

SUBMILLIMETER ASTRONOMY

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Abstract. For submillimeter astronomy, particularly at $200\,\mu\text{m}$, the ARENA working group has proposed a 25 m telescope at the Concordia station on Dome C. Issues related to this suggestion are reviewed.

1 Submillimeter Astronomy

Twenty five years ago, astronomy at submillimeter wavelengths was just beginning. Observations since then have advanced our understanding of star formation, circumstellar envelopes, astrochemistry, debris disks, the structure and evolution of the Galactic interstellar medium, and the solar system. In extragalactic research, two results are particularly notable. First, a population of optically inconspicuous but submillimeter luminous galaxies was discovered with the SCUBA camera (Holland *et al.* 1999). The rest frame spectral energy distributions of these galaxies peak around $100\,\mu\text{m}$. At longer wavelengths, their steep dust spectra compensate for distance as redshift increases, so their submillimeter fluxes are almost redshift independent and they are visible at great distances. Representative of this population is GOODS 850-5, a distant starburst system that is undetected in deep optical and near IR imaging with HST and Subaru but is bright in the submillimeter (Wang *et al.* 2009). Its redshift, $z = 4$, has been determined by measurement of a CO line, putting its luminosity, $10^{13} L_{\odot}$, among the greatest known (Daddi *et al.* 2009). These objects provide clues to understanding the formation and evolution of galaxies in the early universe, including the rapid genesis of metals and the effect of collisions and mergers on galaxy assembly. Second was the recognition the integrated intensity of the far IR and submillimeter radiation in the universe equals the intensity at optical wavelengths (Hauser & Dwek 2001; Dole *et al.* 2006). Whereas the optical radiation is direct starlight primarily emitted by relatively nearby galaxies, the FIR and submm radiation is starlight that has been absorbed and reemitted by more distant dusty galaxies. Recent observations

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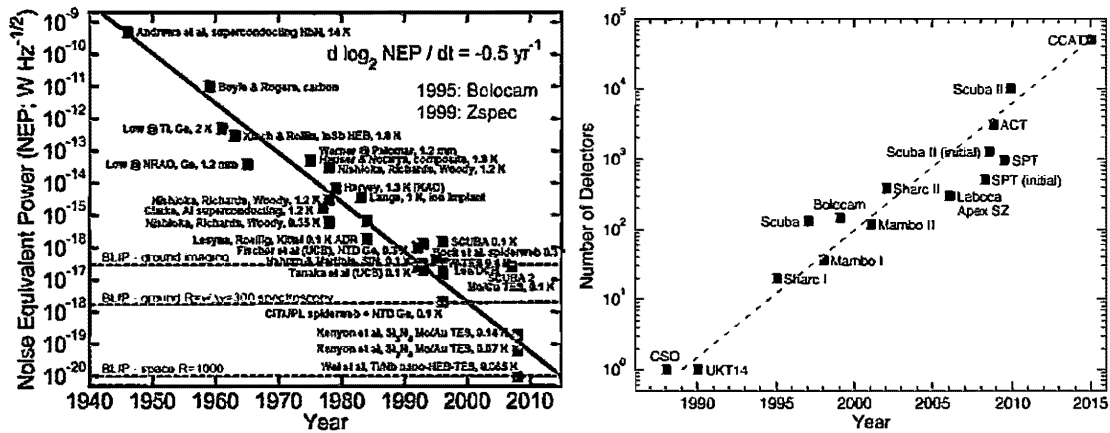


Fig. 1. *Left:* historically, the sensitivity of bolometers for millimeter and submillimeter wavelengths has doubled every two years. *Right:* likewise, the size of (almost) background limited array cameras has doubled a bit faster than every two years. (Courtesy J. Zmuidzinas).

confirm galaxies at $z > 1$ generate the majority of the FIR and submm background light (Devlin *et al.* 2009).

New instrumentation is now poised to capitalize on these discoveries and further our understanding. Perhaps the most notable project, ALMA, is the epitome of heterodyne interferometry. With many antennas adding up to an unsurpassed collecting area, flexible configurations extending to long baselines, sensitive receivers, and a powerful correlator, ALMA will provide high quality of individual objects images with exquisite spatial and spectral resolution (Testi 2009). Despite its capabilities, however, even ALMA cannot do everything. In particular, it is not efficient at wide field surveys. As P. Thaddeus (1996) quoted J. Ostriker (with apologies to V. Lombardi), “Surveys aren’t the most important thing in astronomy, they’re the only thing.” Several groups have noted this opportunity and have proposed telescopes designed for surveys and outfitted with array cameras (Stark 2003; Herter *et al.* 2004; Holland *et al.* 2004). The ARENA working group has advanced the idea of a 25 m telescope at the Concordia station on Dome C (Minier *et al.* 2008, 2009).

2 Submillimeter Cameras

Bolometer array cameras, which are well suited to high sensitivity, wide field surveys, are fundamentally complementary to the heterodyne technology used in interferometers such as ALMA. Over the past 50 years, the sensitivity of bolometers for submm wavelengths has shown a remarkable improvement, doubling every two years. Around 1990, the sensitivity of individual detector elements reached the background limit for ground based observations at a good site. Since then, array sizes have doubled a bit faster than every two years (Fig. 1). Extrapolating these trends, such cameras will soon outstrip the capabilities of existing telescopes. On

a 25 m telescope at a good site, the per pixel sensitivity of a background limited bolometer array observing at $350\ \mu\text{m}$ is about the same as ALMA, but the survey speed would be many times faster because of the large instantaneous field of view. Such an instrument would reach the background confusion limit in about an hour. Megapixel cameras might be anticipated about 2025, which is about mid career for any major telescope now under development. At $350\ \mu\text{m}$ on a 25 m telescope, a megapixel camera would Nyquist sample a field of view more than $30'$ in diameter. Clearly any new telescope design must consider the instantaneous field of view and be designed with such cameras in mind.

Furthermore, non heterodyne spectrometers using gratings or other dispersive elements and direct detectors are undergoing rapid development. While they offer only relatively modest spectral resolution, they can cover extremely wide bandwidths and are limited by background rather than heterodyne quantum noise, making them well suited for extragalactic surveys (Nikola *et al.* 2008). Laboratory studies of flexible dielectric waveguides point the way to multiobject spectrometers.

3 Site Conditions

In order to achieve the science goals and to justify the investment of a major submillimeter telescope, excellent observing conditions are necessary. Submillimeter radiation is strongly attenuated by the atmosphere, in particular by water vapor. As a result, ground based observations are only possible from a handful of very dry locations. For many years, Mauna Kea has been the premiere site for submillimeter astronomy. In northern Chile, the 5000 m Chajnantor plateau was selected for ALMA and other telescopes because it enjoys excellent observing conditions (Radford & Holdaway 1998). Even better conditions exist at 5600 m on higher peaks in the vicinity (Marrone *et al.* 2005; Radford *et al.* 2008). The potential of Antarctica has been recognized for some time (Chamberlin & Bally 1994) leading to the installation of major telescopes at the South Pole station, most recently the 10 m diameter SPT (Padin *et al.* 2008). Conditions at the South Pole and on the Chajnantor plateau are comparable (Radford & Chamberlin 2000; Radford 2001).

On the basis of meteorological data, it has been expected that Dome C would have better observing conditions, in particular, better transparency, than the South Pole. Recent measurements at $200\ \mu\text{m}$ indicate this is indeed the case (Tremblin *et al.* 2009). Although these preliminary measurements are encouraging, comparison with other sites should be approached carefully as cross calibration of different instruments can be difficult. Additional transparency measurements, for example with a 183 GHz water line radiometer, and the planned measurements of sky brightness stability with CAMISTIC on IRAIT would corroborate these preliminary results.

In site selection, sky coverage should not be neglected. The good zenith transparency of an Antarctic site would be quickly nullified by observing low declination fields. At a tropical site more of sky may be observed at smaller zenith angle than at a polar site. Although the distant Universe can be observed in any direction, the wider astronomical community has placed tremendous resources into the study

of several deep survey fields, *i.e.*, GOODS, COSMOS, XMM-LSS, etc. These fields are (mostly) equatorial to allow observations by telescopes in both hemispheres. The observations of these fields, including major allocations of spacecraft time, are unlikely to be repeated at other places. Similarly, solar system objects and the Galactic center, targets of some interest, are inconveniently low when viewed from Antarctica.

4 200 μm Observations

The possibility of frequent time for observations at 200 μm is an attractive feature of Dome C. In the rest frame, the spectral energy distribution of starburst galaxies peaks close to 100 μm . At shorter wavelengths, the luminosity drops rapidly. Hence 200 μm surveys will preferentially detect galaxies at $z < 1$. For more distant galaxies, including the most active epoch of galaxy formation at $1 < z < 2$, the 200 μm flux will drop out. Indeed this may be very useful, in conjunction with longer wavelength observations, as a selection strategy for high redshift objects.

5 Telescope

At short submillimeter wavelengths, especially at 200 μm , an excellent telescope will be essential. Otherwise the quality of the observations will be determined by the telescope performance, rather than natural limitations such as the atmosphere. For high aperture efficiency, the half wavefront error of the entire system should be better than 1/20 of a wavelength, or 10 μm rms for observations at 200 μm . Commensurate pointing knowledge is required, better than 1/10 of the diffraction beam, or better than 0.2'' for observations at 200 μm with a 25 m telescope. These are challenging requirements (Fig. 2), unmet by any existing telescopes. Although design work is underway for CCAT (Woody *et al.* 2008), the technical challenges are not yet solved for a telescope at a temperate site. The size and specifications of the SPT and the ALMA antennas are similar enough the SPT was able to use a design based on the Vertex ALMA antenna. Antarctic conditions pose additional challenges (Durand *et al.* 2008), for example the formation of frost on exposed surfaces. Heating the telescope surface to remove this frost may compromise the thermal stability needed to maintain the surface precision.

6 Logistics

In considering a major telescope in Antarctica, the logistics must be carefully considered. Although Antarctic bases are operated in support of scientific research, there are considerable political reasons behind their establishment. Hence while an excellent science case is certainly necessary to justify construction and operation of a major telescope in Antarctica, it may not be sufficient. Full support from the polar agencies will be essential to success of such a project.

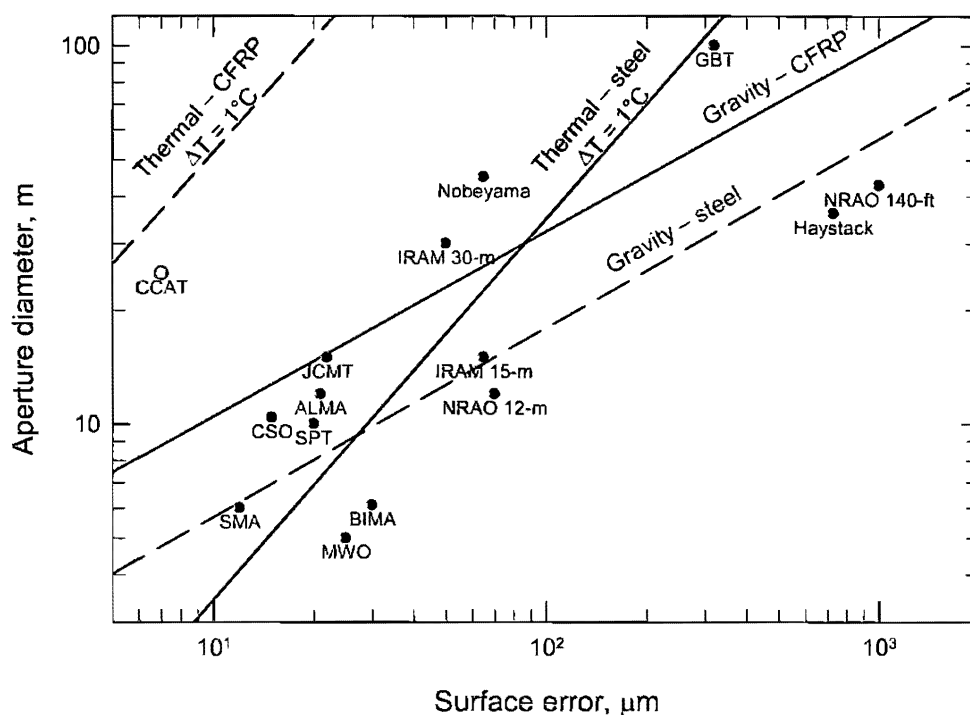


Fig. 2. Surface precision of radio telescopes and natural limits imposed by material properties. The CSO and GBT have open loop active surfaces; all others are passive designs. (After von Hoerner 1967.)

The costs of an Antarctic telescope must be acknowledged. A rough breakdown of the 2010 budget for the US NSF Office of Polar Programs (www.nsf.gov) suggests the total annual cost of operating the South Pole station, including the proportional share of the supply chain as well as the research activities, is about 90 million USD. This amount supports, of course, several science activities at the Pole, but indicates the scale of the required expenditures. To support a major telescope at Dome C, proportionate operating costs must be foreseen. This will require a major commitment by the funding agencies.

In considering the prospects for a major submillimeter telescope at Dome C, it may be instructive to review the history of astronomy at the South Pole, where summer experiments in the late 1970s and through the 1980s paved the way for the first all year telescope, AST/RO, in 1995, and ultimately the SPT ten years after that (Lynch 1998). Up to now, only summer experiments and site characterization measurements have been carried out at Dome C. A 25 m telescope would be a big step requiring significantly enhanced logistic support.

7 Summary

Submillimeter astronomy has developed significantly in recent years and, with the advent of ALMA, is now poised for further discoveries. An important complement

to ALMA will be wide field surveys with large array cameras, which are rapidly increasing in size and mapping speed. Observing conditions at Dome C promise considerable observing time at 200 μm , suggesting an emphasis on this wavelength. The technical and logistics issues, however, involved in constructing and operating a major telescope at Dome C are considerable.

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