces a financial crisis. Without external sponsorship, Caltech will be forced to close the observatory within a year. Although the CSO has always followed a spartan operations philosophy, adequate financial resources are necessary to make effective use of the telescope. In response to the NSF decision, operating expenses have been cut to the bare minimum, which will entail the dismissal of long term, highly skilled technical staff. Other institutions, both in the US and overseas, have pledged some support, but not enough to make up for the loss of NSF funding. The CSO faces an annual shortfall of nearly $ 1.5 million, about half the NSF's previous support level. This support is needed for calendar years 2013–2016.

Sponsorship opportunities and benefits

Caltech would gratefully appreciate annual sponsorship of any amount to the CSO. Mr. Davis, along with any other benefactors, would become a partner with the CSO, would receives annual research reports, and would have full access to the facility, research and technology, and the faculty, students, and postdocs, throughout the year.

In addition to these benefits, Caltech would be honored to rename the CSO for Mr. Allen Davis should the annual support reach $ 1.5 million. Mr. Davis's name would be featured on all reports, web sites, and other public material.

Supporting the CSO will provide ties to the talented group of scientists, faculty, and most importantly the many students involved with the telescope. There will be a direct window into current and proposed research activities at the CSO and the funds will furnish extraordinary incentives to new faculty and students, directly benefiting these young investigators at the onset of their research careers.

Involvement in this ambitious campaign is vital to the ongoing success of the many students, faculty, and researchers at the CSO who explore the frontiers of knowledge.