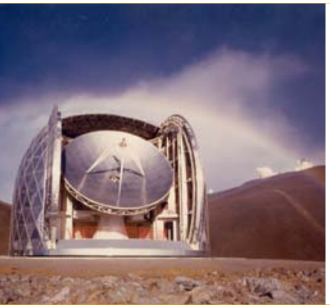
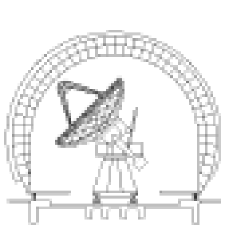


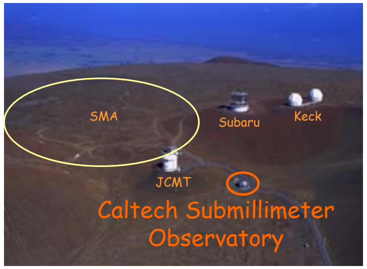


Caltech Submillimeter Observatory

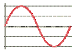
Catching small waves on the Big island

Welcome to Caltech Submillimeter Observatory

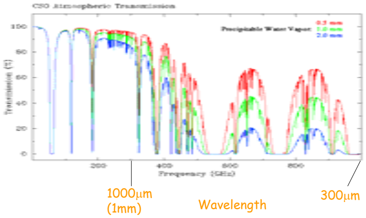
•The Caltech Submillimeter Observatory (CSO) is a cutting-edge facility for astronomical research and instrumentation development. It is simultaneously one of the world's premier submillimeter telescopes and one of the easiest to use. It consists of a 10.4-meter diameter Leighton radio dish situated in a compact dome near the summit of Mauna Kea, Hawai'i. The telescope is operated by Caltech under a contract from the National Science Foundation and has been operating on a regular basis since 1988. It is open to the astronomical community, with most of the observing time available for non-Caltech observers.



What is Submillimeter wavelength?



- The 'submillimeter' region of the electromagnetic spectrum is at the border between the far infrared and the short-wavelength radio regions. As such, it borrows technologies from both regimes: bolometers from the infrared, heterodyne receivers from the radio
  - Wavelength: 300 microns to 1 millimeter
    - cf. human hair diameter : 20 – 180 microns
  - Frequency: 300 Gigahertz to 1 Terahertz
- In Practice, the atmosphere is the greatest problem faced by submillimeter astronomers, which, combined with the lack of high-performance instrumentation, explains why the submillimeter region of the spectrum is currently the least well studied. Submillimeter astronomy can only be done in the submillimeter at sites with extremely dry atmospheres, such as the tops of mountains and the antarctic.

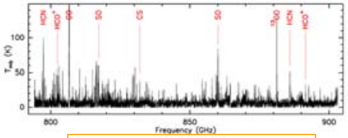


Why Submillimeter Astronomy?

- With this wavelengths, cold dust and cold/hot gas can be traced efficiently.
  - Combining dust and gas information, one can investigate the distribution of medium as well as the kinematics of detected astronomical objects.
- Cutting edge field in radio astronomy.
  - Technical challenges and hard condition from ground.

Line Surveys at CSO

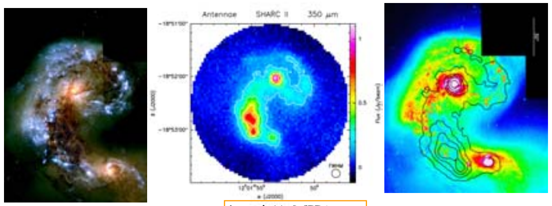
- Line Forest towards Orion



350 micron (850 GHz) Line Survey
(Comito et al. '05)

Colliding Galaxies

Antennae



HST Image (Whitmore et al. '99)
CO Gas (Contour, Wilson et al '00)

Dust (SHARCII image, Dowell et al. in prep)

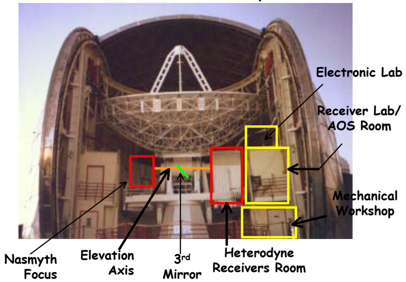
Instruments at CSO

- Heterodyne receivers (covers 180 – 950 GHz) with wide band spectrometer (up to 4 GHz band width)
- Dish Surface Optimization System (DSOS)
  - Our DSOS is used when observing so that the telescope can have very high efficiency.
- SHARCII (350/450/850 micron)
- Bolocam (1100/2100 micron)
- Hertz / SHARP polarimeter
  - Hertz: the 350 micron polarimeter developed by Dr. Roger Hildebrand at University of Chicago
  - SHARP: SHARCII Polarimeter led by Dr. G. Novak (Northwestern Univerisity) and Dr. C.D. Dowell (JPL/Caltech)

CSO in World Wide

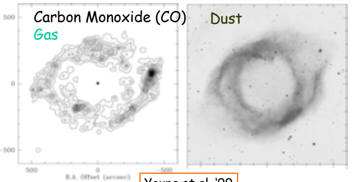
- CSO is the observatory that provides opportunities to make highest submillimeter bands (up to 300 micron/950 GHz) observation with high angular resolution efficiently in the world.
  - Mauna kea is one of the best sites in the world to carry out submillimeter astronomy.
    - » CSO-JCMT-SMA interferometer will be the most powerful submillimeter interferometer before Atacama large millimeter array (ALMA).
- Many students and postdoctoral scholars graduated from CSO.
- CSO has been used by many researchers at Caltech, University of Hawaii, JPL, the University of Texas Austin, and other users world-wide (e.g., Europe, Asia, North/south America) to carry out cutting edge sciences.
- CSO is led by Prof. Tom Phillips group, in the Physics department at Caltech.
  - Other similar examples: Mt. Fuji Submillimeter-wave Telescope (Yamamoto Group at the University of Tokyo) (350/492/809 GHz)
    - » Diameter: 1.2m; Completely remote observation; Open to public
- CSO has relatively small number of people among the observatories at Mauna Kea.
  - 10 people dedicated for the observatory locally.

The Observatory



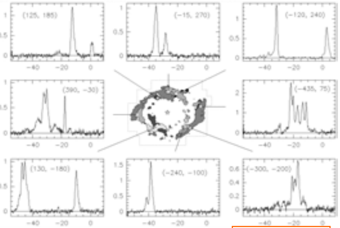
Evolved Star

Helix Nebula



Young et al. '99

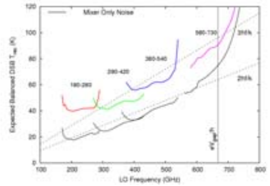
Kinematics of the Gas



Gas Distribution

Young et al. '99

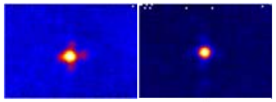
Heterodyne Receivers

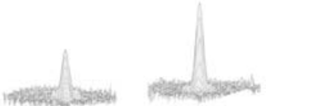


(Kooi et al. '03)

Dish Surface Optimization System (DSOS)

DSOS is a CSO Submillimeter Active Optics System.





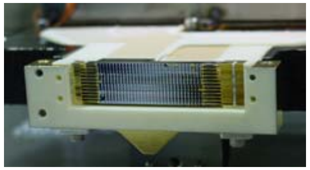
DSOS Off

DSOS On
(18% improvement in beam width , 50% improvement in signal power compared with Off)

The DSOS improves the aperture efficiency by a factor of 2, and integration time by a factor of 4.
This has aided observers to detect new and/or weak/ distant objects in the 350μm wavelength range (e.g., see pictures of Fomalhaut, epsilon Eridani, high redshifted galaxies) .

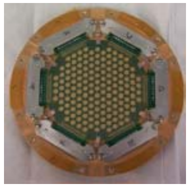
(Leong et al. '03)

SHARCII



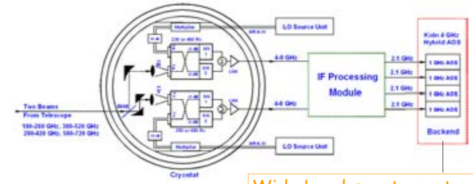
12 x 32 (384) array (Dowell et al. '02)
350/450/850 micron filters
10" resolution at 350 micron

Bolocam



119 pixels (Glenn et al. '98)
Wavelengths: 1100/2100 micron
31" resolution at 1100 micron

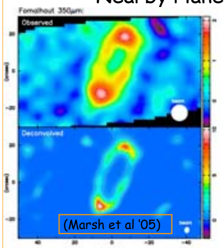
A Receiver Layout



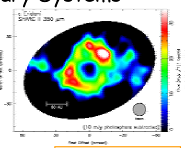
(Kooi et al. '04)

Wide band spectrometer

Nearby Planetary Systems



(Marsh et al '05)



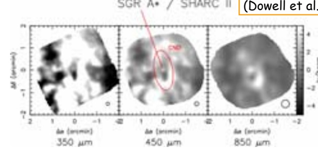
(Wilner et al. in prep)

The orbiting debris disk resulting from collisions of solid bodies during the formation of new solar systems. The debris is distributed in rings of radius 50 – 150 AU that are sculpted by planets invisible in these images. Detailed analysis of Fomalhaut indicates the debris is in an eccentric orbit around the star which is shaped by a planet.

Galactic Center

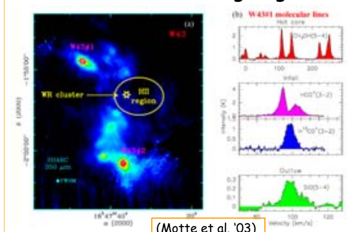
- In 2004, two monitoring campaigns were carried out in Dowell and Yusef-Zaher in coordination with many other facilities observing at X-ray through radio wavelengths(Dowell et al. '05). The flat submillimeter spectrum, during this relatively quiescent phase, is confirmed to wavelengths as short as 350 micron. Evidences for day to day variability at 450 micron was seen for the first time at a level of 30%, similar to the longer wavelengths (e.g. Zhao et al. '03)

SGR A* / SHARC II (Dowell et al. '05)



Submillimeter images taken with SHARCII. The synchrotron emission from the central point source is detected at all three wavelengths with a flat spectrum and a flux of 3 Jy. The surrounding emission is dust, much of it concentrated in the rotating circumnuclear disk, with a spectrum declining with increasing wavelength.

Massive Star Forming Region



(Motte et al. '03)

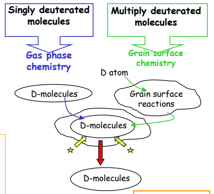
Large-scale Fast Collapse in W43:
A fundamental, yet unresolved issue is the determination of the main physical process leading to the formation of high-mass (>8 solarmass) stars. There is basically two competing theories: the accretion versus coalescence models. Submillimeter continuum images taken with the SHARC camera recently revealed about ten high-mass protostars in W43 The kinematics of these rare objects surprisingly show that they are undergoing a global and fast contraction (see figure b; cf. HCO+ lines measured at the CSO). This is the fastest (~ 2 km/s), and the only supersonic infall ever observed on parsec scales in star-forming regions. It may strengthen the infall/accretion rate by 2 orders of magnitude (~ 10^{-3} solarmass per year) and thus permit high-mass stars to be built by a scaled-up version of the process at work for solar-type (~ 1 solarmass) stars: accretion.

Deuterium Fractionation

- Deuterated molecules observed in interstellar medium

(HD, C_2D, CD_3OH, C_4D, CH_3CCD, HDO, DCO^+, CHD_2OH, CH_2DOH, CHD_2OH, HDS ,N_2D^+, D_2CO, DC_3N, D_2S,H_2D^+ ,NH_2D, ND_3, DC_5N, D_2H^+, DCN, NHD_2, HDCS, CH_2DCN,DNC, HDCS, CH_3OD, CH_2DCCH…)

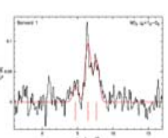
- Fractionation Process:
- It's dificult to disentangle between these two processes and the models are still struggling to explain the observed abundances.
- Nevertheless, the inclusion of the deuterated forms of H3+ in the models has recently been able to explain many observed abundance.



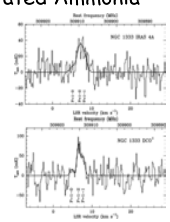
•Their abundances are much larger than the cosmic D/H of 1.5 10^{-5} (Linsky et al. 1998). HOW IS IT POSSIBLE? Deuterium can't be created and is only destroyed by nuclear reaction inside stars. Surprisingly even triply deuterated molecules are detected!

(Vastel '05)

Triply Deuterated Ammonia



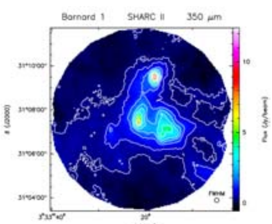
(Lis et al '02)



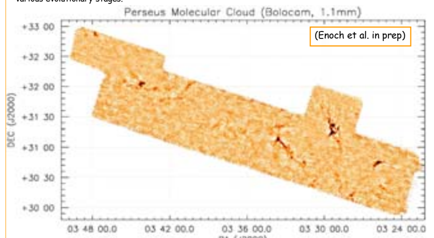
(van der Tak et al '02)

Low/Intermediate Star Formation

How do stars form?
A large cloud of hydrogen begins to contract due to its own internal gravity. As the cloud contracts, conservation of angular momentum causes a rotating disk to form. Eventually the internal pressure gets high enough that hydrogen begins fusing in the middle of the newly formed proto-star. Large clumps of heavier compounds coalesce into planetesimals. The new star's solar wind blows away left over dust leaving behind a new star and solar system. The young proto-stars are hidden from view inside dusty cocoons, which prevent much of the visible light from ever reaching us. However, submillimeter radiation, which is not blocked as effectively by the surrounding dusty material allows us to see deeper inside the dust clouds and study their internal structures. The SHARC II camera enables observations crucial to our further understanding of the initial stages of star formation. The attached figure shows the distribution of 350 μm dust emission in the nearby dark cloud Barnard 1. A group of sources can be seen, some of them including young, dust-enshrouded proto-stars at various evolutionary stages.



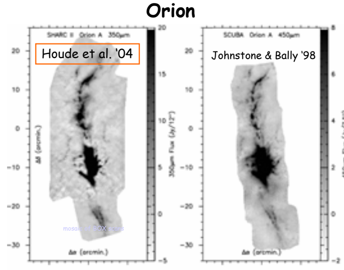
(Lis et al. '05)



(Enoch et al. in prep)

This image of the Perseus Molecular cloud covers an area in the sky equivalent to 40 times the size of the moon, while still enabling us to resolve objects as close 1/60 the size of the moon. Understanding the relationship between protostars and star-forming cores in a large cloud such as this one is important to fully understanding the star formation process. The smaller image of NGC 1333 (above) is one of the dense star-forming clusters within the Perseus Molecular cloud.

Orion

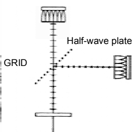


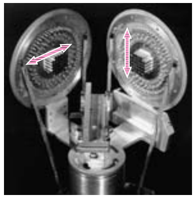
Houde et al. '04

Johnstone & Bally '98

This is a long elongated filament, over 5 pc (10^6AU), in the northern portion of the Orion A molecular cloud is one of the most active sites of massive star formation, at a distance of 500 pc. It is associated with the Orion Nebula and the Trapezium Cluster of about 700 young stars. This filament contains of the OMC1 cloud core immediately behind the Nebula and two other cores, called OMC2 and OMC3 (located about 15' and 25' to the north, in the figure, to the top). The filament has spawned several thousand young stars in the past few million years and contains dozens (possibly hundreds) of embedded young stellar objects that power dozens of molecular outflows, Herbig-Haro objects, and molecular hydrogen emitting shocks and jets. Comparing with 350 and 450 micron data, one can infer temperature and the grain properties of dust in this active star forming region.

Hertz, the 350 micron Polarimeter

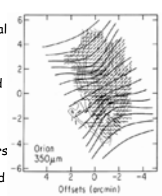




(Hildebrand et al. '98)

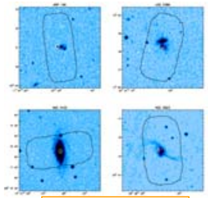
Tracing Magnetic Field

- On a process of star formation, magnetic field may play a critical role. Using 350 micron polarimeter, Hertz, magnetic field lines are traced towards Orion OMC1 region. It revealed the pinched magnetic field. B vectors are shown as solid (> 3 σ) and dashed (> 2 σ) bars. Photometry contours are also from Hertz.Photometry contours are also measured with Hertz. Curved lines show magnetic field "profiles" that are fit to the B-vectors, but not including data near the Orion "bar" (southeast edge).



(Houde et al. '04)

Star Formation History of the Universe



Stars produce all of the elements that are needed to create things such as planets and even your body. Much of the stellar debris exists in the form of small dust particles which is like a thick fog that blocks light that stars produce. When the dust absorbs the light, it heats it up. Using cameras that are sensitive to the infrared light this heated dust produces, we can probe where in a galaxy that stars are being actively formed. In the above image, we show four galaxies viewed with the SHARC-II camera. <u>The background image is an optical picture, and the black outline shows the area that SHARC-II studied</u>. <u>The white contours show where dust, and hence regions of vigorous star formation, was detected</u>.

Extragalaxies $z<0.05$
(Borys et al. '05)

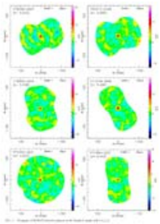
$0.1<z<1$ Ultraluminous Infrared Galaxies

The images presented here show emission from interstellar dust in galaxies that are billions of light years away from the Earth. It enables us to probe physical conditions in these galaxies, such as dust temperature and star formation rate. Given the age of these galaxies, such important information is important for understanding how galaxies evolve.

The sample was compiled from cross-correlation of the faint-IRAS catalog and the FIRST 21cm radio catalog.

The sources are ULIRG's lying within redshift range of 0.1 and 1; near infrared morphologies of these objects reveal they tend to be interacting systems

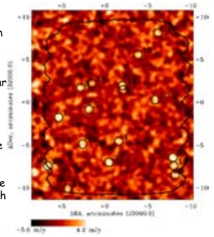
Far infrared/submillimeter fluxes were obtained for the first time on these targets, so were SED fits in the FIR



(Yang et al. '05)

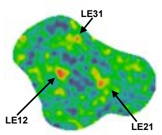
Extremely luminous high redshift ($z > 1$) Galaxies

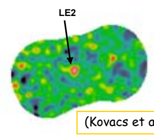
This is a map of a tenth of a square degree made at a wavelength of 1.1 mm with Bolocam. At 1.1 mm, our observations are sensitive to dust in distant galaxies heated by stars forming deep within clouds of molecular gas. The bright white spots with dark circles around them are galaxies that we detected. They do not appear as galaxies do in visible-light images because we cannot resolve them at the long 1.1 mm wavelength: because of their great distance, the galaxies appear about 30 times smaller than the smallest structures we can resolve with the CSO.



(Laurent et al. '05)

High Redshift ($1<z<4$) SHARCII images





(Kovacs et al. '05)