# Appendix B

# Millimeter/Submillimeter Telescopes

## US Millimeter Telescopes

Here we briefly introduce and summarize a number of the most impactful single-dish millimeter wavelength telescopes constructed in the late twentieth century. These built the legacy of millimeter wave astronomy that led to ALMA.

*University of Texas Millimeter Wave Observatory* – Observations began with the 4.9 m diameter telescope of the Electrical Engineering Research Laboratory of the University of Texas in June of 1963, at its off-campus site at the J.J. Pickle Research Center in the northern outskirts of Austin, Texas. After measuring the brightness at 35, 70, and 94 GHz of a number of planets, the antenna was moved to Mt. Locke, the site of McDonald Observatory in the Davis Mountains of West Texas, where it was housed in an astrodome, shown in Figure B.1. In 1971, the antenna was "discovered" by Pat Thaddeus and one of the authors (Vanden Bout), who were observing on the McDonald 107 Inch Telescope. The antenna was idle. By the fall of 1972, a partnership began using the Millimeter Wave Observatory (MWO) to exploit the potential of the recently discovered interstellar CO. Bell Labs contributed the receivers, the Goddard Institute of Space Studies (GISS) purchased the klystron oscillators required for the receiver system, and Harvard College Observatory built the spectrometer or "backend." The observing time was shared equally among the four partners. The MWO had a large number of observers from the United States and abroad, and MWO data have been included in at least 23 doctoral dissertations. Research tended to be concentrated on mapping individual CO sources in the Galaxy. Perhaps



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**Figure B.1** The MWO 4.9 Meter Telescope in its renovated astrodome equipped with an error-correcting subreflector. Credit: McDonald Observatory, University of Texas at Austin, reproduced by permission.

the most significant discovery was of jets of gas known as bipolar outflows that are the by-product of young stars, most importantly, the source known as L1551.[1] The MWO was decommissioned in 1988. The reflecting surface of the 4.9 Meter Telescope is at the campus of the Instituto Nacional de Astrofísica, Óptica y Electrónica in Tonanzintla, near Puebla, Mexico[2]; the astrodome and mount have been moved to Sierra Negra, the site of the Large Millimeter Telescope (LMT).

*Columbia University Mini Telescope* – In 1974, Thaddeus and his group at GISS installed a 1.2 m diameter antenna in a dome on the roof of the Pupin Physics Building of Columbia University. The relatively small size of the antenna was deliberately chosen, as a smaller telescope with its wide field of view can rapidly construct maps of the CO distribution in the plane of the Milky Way. The "Mini" was highly successful, producing maps of Galactic CO, which led to numerous studies[3] interpreting these maps and features within. Figure B.2

**Figure B.2** The Southern Mini in its astrodome at CTIO. Courtesy of Thomas Dame, reproduced by permission.

shows the Southern Mini, installed in 1982 at the Cerro Tololo Inter-American Observatory (CTIO) in Chile, which supplied the complementary data from the southern hemisphere. Observations of Galactic CO with the Southern Mini were conducted by Leo Bronfman of the U. Chile. The first Mini was moved to Harvard College Observatory in 1986 and its operation continues to the present under the leadership of Tom Dame.

*Aerospace Corporation Millimeter Telescope* – The Aerospace Corporation is a research organization originally supported by the Air Force to conduct defense research. It also had a vigorous program of research in optical and x-ray astronomy through the 1970s when a 4.6 m diameter antenna for millimeter wavelength observing was constructed. The antenna resided on the roof of the Aerospace building just south of the Los Angeles International Airport. It had been built by the Rohr Corporation, shortly before Rohr built the NRAO 36 Foot Telescope. The proximity to the Pacific Ocean made for a less than desirable site for a millimeter telescope but it was adequate for observations at 3 mm wavelength. It made observations of planets, quasars, and the association of CO emission with individual objects in the Galaxy. A report of the activities in 1975 is typical of the observing programs[4] which involved mapping CO emission from Galactic molecular clouds. A significant contribution

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of the Aerospace telescope was a map of the emission from the two isotopologues, $^{13}CO$ and $^{12}CO$, in L134 which showed that the abundance of $^{13}CO$ with respect to $^{12}CO$ increased toward the center of the molecular cloud, as was predicted by models of isotopic fractionation in dense clouds. Anneila Sargent commuted from Caltech in Pasadena to make the observations for her PhD dissertation using the Aerospace antenna. The staff of the Aerospace Telescope included William Wilson, Eugene Epstein, and one of the authors (Dickman), who was in charge of operations.

*Five College Radio Astronomy Observatory* – The Five College Radio Astronomy Observatory (FCRAO) was organized in 1970 as a partnership between Hampshire, Amherst, Smith, Mount Holyoke Colleges, and the University of Massachusetts, Amherst. The first research project was the study of pulsars using a cluster of four "mini-Arecibo" telescopes, consisting of reflecting mesh draped between utility poles. The telescope was located in a wooded reserve at Quabbin Reservoir. This work led in time to the discovery by Hulse and Taylor, at the Arecibo Observatory, of a binary pulsar with a millisecond period. The properties of the pulsar could be explained if it emitted gravitational waves. In the meanwhile, research had changed directions at FCRAO, turning to interstellar molecular spectroscopy.

In late 1972, ESSCO offered to provide a 14 m diameter antenna, in a protective radome, with a surface of accuracy sufficient for observing at millimeter wavelengths. The telescope was dedicated in 1976 and reached routine operation in 1978. Dickman was the FCRAO manager for a number of years. The radome is shown in Figure B.3. Although studies were made of multiple molecular species, its *forte* was surveys of CO in our Galaxy, the Milky Way, and in nearby galaxies. The Milky Way surveys were of necessity more limited in extent than those of the Columbia Mini because of the more than 100 times finer resolution in the maps produced, but although they take took longer, more detail was discerned in the final product. The resulting detail allowed for significant new results. For example, it became clear that most of the interstellar molecular gas is in huge, dense clouds, called Giant Molecular Clouds (GMCs). The bulk of star formation in our Galaxy, and presumably other galaxies, occurs in GMCs. FCRAO was also well known for its technical expertise, most notably its array receivers: the 16-element QUARRY and the 32-element SEQUOIA arrays. FCRAO closed in 2006, but its legacy lives on in the careers of many leaders in millimeter astronomy. Its receivers have been repurposed and installed in other telescope projects around the world, most notably, the LMT in Mexico.

**Figure B.3** The radome of the FCRAO 14 Meter Telescope at Quabbin Reservoir. Courtesy of Mark Heyer, University of Massachusetts at Amherst, reproduced by permission.

*Bell Telephone Laboratories Telescope* – Following years of observing at the MWO, the Bell Labs team built their own antenna. It had a unique design that featured an unblocked aperture of 7 m diameter with nothing between the reflecting surface and the sky. The telescope was completed in 1978.[5] Work at the facility included studies of isotopic species of interstellar molecules, observations of individual molecular clouds, and surveys[6] of CO emission, particularly the $^{13}CO$ isotopologue. The observing was largely done by Bell Labs staff members, but there was also a visiting observer program. The 7 Meter Telescope is shown in Figure B.4.

## Millimeter Telescopes Outside the United States

The establishment of millimeter wavelength observatories in the United States was quickly followed abroad. Two large-diameter telescopes were built in the early 1980s which completely outclassed all those in the United States.

*Institut de Radio Astronomie Millimétrique* – The Institut Radio Astronomie Millimétrique (IRAM) had a somewhat fraught beginning.[7] In the 1970s, discussions among the French, German, and British radio astronomers led to an

**Figure B.4** The Bell Labs 7 Meter Telescope with its unblocked aperture. Arno Penzias is in the foreground. (Note: This is not the horn telescope Penzias and Robert Wilson used for their discovery of the cosmic background radiation.) Credit: Nokia Corporation and AT&T Archives, reproduced by permission.

agreement to form the Joint Institute for Millimetre Astronomy. The plan collapsed when the British withdrew. This left the French and German participants to decide what they alone would build, the Germans favoring a large 30 m diameter antenna and the French a millimeter interferometer. When Spain joined the partnership, it became possible to do both. IRAM was founded on 2 August 1979. The 30 Meter Telescope, shown in Figure B.5, was the first of the IRAM facilities to be completed. It is located on Pico Velata near Granada, Spain. Later, an interferometer was completed on the Plateau de Bure, near Grenoble, France. The upgrade of the Plateau de Bure Interferometer, the Northern Extended Millimetre Array (NOEMA) is in operation today, as the premier interferometer for millimeter wavelengths in Europe. IRAM is also a major center for the development of radio astronomy instrumentation and technology.

**Figure B.5** The IRAM 30 Meter Telescope on Pico Velata, Spain. Credit: ©IRAM, reproduced by permission.

*Nobeyama Radio Observatory* – Japanese radio astronomy began in the late 1940s with observations of the Sun by researchers at several institutions. A community-wide forum for the promotion of radio astronomy in Japan was organized in December 1969 called the Japan Radio Astronomy Forum. The first millimeter wave telescope was a 6 m antenna installed in 1970 at the Mitaka site of the Tokyo Astronomical Observatory, which later became the National Astronomical Observatory of Japan (NAOJ). In the early 1970s, a plan was developed to construct a 45 m diameter telescope in combination with a five-element millimeter interferometer. These efforts combined at the Nobeyama Radio Observatory (NRO) under the leadership of Masaki Morimoto. The 45 Meter Telescope was to operate at wavelengths from 3 mm to 1 cm. An interferometer for solar observations was also part of the plan. Construction began in 1978 and was completed in 1982. Observations at 1 cm with the 45 Meter Telescope were first made in 1984 and true millimeter observations began in 1988. The NRO 45 Meter Telescope continues operations today. It has a novel acoustic spectrometer of 16,000 channels that has been used to discover a number of interstellar molecules. The NAOJ Advanced Technology Center is a major player in the development of millimeter/submillimeter receivers and instrumentation. The 45 Meter Telescope is shown in Figure B.6.

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**Figure B.6** The NRO 45 Meter Telescope in its mountain valley site. Credit: ©NAOJ, reproduced by permission.

*Onsala Space Observatory* – The Onsala Space Observatory (OSO) was founded in 1949 by Olaf Rydberg of Chalmers University. The OSO was dedicated in 1955 and its signature telescope, a 25.6 m diameter antenna, was first operational in 1963. Among the chief programs of research were studies of interstellar CH spectral lines at 9 cm wavelength. These lines were used to study the large-scale structure of the Milky Way. In 1976, a near-twin of the FCRAO millimeter telescope was completed at the OSO. Projects undertaken with this 20 m diameter telescope included a survey of interstellar spectral lines between 72 and 91 GHz emitted from the Orion Nebula and a dust-enshrouded star known as IRC +10216, observations showing that the CO emission from the galaxy M51 follows the spiral arms seen in visible light, and numerous other projects conducted by staff and visiting observers.

## Submillimeter Telescopes

One can argue that the history of radio astronomy is a progression from observations at long to ever shorter wavelengths. The field began with

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**Figure B.7** The SEST telescope at ESO, La Silla, Chile. Credit: ESO, CC BY 4.0.

Karl Jansky's discovery of galactic radiation at a wavelength of 14.6 m. In contrast, interstellar CO was discovered at a wavelength of 2.6 mm. The factor of nearly 5,600 in wavelength between these observations was made possible by advances in receiver electronics. As that progression in technology continued, it was inevitable that astronomers would turn to the submillimeter band, that is, wavelengths shorter than 1 mm. Accordingly, starting in the 1980s and up to the time of the writing of this book, the following eight single-dish submillimeter telescopes were built.

*James Clerk Maxwell Telescope* In 1983, a partnership between the United Kingdom (UK), the Netherlands, and Canada built the James Clerk Maxwell Telescope (JCMT) on Maunakea. It had a high-accuracy reflecting surface of 15 m diameter capable of submillimeter observations. The main instrument of the JCMT was a pair of receiver arrays, composed of bolometer detectors, called SCUBA. Using SCUBA, observers were able to establish a new class of galaxies called submillimeter galaxies. Today, the telescope has a much more powerful array detector, SCUBA-2, and is operated by a consortium of East Asian countries and UK universities.

*Sweden-ESO Submillimetre Telescope* – The success of the OSO 20 Meter Telescope's programs led to the construction of the 15 m Sweden-ESO Submillimetre Telescope (SEST) at ESO's La Silla site in Chile. Among its successes was a survey of spectral lines from Sgr B2, a strong molecular line source near the center of the Galaxy, over the frequency range 225–250 GHz. Figure B.7 is a photograph of SEST. It was the second millimeter-wavelength telescope built in Chile; a small 60 cm diameter dish had been installed earlier as a test facility by the NAOJ. SEST was decommissioned in 2003. Plans have been announced for moving the SEST antenna to Namibia, where it would serve as a far-south element of the EHT.

*Caltech Submillimeter Observatory* – Bob Leighton built a total of seven aluminum honeycomb sandwich reflector antennas of diameter 10.6 m, Dave Woody overseeing the construction and implementation of the last three. Six went into the OVRO Millimeter Array and the one with the best surface accuracy was used at the Caltech Submillimeter Observatory (CSO), shown in Figure B.8. The CSO was located in the saddle area just below the peak of Maunakea in

**Figure B.8** The Caltech Submillimeter Telescope in its astrodome on Maunakea. The JCMT dome is in the upper left. Courtesy of Sunil Gowala, reproduced by permission.

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**Figure B.9** The Submillimeter Telescope (SMT) of the University of Arizona. It is one of three telescopes on Mt. Graham, the others being the Large Binocular Telescope and the Vatican Advanced Technology Telescope. Credit: ESO, CC BY 4.0.

Hawaii. The measured surface accuracy using astronomical sources is about 20 μm. Submillimeter observing requires very low atmospheric water vapor and even on Maunakea this could be challenging. The CSO was only operated at night to minimize thermal deformations of the reflecting surface. An astrodome reduced the effect of wind. CSO operations began in the 1990s and continued until it was decommissioned in 2015. Over that period the detectors and associated analysis software were steadily improved for use in a variety of research programs. Tom Phillips was the long-time director of the CSO and has written a summary[8] of its history and scientific results. Among the more significant are the spectral line surveys, and the discovery that deuterated molecules were much more abundant than anticipated, with even triply deuterated ammonia detectable.[9] On 2 March 2021, the Maunakea Management Board approved a plan to deconstruct the CSO and restore its site in 2022. It has been suggested that the CSO be moved to Chile.

*The Submillimeter Telescope* – The push to the submillimeter band also led to the construction of the SMT at the University of Arizona. The SMT is a 10 m diameter telescope housed in an enclosure with large doors that open to the sky. Its construction was completed in 1993 following a fractious debate over the possible impact on the endangered Mt. Graham red squirrel, a situation settled by an act of the US Congress. It was originally built in partnership with the MPIfR and at that time called the Heinrich Hertz Telescope. The SMT is shown in Figure B.9, peering out between the massive open doors of its enclosure.

*Mt. Fuji Submillimeter Telescope* – In 1998, the Japanese, under the leadership of Yutaro Sekimoto, began operation of a submillimeter telescope[10] on the summit of Mt. Fuji, at an elevation of 3,725 m. The antenna had a diameter of 1.2 m and was housed in a rotating dome. It was equipped with receivers operating in the 345, 492, and 810 GHz bands and an acoustic-optical spectrometer of 1,024 channels. The telescope is shown in Figure B.10. The principal observing program of this telescope was a survey of emission from neutral carbon atoms in the interstellar medium of the Milky Way.

*Cologne Observatory for Submillimeter Astronomy* – In 1985, Gisbert Winnewisser installed a 3 m diameter antenna in the south tower of the Külm Hotel on the Gornergrat peak above the Swiss village of Zermatt. The telescope's

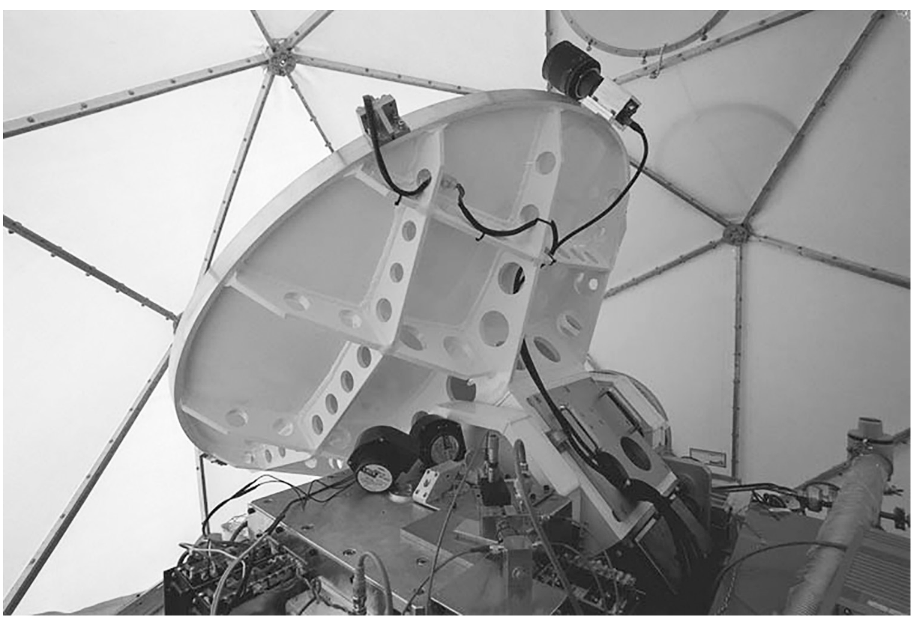

**Figure B.10** The Mt. Fuji Telescope in its radome. Courtesy of Yutaro Sekimoto, reproduced by permission.

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**Figure B.11** The Atacama Submillimeter Telescope Experiment (ASTE) at Pampa la Bola east of the ALMA site on the Llano de Chajnantor. Credit: ©NAOJ, reproduced by permission.

receivers, covering the frequency range of 210–820 GHz, were used to study interstellar molecular lines. In 1985, the telescope was upgraded with a new mount and reflecting surface. In a partnership with the National Astronomical Observatories of China, the telescope was moved to Tibet in 2010 to become the China-Cologne Observatory for Submillimeter Astronomy. Telescope operation resumed in 2013 following the installation of improved instrumentation.

*Atacama Submillimeter Telescope Experiment* – Over the two-year period 2002–2004, the NAOJ installed a 10 m diameter telescope at Pampa la Bola, near the future site of ALMA. The site is at an elevation of 4,650 m, slightly lower than the ALMA site. The Atacama Submillimeter Telescope Experiment (ASTE) supports spectroscopic observations at frequencies as high as 350 GHz, or a wavelength as short as 0.87 mm. Figure B.11 shows the telescope with a vehicle for size comparison. ASTE has been a very productive facility since it began operation, with close to 200 science publications and dozens of technical

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**Figure B.12** The Atacama Pathfinder Experiment (APEX) on its Llano de Chajnantor site. Credit: ESO, CC BY 4.0.

articles. Research has included observations of Galactic molecular clouds and protoplanetary disks, and observations of external galaxies including the Magellanic Clouds.

*Atacama Pathfinder Experiment* – In a joint venture between MPIfR, OSO, and ESO, a copy of the 12 m diameter ALMA antenna was installed on the Llano de Chajnantor, near ALMA, shown in Figure B.12. The Atacama Pathfinder Experiment (APEX) began operations in 2004. Over 750 scientific articles have resulted from APEX observations, exploring a wide variety of topics. Many of these observations point to further studies with ALMA, but the telescope has proven to be much more than an "ALMA Pathfinder."

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**Figure B.13** The Large Millimeter Telescope (LMT) at an elevation of 4,600 m on Volcán Sierra Negro, the highest mountain in Mexico. Courtesy of Peter Schloerb, reproduced by permission.

## Giant Millimeter Telescopes

*Large Millimeter Telescope* – A joint project between the United States and Mexico produced the world's largest millimeter/submillimeter wavelength telescope, the Large Millimeter Telescope (LMT), also known as the Gran Telescopio Millimétrico Alfonso Serrano. The partners are the Instituto Nacional de Astrofísica, Óptica y Electrónica, and the University of Massachusetts, Amherst. Figure B.13 shows the telescope in February 2018, shortly after the 50 m diameter reflecting surface was installed. The telescope operates at wavelengths from 0.85 to 4 mm. An image of the disk surrounding the young star ε Eridani was obtained as an early science result using the AzTEC 1.1 mm continuum camera.[11] The LMT has discovered numerous dusty star-forming galaxies at high redshift.[12] It is a key element of the EHT.

*Green Bank Telescope* – The Robert C. Byrd Green Bank Telescope (GBT) began operation in 2001. The GBT, shown in Figure B.14, is the world's largest fully steerable radio telescope. The subreflector and receiver cabin are offset from the telescope's view of the sky, improving its performance. It has an effective collecting area of 100 m diameter and can support observations at frequencies from 0.1 to 115 GHz. The reflecting surface is made up of 2004 panels

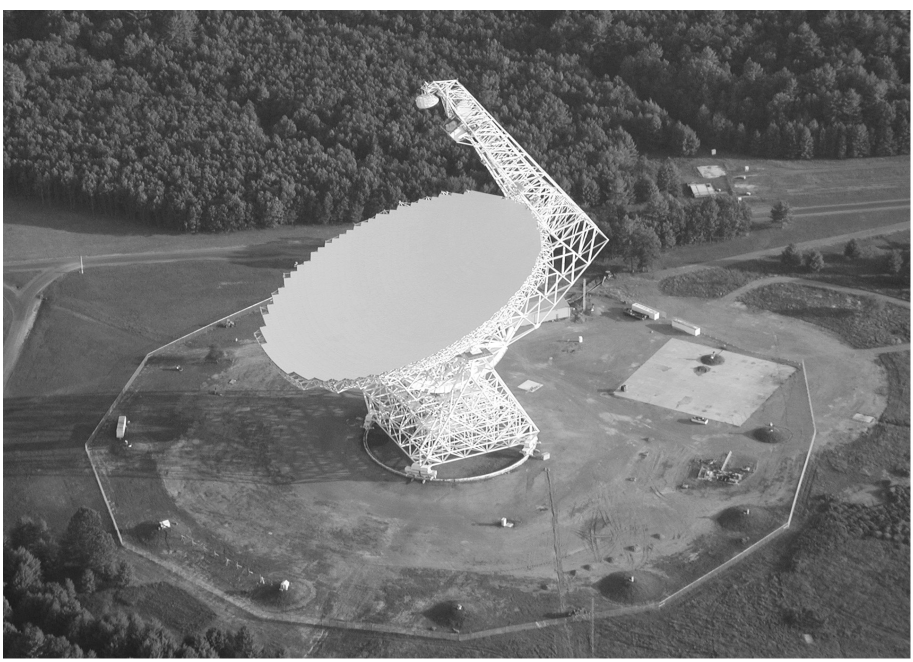

**Figure B.14** The Robert C. Byrd Green Bank Telescope in the Allegheny Mountains site of the Green Bank Observatory. Credit: GBO/AUI/NSF, CC BY 3.0.

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supported by motor-driven actuators. On calm winter nights, the actuators can be driven to set the reflecting surface to an accuracy that allows for observing at 3 mm wavelength. The GBT has a large instrumentation suite with the flexibility to support a wide variety of studies: pulsars, atomic hydrogen emission, interstellar molecules, dust emission, radar imaging of solar system objects, and very long baseline interferometry.

## Notes

1 The simultaneous discoveries of the first CO outflow sources are reported in Snell, Loren, and Plambeck (1980) and Rodriguez et al. (1980).

2 For a more complete history of the MWO, see Vanden Bout, Davis, and Loren (2012).

3 See Dame et al. (1987) and Dame and Thaddeus (2022).

4 Paulikas (1976) gives the 1975 annual report for the Aerospace Corp. Millimeter Telescope. See also Dickman, McCutcheon, and Shuter (1979) and Sargent (1977).

5 The construction of the 7 Meter Telescope is described in a report published in *The Bell System Technical Journal* (Chu et al., 1978).

6 Stark et al. (1988).

7 The origins of IRAM are given in *Open Skies* (Kellerman, Bouton, and Brandt, 2020). Also, *Proposition Commune Pour un Observatoire sur Ondes Millimétriques,* February 1975, (NAA-NRAO, MMA, MMA Planning).

8 Phillips (2009).

9 Lis et al. (2002).

10 A description of the Mt. Fuji Submillimeter Telescope has been published by Sekimoto et al. (2000).

11 See Chavez-Dagostrino et al. (2016).

12 See Berman et al. (2022) and references therein.