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Gran Telescopio Milimétrico (GTM)

The “Gran Telescopio Milimétrico” (GTM), built in México, will be the largest and most powerful telescope of its kind in the world. Operating at wavelengths as short as 1mm, it will probe the early universe to study the processes which ultimately formed the galaxies, stars, and planets that we observe today. GTM has been constructed by The University of Massachusetts Amherst (UMass Amherst) in the United States and by the Instituto Nacional de Astrofísica, Óptica y Electrónica (INAOE) in México.

The GTM includes a single, extremely high precision alt-azimuth antenna 50 meters in diameter. It is located at an altitude of 4580 m above sea level on an extinct volcano, the Tliltépetl, within the National Park Pico de Orizaba, about 100 km east of the city of Puebla and to the west of the Gulf of México.

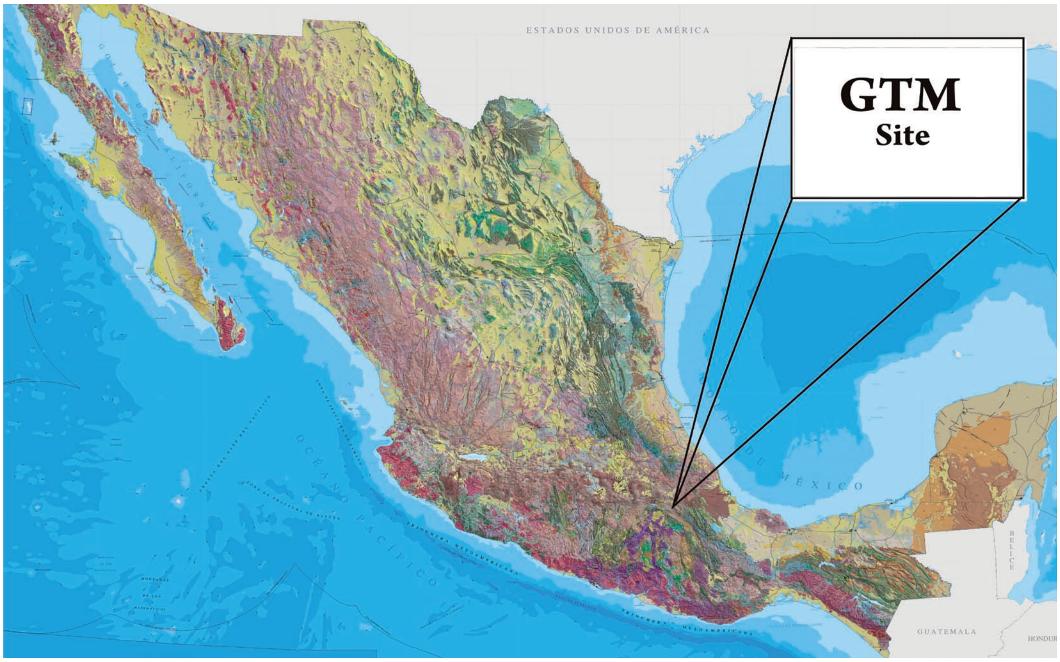


Figure 1. Location of GTM

The GTM is the largest scientific project ever undertaken in México in any field. The national development of novel technologies was set as a requirement for approving the project, a test in itself of the capabilities of México to construct large and sophisticated scientific instruments.

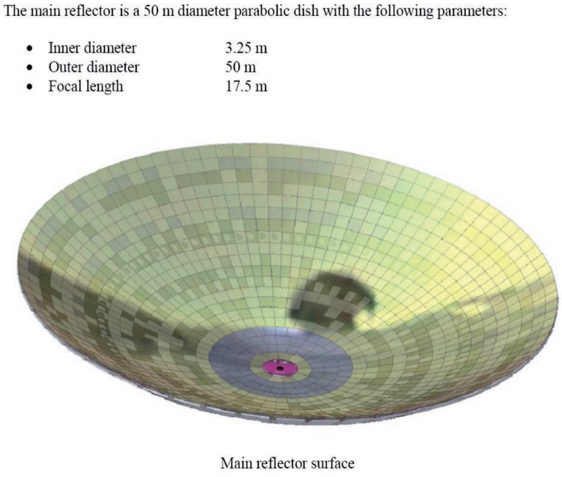
Figure 2. The GTM

Why are observations at mm wavelengths important? Much of the material in the universe is in “dust” or “grains”, too cold to radiate at wavelengths shorter than the mm/submm range, and so only observable in emission at these longer wavelengths.

Moreover, the dust in the Milky Way and other spiral galaxies is concentrated in the clouds where new stars form, and it obscures the most interesting interior regions of these clouds at optical, ultraviolet, and even infrared wavelengths. However, it is transparent at mm wavelengths, since the dust grain dimensions are smaller than this. The dust is concentrated in the plane of a typical spiral galaxy. Much of the ultraviolet and visible radiation emitted by young stars is absorbed by dust and re-radiated in the infrared.

Galaxies that are forming massive stars or that contain active galactic nuclei (AGN), presumably powered by super massive black holes, emit the bulk of their energy in the mid and far infrared. But the expansion of the universe shifts this emission for very distant galaxies into the millimeter and submillimeter range. Consequently, one of the major research areas for the GTM will be the study of the early universe and the origin of the structures that became galaxies, stars, and planets.

GTM will be an open-air telescope with no radome enclosure. Much of the improvement over existing telescopes can be obtained with an open loop active surface that includes 180 moveable surface segments. In each segment eight sandwiches of electroformed nickel are supported by a very stiff reaction structure, which is attached to the reflector back structure by a space frame: a 1440 ensemble of such panels.



The main reflector is a 50 m diameter parabolic dish with the following parameters:

Inner diameter	3.25 m
Outer diameter	50 m
Focal length	17.5 m

Main reflector surface

Figure 3. The primary surface of GTM, formed by 1440 panels of electroformed Ni.

Four actuators can adjust each space frame in relation to the back structure to correct for deformations due to gravity, thermal gradients and wind. Temperature sensors on all relevant parts of the structure will report to the control system, and the surface will be periodically measured by holographic techniques. Simulations indicate that the GTM should be able to maintain surface accuracy in the presence of winds up to 10 m/s.

Under good conditions, with low wind and stable nighttime temperatures, the structure is capable of satisfying the basic pointing requirements. However, wind and thermal loads introduce significant pointing errors that must be sensed and compensated for. The initial system will rely on standard techniques, such as the use of an antenna pointing model, thermal stabilization of the structure, and careful attention to the design of the antenna motion controllers. These basic principles will be supplemented by measurements to characterize the behavior of the structure, including inclinometers mounted near the telescope elevation axis and temperature sensors on the structure, which may be used with finite element models to determine structural deformations and predict pointing behavior.

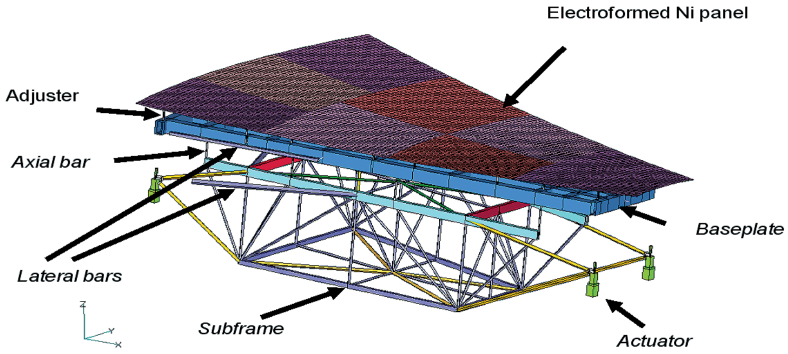


Figure 4. One of 180 segments formed by a subframe, a stiff baseplate, 40 adjusters and 8 panels of electroformed Ni.

SPECIFICATIONS OF GTM				
Property	**Specification**		**Goal**	
	1.2 mm	3 mm		
Effective Surface Accuracy	75 µm rms	75 µm rms	70 µm rms	
Pointing Accuracy	1 arcsec		0.6 arcsec	
Aperture efficiency	0.4	0.65	0.45	0.70
Sensitivity	3.5 Jy/K	2.2 Jy/K	3.1 Jy/K	2.0 Jy/K
FWHM beam size	5 arc sec	16 arcsec		

Ultimately, metrology systems to actually measure structural deformations, such as the shape of the primary mirror and the location of the sub reflector with respect to the best fit parabola, will be used to bring the pointing properties of the antenna to the final performance goal.

The GTM is sited at an altitude of 4585 m (about 15,000 feet) atop Tliltepetl (Volcan Sierra Negra), an extinct volcano in the state of Puebla that is adjacent to Citlaltepetl (Pico de Orizaba), the highest mountain in México. The atmospheric opacity is low, with a median value of 2 mm of precipitable water vapor during approximately nine months of the year.

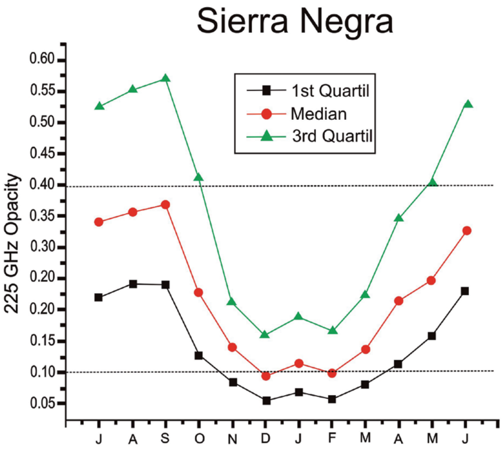


Figure 5. Opacity of GTM site at 4600 m altitude.

In spectroscopy the detected radiation is analyzed to measure the signal strength as a function of frequency, utilizing heterodyne techniques to obtain extremely high frequency resolution. Continuum systems, in contrast, measure the entire amount of energy received within a broad frequency range.

Figure 6. Tliltepetl, a 4600 m mountain site of GTM.

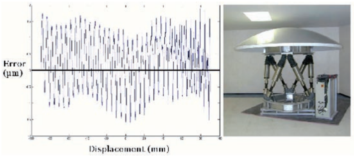


Figure 7. Secondary mirror and hexapod

In spectroscopy the detected radiation is analyzed to measure the signal strength as a function of frequency, utilizing heterodyne techniques to obtain extremely high frequency resolution. Continuum systems, in contrast, measure the entire amount of energy received within a broad frequency range. With nearly 2000 m of collecting area and excellent surface accuracy, the GTM's sensitivity will exceed that of existing mm wavelength telescopes by a wide margin. This basic sensitivity is enhanced for continuum observations by the single dish's ability to make use of very wide bandwidth incoherent bolometers. The GTM will consequently take an important place in the world's complement of mm wave facilities.

Already operating is a 32 pixel, dual polarization heterodyne focal plane array for spectroscopy in the 80 to 115.6 GHz frequency band, SEQUOIA, with an associated digital autocorrelation spectrometer. It represents a real breakthrough in mm wave radio astronomy receivers, utilizing the lowest noise amplifiers ever built in this frequency range (InP MMICs), with narrow band noise as low as 30K at 103 GHz.

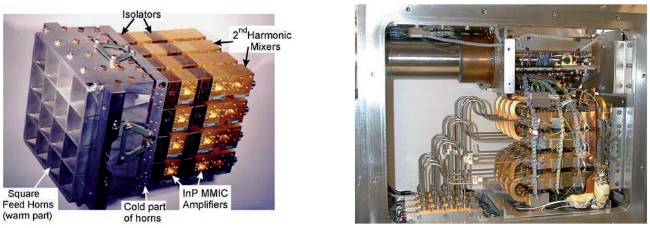


Figure 8. SEQUOIA heterodyne array.

SEQUOIA has already produced, for example, by far the largest scale images of the gas distribution in the Milky Way ever obtained. It plays a major role in studies of the physics and chemistry of interstellar material in the Milky Way and other galaxies.

The other system in the 3 mm band is an ultra wideband receiver/spectrometer which switches rapidly between two positions on the sky with dual polarization feeds which simultaneously cover the range from 75-111 GHz with a spectral resolution of 30 MHz, Called the Redshift Search Receiver, its principal purpose is to measure the redshift of spectral lines from galaxies in the early universe, thus determining their distance and properties. The associated spectrometer is an analog autocorrelator with a large dynamic range. The 1.3 mm wavelength atmospheric window will be its primary frequency band.

AzTEC (Astronomical Thermal Emission Camera), which is a sensitive bolometer array for the GTM, has been built by the GTM project team with an international group. It is a second realization of the Bolocam I instrument, which is being used successfully at the CSO. It provides 144 pixels and is designed to operate in the 2.1 and 1.1 mm bands. It will be a principal tool in the search for newly forming galaxies in the young universe, for astrochemical studies of dust in galaxies, for identifying protostellar cores in molecular clouds, and for the study of asteroids and comets in the solar system.

A second continuum instrument known as the SPEctral Energy Distribution (SPEED) camera will be used for simultaneous multiband photometry. SPEED uses a recently developed bolometer technology known as Frequency Selective Bolometers (FSBs) to simultaneously measure power in four frequency bands ranging from 2.1 mm to 0.85 mm wavelength. Measurements of the spectral energy distribution with SPEED will, for example, locate and study distant galaxy clusters by the distortions that they imprint on the Cosmic Microwave Background, and determine the temperature of dust emission in cometary atmospheres or interstellar molecular clouds in the Milky Way and other galaxies.

Figure 9. AzTEC cryostat and readout electronics.

Very Long Baseline Interferometry (VLBI) delivers submilliarc second angular resolutions, and provides a singularly powerful method of studying energetic astrophysical phenomena on the smallest size scales. The commissioning and planning of new mm and submm wavelength telescopes will significantly increase the collecting area of VLBI arrays in the 86 GHz to 230 GHz frequency ranges. Chief among these new facilities is the GTM. At 86 GHz, an array comprising the Very Long Baseline Array (VLBA) and the GTM would be over twice as sensitive as the VLBA alone. At 230 GHz, the difference is even more striking, with the addition of the GTM increasing current sensitivities of 1 mm wavelength VLBI arrays by more than a factor of 3.

The 50 m GTM is a unique facility, equipped with an array of state-of-the-art instruments that are complemented by the high angular resolution and sensitivity provided by the large collecting area. These properties give the capability to carry out critical new scientific research. For example, the resolution of the GTM, 4.2 to 14.8 arcsec between 850 µm and 3 mm, is higher by a factor 3 to 5 than that provided at the same wavelengths by current single dish telescopes such as the CSO 10 m, the JCMT 15 m, and the IRAM 30 m, and is hence sufficient to resolve the extragalactic background into discrete sources. In contrast, the deepest imaging surveys conducted by the existing submm/mm telescopes are confusion limited at a sensitivity level that can resolve only 20-50% of the individual sources that contribute to the integrated emission of

	GBT	CARMA	ALMA	LMT
Flux sensitivity				
Line (3 mm)	0.6	2.5	0.3	1
Continuum (1mm)		19	0.7	1
Surface Brightnes sensitivity				
Line (3 mm)	2.3	3.3	2.5	1
Continuum (1mm)		25	6.6	1
Mapping Speed				
(Point Sources)				
Line (3 mm)	15	4.5	0.1	1
Continuum (1mm)		1100	2.2	1
Mapping Speeded				
(Extended emission)				
Line (3 mm)	350	7.7	5.8	1
Continuum (1mm)		1900	180	1

Table 2. Performance values of different mm facilities normalized to the GTM. For values in red GTM is better, for those in blue, GTM is worse.

the extragalactic background. Less than 0.01% of the sky has been mapped and resolved at mm wavelengths. Hence, the GTM can survey large regions of the sky to characterize the typical properties of the extragalactic millimeter population.

The GTM offers a natural complement to the next generation of mm interferometers such as ALMA and the Combined Array for Research in Millimeter wave Astronomy (CARMA). The GTM's extended imaging will place the high resolution interferometer maps into an environmental context and will provide the emission that will be resolved out in the interferometric maps, even when they operate in their most compact configurations. The large primary aperture of the GTM, coupled with its sensitive imaging cameras, results in a mapping speed 100 times faster than other facilities.

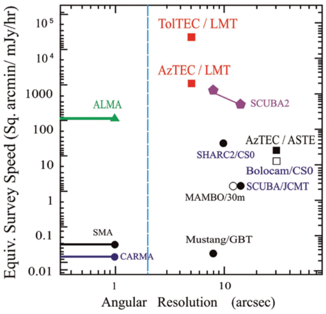


Figure 10. A comparison of survey speed on GTM with respect to other present and future instruments. High angular resolution is needed to probe deeper into the fainter population through reduced confusion and better identification of the counterpart detected at other wavelengths.

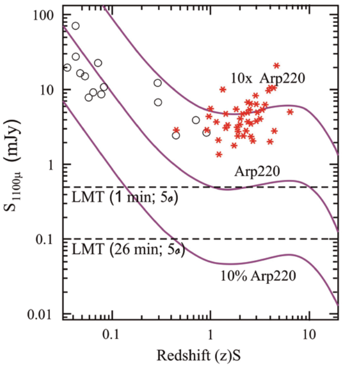
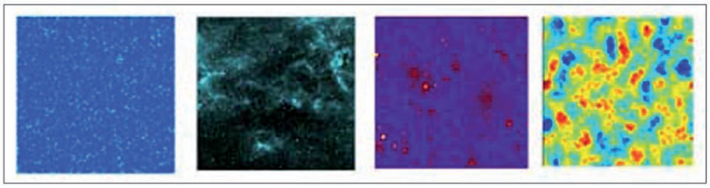


Figure 11. The 5s detection sensitivity of AzTEC on GTM at 1.1mm. Expected 1.1mm continuum flux for an Arp220-like (SFR=200 Msun/yr) object is shown.

Much of the ongoing star formation in the universe takes place in the dusty, heavily obscured interstellar medium (ISM) in galaxies. Hence, the star formation activity cannot be observed by ultraviolet, optical, or infrared surveys. A more transparent view of the universe can be provided by sub-millimeter and millimeter wavelength observations, which are insensitive to the obscuring effects of dust.

When the universe was less than 10% of its current age, the first galaxies had already formed from the first generations of stars, which then proceeded to enrich the primeval ISM with heavy elements and the other by products of star formation. The physical environment of the high-redshift universe (and therefore presumably in high-redshift galaxies) is potentially different from the presently observed, with different processes and efficiencies of star formation. Thus, in order to understand the formation and evolution of galaxies, we must also understand the formation and evolutionary history of stars, and then place the galaxies and clusters in the context of the larger-scale distributions of matter that have evolved from the initial structures observed in the cosmic microwave background anisotropies.

Figure 12. From left to right: Mm wavelength simulations of a strongly evolving and clustered starburst galaxy population, Galactic cirrus, Sunyaev Zel'dovich clusters, and fluctuations in the Cosmic Microwave Background. These simulations are merged to provide realistic maps of the extragalactic sky, which can be combined with an instrument and telescope simulator to estimate the feasibility of possible GTM surveys.



The history of High Redshift violent star formation in dusty, optically obscured galaxies manifests itself in far infrared (FIR) to mm wavelength observations. Because the strong FIR emission peak is increasingly shifted into the submm and millimeter range as the distance and hence redshift (z) increases, millimeter wavelength observations are able to trace the evolution of star formation in dusty galaxies throughout a large volume of the high redshift universe (as easily at redshift z ~ 8 as at z ~ 1), and therefore back to extremely early epochs. With a large accessible volume from mm surveys, it is possible to test whether galaxies observed at these wavelengths represent the rapid formation of massive (elliptical) systems in a single violent collapse of the highest density peaks of the underlying large-scale matter distribution, or whether they are built over a longer period from the continuous merging of lower mass systems with much more modest rates of star formation.

A major scientific goal for the GTM is therefore to exploit its higher angular resolution, sensitivity and mapping speed, in the effort to understand the evolutionary history of the galaxy populations that dominate the integrated FIR mm extragalactic background emission. More specifically, the GTM will conduct a range of narrow, confusion limited surveys and larger area, shallower surveys of the high redshift universe at mm wavelengths.

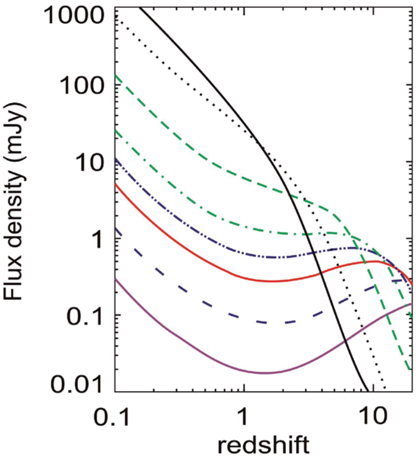


Figure 13. The effect of redshift on flux density at far infrared to mm wavelengths for an object similar to the ultraluminous galaxy Arp220. From top to bottom (at a redshift of z=0.1) the colored curves show this effect at 160, 250, 500, 850, 1100, 1400, 2100, 3300 microns, respectively.

Together with complementary multiwavelength observations, these data will (a) identify the individual galaxies that supply that part of the FIR mm background (~ 50% of the integrated energy budget of the universe emitted by discrete sources) and determine their redshifts; (b) measure their individual bolometric luminosities, star formation rates and the evolution of their integrated luminosity functions; (c) determine the fraction of active galactic nuclei (AGN) in the various FIR mm galaxy populations; (d) measure the spatial clustering properties of these galaxies; and (e) characterize the multiwavelength spectroscopic and continuum properties of these dusty galaxy populations. These various mm surveys, which covered areas ranging from a few square arc minutes to 0.5 square degrees, have contributed significantly to the first efforts to understand the history of obscured star formation in the early universe.

Figure 14. The predicted redshift distribution of dusty starburst galaxies for different GTM surveys. The deep, small area surveys (solid line) will be dominated by a high redshift (z > 2), while the shallower and wider area GTM surveys (dashed line) will contain a bimodal population that also includes bright galaxies in the local universe (z < 0.05).

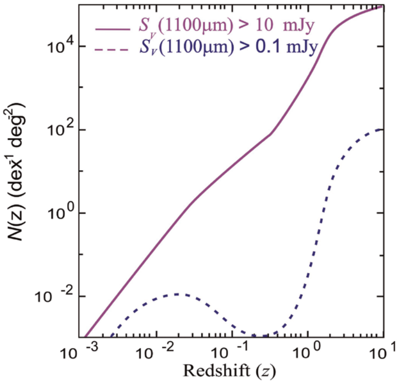
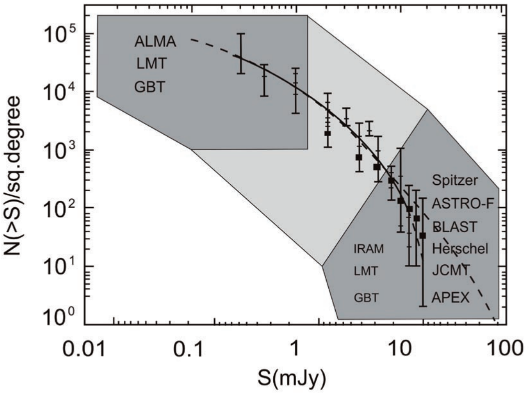


Figure 13 illustrates: first, the measured submm source counts from the extragalactic surveys cover only a narrow range of source brightness; second, the uncertainty in source count is substantial, because the total number of sources detected with a signal to noise of at least four is less than 100.

Thus, it is difficult to determine the flux density at which the faint end source counts converge, and therefore determine the contribution of this mm population to the extragalactic background emission. Galaxy clustering and the small areas covered by the surveys also make the count of faint sources uncertain, and it is difficult to know whether there is a cutoff in the evolving luminosity function because of the scarcity of bright sources.

Figure 15. Extragalactic 850 µm source counts as a function of flux. The solid line represents one of many possible strongly evolving models that fit the 850 µm data. The measured source counts cover a narrow range of flux densities (~ 0.5 – 12 mJy) and therefore leave two unexplored regions (shown as dark grey shaded polygons) populated by the numerous, faint galaxies below the existing observational confusion limits, and the brightest, but rarer galaxies that can only be detected in the widest area surveys.



Restricted wavelength coverage; low spatial resolution; restricted field of view with the current mm bolometer arrays (typically 5 square arcmin); and low system sensitivity are factors that restrict even the widest and shallowest mm surveys to areas smaller than half a square degree. Hence, the existing mm observations are necessarily only sensitive to the most luminous and massive star forming galaxies corresponding to a star formation rate (SFR) greater than 300 solar masses per year.

Cosmological surveys with the GTM will improve upon all of the above limitations. The GTM will use its very high mapping speed, sensitivity, and angular resolution to measure the surface density and clustering properties of dusty starburst galaxies detected between 850 μm and 3 mm over a wide dynamic range of flux densities, making it one of the most powerful of all the future FIR mm experiments.

The capabilities of the GTM allow it to simultaneously search for and detect the optically obscured galaxies with low FIR luminosities and star formation rates (~10-50 solar masses per year), as well as discover the brightest mm sources in the high redshift universe. For example, a search for the most extreme star forming galaxies (SFR >> 5000 solar masses per year), associated perhaps with the rapid formation of a massive elliptical in less than a few billion years, would require a submm survey covering > 100 square degrees.

The integrated FIR mm emission from all the galaxies in the universe peaks at ~ 250 μm and contributes approximately 50% of the total radio to X-ray extragalactic background light, and it is a component that needs to be spatially resolved and understood. It is also important to note that << 1 square degree of the extragalactic sky has been mapped at mm wavelengths with sufficient resolution and sensitivity to resolve a major fraction of this background emission. For example, it is only in the deepest surveys (rms > 0.5 mJy at 850 μm) that a significant fraction (= 30%) of the 850 μm background has been resolved into discrete galaxies, yet these same surveys have only observed = 100 square arcmin in total. Furthermore, an extrapolation of the source counts to shorter submm wavelengths indicates that the same populations of galaxies detected in these deepest surveys contribute less than 15% of the FIR (250 μm) background emission, while the combined shallower (rms ~ 2.5 mJy at 850 μm) and

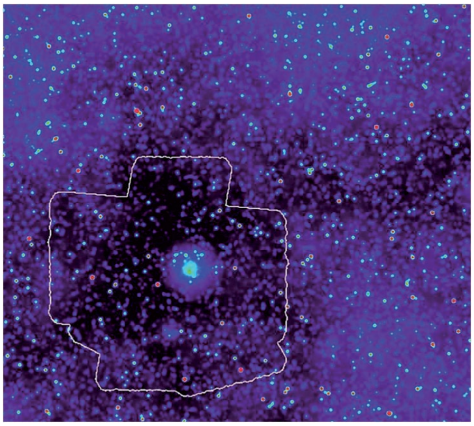


Figure 16. Simulated emission from extragalactic point sources at 1.1 mm for an area 0.5 x 0.5 square degrees, including contributions from the spectral Sunyaev-Zel'dovich increment caused by the thermal effect in the cluster near the map center (the extended source) and foreground Galactic dust ("cirrus"). More than 100 starburst galaxies would be detected in a 2 hour integration with AzTEC in the outlined region.

wider area (~ 2000 square arcmin) mm surveys provide only a few percent of the FIR background.

The GTM will have an extremely low confusion limit due to extragalactic sources. The opportunity to resolve the entire millimeter wavelength background into individual galaxies is thus well within the capabilities of the GTM and the first light continuum camera, AzTEC.

Dusty mm galaxies at high redshift contain enormous reservoirs of molecular gas (mass of H ~ 102 10 solar masses) that fuel the high rates of star formation. Given these expected gas masses, the GTM has sufficient sensitivity to conduct a blind search for molecular line emission from the rotational transitions of CO in the galaxies identified in the GTM blank field surveys.

Taken together with the two-dimensional GTM surveys describing their angular distribution, it will be possible to measure the spatial clustering of these luminous starburst galaxies over a wide range of redshifts and cosmological epochs. Once a spectroscopic redshift is measured for a mm galaxy, the GTM can carry out higher spectral resolution observations to resolve the line profile, and hence estimate the rotational velocity of the gas and infer a dynamical gas mass.

A measure of the distribution of high redshift massive (elliptical) galaxies, which are thought to trace the underlying dark matter distribution, offers one way to map out over densities. It is needed to search the high redshift universe for clear signatures of the short, yet powerful bursts of obscured star formation (>> 100 solar masses per year) associated with the building of elliptical galaxies or their progenitors. GTM can efficiently target fields in which we expect to sample high density peaks in the underlying mass distribution. Observations towards high redshift AGN are examples of these special environments, where, e.g., over densities of Lyman break galaxies and mm sources have been found. The most massive galaxies in the local universe are giant ellipticals which are also found in the centers of rich clusters. The most luminous radio quiet quasars (RQQs) at high redshift are also expected to be found inside massive ellipticals.

The Cosmic Microwave Background (CMB) is both a perfect 2.73K blackbody (with fluctuations over the entire sky smaller than ~ 80 μK) and is isotropic. This background is the primordial light from the surface of last scattering, the epoch at which the universe first cooled below the ionization temperature of hydrogen some 380,000 years after the Big Bang. As neutral atoms recombined from the hot plasma, radiation decoupled from matter, leaving the photons free to travel relatively unhindered until detected by CMB experiments some 13 billion years later.

Small deviations from a perfectly smooth cosmic background have been observed at a level of one part in 100,000 ($dT/T = 10^{-5}$). Primary fluctuations contain information about the conditions of the universe at the earliest moment that can be directly observed, the time of decoupling. Secondary fluctuations arise from the scattering of photons as they interact with gravitational potentials and sources of local ionization along the line of sight to the present-day observer.

Measurements of the CMB power spectrum on the small angular scales probed by the GTM can be used to constrain the shape and Gaussian nature of the primordial spectrum of density fluctuations, which provide a test of the inflation theories, and also provide an estimate of the epoch of hydrogen reionization in the early universe due to the formation of the first stars and powerful AGN.

The dominant source of secondary CMB fluctuations, caused by local ionization in clusters, will be detectable by the GTM. Plasma in the intergalactic medium within clusters interacts with CMB photons through inverse Compton scattering, whereby hot electrons preferentially scatter lower energy photons to higher energies. This thermal Sunyaev Zel'dovich (SZ) effect distorts the mm wavelength spectrum of the CMB in the vicinity of clusters to produce a maximum decrement at 2.3 mm, a maximum increment at 0.85 mm, and a null at 1.4 mm. This distinctive spectral feature, combined with the sensitivity and resolution of the GTM, makes it possible to identify distant clusters from the confused foreground and background mm wavelength radiation due to point like galaxies and Galactic cirrus. The combination of GTM observations of the SZ effect (independent of redshift) at mm wavelengths with X-ray observations can constrain the mass of an individual cluster. Follow-up optical and IR imaging and spectroscopy of the galaxies associated with the identified clusters will provide measurements of their redshifts and velocity dispersions. This collective information will provide strong constraints on the growth of structure.

The GTM will accurately image complexes of molecular gas and dust that are current or future sites of star formation within the disks of galaxies, and, rapidly conduct unbiased surveys of the properties of these disks. For example, the angular resolution of the GTM corresponds to about 20 parsec at the distances of the Andromeda Galaxy (M31) and the Triangulum Galaxy; sufficient to resolve individual giant

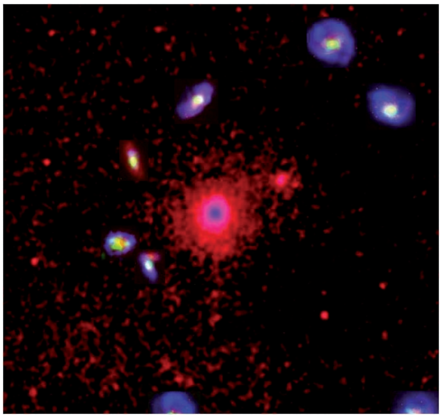


***Figure 17.** Color composite images of nine Virgo cluster galaxies (CO in green, HI in blue, and optical, inside individual galaxy images, in red). The CO emission has been imaged using the SEQUOIA array. The X-ray emission in the cluster is shown in red and magenta.*

molecular gas clouds. The GTM will be able to map the location and kinematics of dense molecular clouds in several hundred nearby spiral galaxies, and to study cloud formation and dissipation as they pass through the shock fronts within galactic spiral arms.

GTM can define the spatial and kinematic relationships between the population of giant molecular clouds and the overlying atomic gas component most readily traced by the HI 21 cm transition. Such relationships can distinguish the most relevant factors responsible for the development of giant molecular clouds and the subsequent formation of stars in galaxies.

GTM can conduct observations to investigate the variation of molecular gas conditions as a function of radial position within a galaxy. These conditions can be directly compared to local star formation rates and efficiencies to assess the regulatory processes within galaxies.

Hundreds of galaxies in clusters like this can be imaged and studied simultaneously using the GTM. The high sensitivity of the GTM increases the number of available target sources to several thousands, and the frequency agility of the GTM instruments is extremely well suited for absorption system searches and detailed follow-up investigations. When a large number of molecular transitions are detected in several systems spanning a wide range of redshifts (distances), interesting insights on variations in physical properties of the ISM, such as gas density, temperature, and chemical abundances, can be obtained.

GTM can perform imaging surveys of molecular gas tracers such as CO for a large sample of nearby galaxies representing different galactic environments, as in the Coma cluster. Comparisons of CO emission with the HI and infrared images should reveal the relationship between the large scale cold gas and stellar structures, the gas distribution, and star formation activity. During the first few years of operation the GTM will image CO emission in hundreds of galaxies with sub kiloparsec spatial resolution out to a distance of 100 megaparsecs.

The GTM can investigate the many scales and processes related to star formation in molecular clouds. The capability of the GTM to rapidly image both molecular line and thermal dust continuum emission provides powerful tools to study the global cloud dynamics, the development of massive cores and pre protostellar condensations from the low density substrate, the gravitational collapse of material onto the central object and circumstellar disk, and the protostellar wind phenomenon.

Accurate descriptions of the dynamics of molecular clouds are essential to our understanding of the star formation process. The dynamics of a cloud plays a pivotal role in setting the time interval over which the cloud can produce stars and the mode (clustered or distributed) in which stars are generated. A high-resolution view of a nearby molecular cloud reveals a web of filaments, shells, and high density cores that attest to a complex dynamical state. The observed complexity is produced by expanding motions from HII regions and stellar winds, and the interplay between magneto turbulent pressures and the self gravity of the cloud. Determining the relative roles of the magnetic field, turbulence, and wind driven shocks is a central goal of molecular cloud studies.

The Taurus molecular cloud is the prototypical example, and much of the observational and theoretical efforts to understand star formation have been focused on this basic mode. The dense regions from which newborn stellar clusters emerge are larger (0.51pc), more massive (1,000 to 10,000 times the solar mass), denser (1 million molecules per cm^3), and more inhomogeneous than the core counterparts

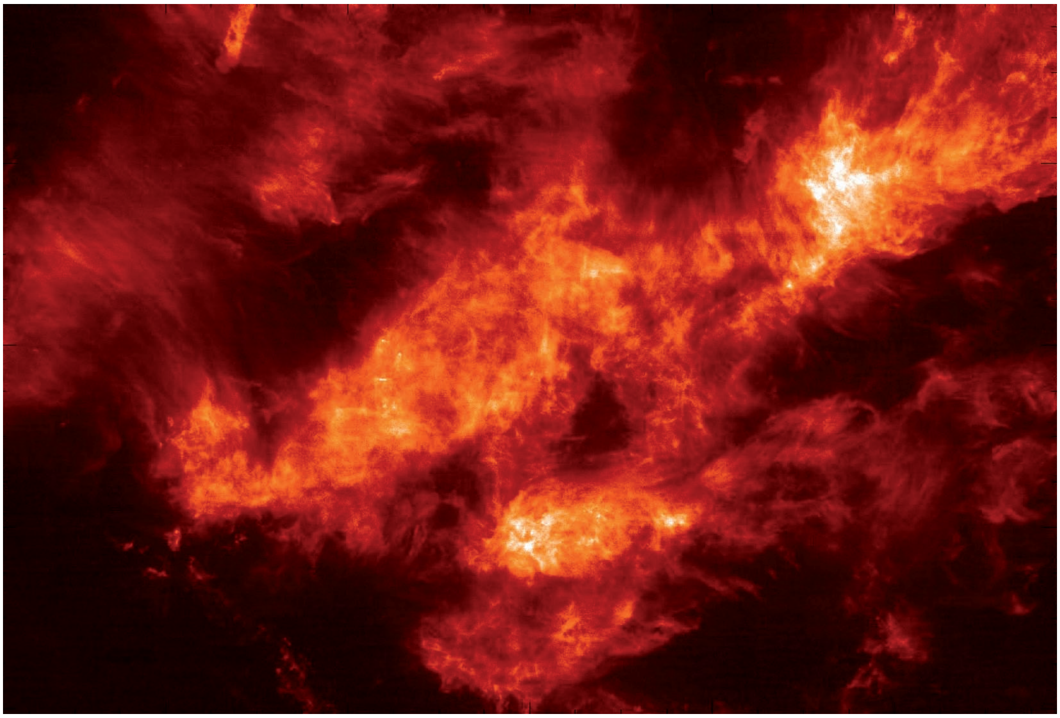


Figure 18. An image of the ^{13}CO J = 10 - 0 emission from the Taurus Molecular Cloud, a nearby star forming region observed with the FCRAO telescope and SEQUOIA receptor. GTM can image similar but more distant star forming systems to sample a broader range of interstellar environments.

associated with distributed star forming regions. Such regions have the capacity to produce 100 to 1,000 stars and are almost the only sites of massive star formation.

The GTM will produce definitive descriptions of massive cores in the interstellar medium of the Milky Way. Mapping of the thermal dust continuum emission with the AzTEC and SPEED bolometer arrays will reveal the column density distribution of material and identify protostellar objects within the massive cores. The local dynamics and chemistry of the massive core will be determined by imaging of spectral line emission that directly traces the dense gas. Such measurements will define the coupling of the dynamics to the protostellar condensation.

The high sensitivity, angular resolution, and mapping speed of the GTM will enable detailed investigations of the chemistry of interstellar molecular clouds, protoplanetary disks, and comets. The mapping speed of the GTM will allow detailed comparisons of the chemical content of a variety of molecular clouds in differing stages of evolution and with differing physical conditions and environments. Likewise, the high spectral resolution and sensitivity available with the GTM will produce data on isotopic fractionation and its dependence on cloud physical parameters and evolution. Such results will address the relative importance of purely gas phase versus grain surface synthesis of complex molecules in the ISM, and the relation between interstellar molecules, the chemistry of primitive solar system bodies such as comets, the delivery of organic molecules to the early Earth from space, and the role of such molecules in the origin of life.

The GTM is an important station in the millimeter VLBI network as it provides a large collecting area at 1 and 3mm bands and a valuable north-south baseline connecting with ALMA. Its participation in the millimeter VLBI campaigns is critical to efforts to resolve the event horizon of the SgrA* SMBH, to reveal shadowing generated by orbiting or infalling plasma, and to measure the spin of the SMBH from flaring events.

The terrestrial planets, planetary satellites, asteroids, and comets have all proved to be fruitful objects for study by radar astronomy. In addition, radar measurements of Near Earth Objects would provide distance and velocity data vastly more accurate than that available from optical images, a critical consideration for the protection of Earth from potentially impacting asteroids and comets.