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Submillimeter Astronomy from the South Pole (AST/RO)

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Abstract. The Antarctic Submillimeter Telescope and Remote Observatory (AST/RO), a 1.7 m diameter offset Gregorian telescope for astronomy and aeronomy studies at wavelengths between 200 and 2000 μm, saw first light in 1995 and operated until 2005. It was the first radio telescope to operate continuously throughout the winter on the Antarctic Plateau. It served as a site testing instrument and prototype for later instruments, as well as executing a wide variety of scientific programs that resulted in six doctoral theses and more than one hundred scientific publications. The South Pole environment is unique among observatory sites for unusually low wind speeds, low absolute humidity, and the consistent clarity of the submillimeter sky. Especially significant are the exceptionally low values of sky noise found at this site, a result of the small water vapor content of the atmosphere. Multiple submillimeter-wave and Terahertz detector systems were in operation on AST/RO, including heterodyne and bolometric arrays. AST/RO's legacy includes comprehensive submillimeter-wave site testing of the South Pole, spectroscopic studies of 492 GHz and 809 GHz neutral atomic carbon and 460 GHz and 806 GHz carbon monoxide in the Milky Way and Magellanic Clouds, and the first detection of the 1.46 THz [N II] line from a ground-based observatory.

Keywords. surveys, site testing, submillimeter, Galaxy: kinematics and dynamics, ISM: kinematics and dynamics, ISM: molecules, ISM: evolution

1. Introduction

Establishment of the Antarctic Submillimeter Telescope and Remote Observatory (AST/RO, Stark *et al.* 2001) as a year-round, permanently-manned facility was an important step in the development of the South Pole as an observatory. It had long been thought that the Antarctic Plateau would be an exceptional site for high-frequency radio (for example Townes & Melnick 1990; see Indermuehle, Burton, & Maddison 2005 for a review), but the demonstration of this ground truth and the persuasion of skeptics required extensive development and site testing during the latter years of the 20$^{\text{th}}$ century. The simultaneous development of the Atacama Large Millimeter Array site in Chile was seen within the astronomical community as a rival for scarce resources; some predicted that winter observations from the Pole would be impossible or unrealistically expensive, and would never surpass what could be better done in Chile. Early attempts at Polar astronomical expeditions in 1984-85 (Pajot *et al.* 1989), 1986-87 (Dragovan *et al.* 1990) and 1988-89 (Meinhold & Lubin 1991, Tucker *et al.* 1993) showed promise, but they also showed the difficulty of setting up summer-only facilities for a few weeks of observing during the warmest and wettest part of the year, only to tear them down a few weeks later in anticipation of the oncoming winter. AST/RO was proposed as stand-alone multi-year observatory to the U.S. National Science Foundation Office of Polar Programs in 1988. It was funded under DPP88-18384 and also supported in part by Bell Laboratories and Boston University. While still under design in 1991, AST/RO was incorporated into

Table 1. AST/RO Personnel and their Institutional Affiliations during AST/RO Operations.

Winter-over Scientists[1]	**Senior Personnel**	**Collaborators**	**Students**[2]
Richard A. Chamberlin	Antony A. Stark[4,3] (PI)	Jürgen Stutzki[5]	Alberto Bolatto[6]
Simon P. Balm	Adair P. Lane[3] (PM)	R. Schieder[5]	Christopher Groppi[7]
Xiaolei Zhang	Christopher K. Walker[7]	Jacob W. Kooi[8]	Maohai Huang[6]
Roopesh Ojha	Robert W. Wilson[4,3]	Peter Zimmermann[9]	A. Hungerford[7]
Rodney D. Marks[10]	Jingquan Cheng[3]	Rüdiger Zimmermann[9]	Henry H. Hsieh[11]
Christopher L. Martin	K.-Y. Lo[12]	Gordon J. Stacey[13]	James Ingalls[6]
Wilfred M. Walsh	Thomas M. Bania[6]	S. Yngvesson[14]	Craig Kulesa[7]
Kecheng Xiao	James M. Jackson[6]	E. Gerecht[14]	Johannes Staguhn[5]
Karina Leppik	Gregory A. Wright[4]	Youngung Lee[3,15]	Gregory Engargiola[12]
Julienne Harnett	Sungeun Kim[3]	Dennis Mumma[4]	
Nicholas F. H. Tothill	John Bally[4]	Karl Jacobs[5]	
Andrea Löhr		Jonas Zmuidzinas[12,8]	

Notes:
1 AST/RO Winter-over Scientists were affiliated with the Smithsonian Astrophysical Observatory during the period of their winterover.
2 Many who were students during the AST/RO project are now distinguished senior scientists.
3 Smithsonian Astrophysical Observatory; Harvard-Smithsonian Center for Astrophysics; 60 Garden St.; Cambridge, MA 02138; USA.
4 AT&T Bell Laboratories; Crawford Hill; Holmdel, NJ 07733; USA.
5 I. Physikalisches Institut, Universität zu Köln; Zülpicher Straße 77; D-50937 Köln; Germany.
6 Boston University; 725 Commonwealth Ave.; Boston, MA 02215; USA.
7 Steward Observatory; 933 N. Cherry Ave.; University of Arizona; Tucson, AZ 85721; USA.
8 Caltech Submillimeter Observatory; Caltech 320-47; Pasadena, CA 91125; USA.
9 Radiometer Physics GmbH; Birkenmaarstraße 10; 53340 Meckenheim, Germany.
10 Rodney Marks died while wintering over in 2000, under circumstances that are still not fully known.
11 Harvard University; Department of Astronomy; 60 Garden St.; Cambridge, MA 02138; USA.
12 University of Illinois; 1002 W. Green St.; Urbana, IL 61801; USA.
13 Department of Astronomy; Cornell University; 610 Space Sciences Building; Ithaca, NY 14853; USA.
14 Department of Electrical and Computer Engineering; University of Massachusetts; Amherst, MA 01103; USA.
15 Taeduk Radio Astronomy Observatory, Korea Astronomy Observatory, Whaam-dong 61-1, Yuseong-gu; Taejon 305-348, Korea.

the Center for Astrophysical Research in Antarctica (CARA, cf. Novak & Landsberg 1998), then a newly-formed NSF Science and Technology Center with an 11-year life-span. AST/RO winter-over operations began in 1995 and concluded in 2005. This article will summarize the operations, site testing and science that demonstrated the feasibility of year-round operations and the quality of the Pole as an observatory site.

2. Operations

The design of AST/RO is described in Stark *et al.* (1997a). AST/RO was located on the roof of a dedicated support building across the aircraft skiway in the *Dark Sector* of the United States National Science Foundation Amundsen-Scott South Pole Station, the first of a group of observatory buildings in an area designated to have low radio emissions and light pollution. The AST/RO building was a single story, 4m × 20m, elevated 3m above the surface on steel columns to reduce snow drifts. The interior was partitioned into six rooms, including laboratory and computer space, storage areas, a telescope control room, and a Coudé room containing the receivers on a large optical table suspended from the telescope. The station provided logistical support for the observatory: room and board for on-site scientific staff, electrical power, network and telephone connections, heavy equipment support, and cargo and personnel transport. The station powerplant provided an average 25 kW of power to the AST/RO building.

Aircraft flights to Pole are scheduled from late October to early February, so that the station is inaccessible for nine months of the year. This long *winter-over* period is central to all logistical planning for Polar operations. Plans and schedules were made in March

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and April for each year's deployment to South Pole: personnel on-site, tasks to be completed, and the tools and equipment needed. All equipment had to be ready for shipment by the end of September. For quick repairs and upgrades during the Austral summer season, it is possible to send equipment between South Pole and anywhere serviced by commercial express delivery in about five days.

AST/RO group members deployed to South Pole in groups of two to six people throughout the Austral summer season, carrying out their planned tasks and returning after stays ranging from 2 weeks to 3 months. Each year there were one or two AST/RO *winter-over scientists* who remained with the telescope for a full year (see Table 1). The winter-over scientist position was usually a three year post-doctoral appointment: one year of preparation and training, one year at South Pole with the telescope, and one year after the winter-over year to reduce data and prepare scientific results. If there were no instrumental difficulties, the winter-over scientist controlled telescope observations through an automated program, carried out routine pointing and calibration tasks, tuned the receivers, and filled the liquid helium dewars. If instrumental difficulties developed, the winter-over scientist carried out repairs with radio or email consultation back to the home institution.

There were five heterodyne receivers mounted on an optical table suspended from the telescope structure in a spacious (5m × 5m × 3m), warm Coudé room:

- 230 GHz SIS receiver, 55–75 K double-sideband (DSB) noise temperature;
- 450–495 GHz SIS waveguide receiver, 200–400 K DSB (Walker *et al.* 1992);
- 450–495 GHz SIS quasi-optical receiver, 165–250 K DSB (Engargiola, Zmuidzinas, & Lo 1994, Zmuidzinas & LeDuc 1992);
- 800-820 GHz fixed-tuned SIS waveguide mixer receiver, 950–1500 K DSB (Honingh *et al.* 1997);
- an array of four 800-820 GHz fixed-tuned SIS waveguide mixer receivers, 850–1500 K DSB, the PoleSTAR array (Groppi *et al.* 2000).

Seven intermediate-frequency bandpasses were processed by acousto-optical spectrometers (AOS; Schieder, Tolls, & Winnewisser 1989):

- two low resolution spectrometers with a bandwidth of 1 GHz (bandpass 1.6–2.6 GHz);
- an array AOS with four low resolution spectrometer channels with a bandwidth of 1 GHz (bandpass 1.6–2.6 GHz) for the PoleSTAR array; and
- one high-resolution AOS with 60 MHz bandwidth (bandpass 60–120 MHz).

The SIS receivers used on AST/RO each required about 2 liters of liquid helium per day continuously throughout the year. The National Science Foundation and its support contractors supplied liquid helium in one or more large (4000 to 12000 liter) storage dewars. Some years this supply lasted the entire winter, but in 1996, 1998, 2000, 2002, and 2004 an insufficiency of supply affected operations—the supply of liquid helium was the main failure mode for AST/RO operations. Newer facilities such as South Pole Telescope and the Keck array make use of closed-cycle cryogenic systems.

3. Site Testing

Submillimeter astronomy requires dry, frigid observatory sites, where the atmosphere contains less than 1 mm of precipitable water vapor (PWV). The South Pole station meteorology office has used balloon-borne radiosondes to measure profiles of temperature, pressure, and water vapor at least once a day for several decades (Schwerdtfeger 1984). These have typically shown atmospheric water vapor values about 90% of saturation for air coexisting with the ice phase at the observed temperature and pressure. The PWV

Figure 1. The AST/RO telescope and building. An insulated steel tower supports the telescope and extends through the building, which houses receivers and electronics in a shirt-sleeve environment. Photo credit A. Lane.

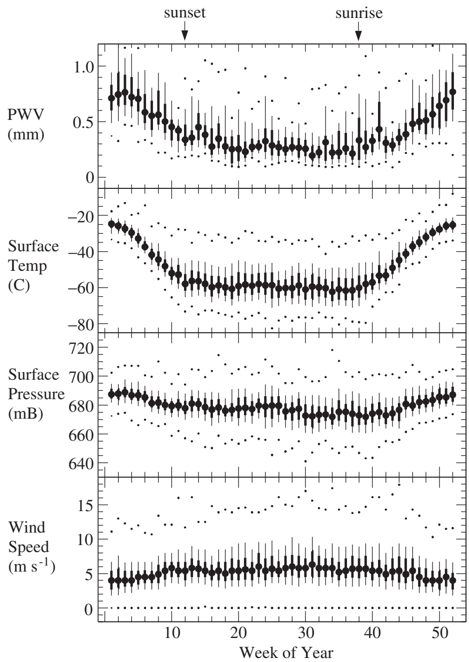

Figure 2. South Pole weather data binned by week of year. The large dot indicates the median value, the thick bar indicates the 25 to 75 percentile, the thin bar indicates 10 to 90 percentile, and the small dots are maximum and minimum measured values. The top panel shows precipitable water vapor as measured by AIR Model 4a weather balloon flights from 1991 to 1996. The bottom 3 panels summarize hourly NOAA weather data from 1977 to 2001. Note the "coreless winter" with typical PWV values of 0.3 mm. The highest recorded wind speed is remarkably small. Analysis and figure by R. Chamberlin.

values consistent with saturation are, however, extremely low because the air is desiccated by the frigid temperatures: at the South Pole's average annual temperature of −49 C, the partial pressure of saturated water vapor is only 1.2% of what it is at 0 C (Goff &

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Gratch 1946). Figure 2 shows the PWV averaged by week of the year. *PWV values at South Pole are small, stable and well-understood.*

Water vapor is usually the dominant source of opacity, but thousands of other molecular lines (Waters 1976, Bally 1989) make a *dry air* contribution to the opacity. Chamberlin & Bally (1994, 1995), Chamberlin, Lane, & Stark (1997), and Chamberlin (2001) showed that the dry air opacity is relatively more important at the South Pole than at other sites such as Chajnantor in Chile, since the total atmospheric pressure is higher. Dry air opacity is, however, less variable than the opacity caused by water vapor, and therefore causes less *sky noise* (Lay & Halverson 2000), a factor of 30 to 50 less at Pole than other sites. This is the critical factor for successful observation because constant white noise and constant opacity can simply be overcome by longer observation, whereas sky noise introduces a "$1/f$" component that requires faster switching or perhaps cannot be overcome at all. Antarctic plateau sites are truly exceptional in this respect.

4. Science Results

Many of AST/RO's scientific results were studies of emission lines from dense interstellar gas in the Milky Way and Magellanic Clouds, in particular the $J = 7 \rightarrow 6$ and $J = 4 \rightarrow 3$ transitions of CO, and the ${}^3P_1 \rightarrow {}^3P_0$ and ${}^3P_2 \rightarrow {}^3P_1$ ground-state transitions of C I. When these transitions are mapped in areas of the sky and combined with millimeter-wave observations of $J = 1 \rightarrow 0$ or $J = 2 \rightarrow 1$ transitions of CO and ^{13}CO, these data can be used to model the density and excitation temperature as a function of radial velocity along many lines of sight and determine the mass and kinematics of dense interstellar clouds.

Studies of star-forming clouds. Hsieh (2000), Huang *et al.* (1999), Huang (2001), Kulesa (2002), Groppi (2003), Groppi *et al.* (2004), Kulesa *et al.* (2005), Walsh & Xiao (2005), Kim & Narayanan (2006), Löhr *et al.* (2009), and Tothill *et al.* (2009) used AST/RO's multi-frequency mapping ability to study the properties of interstellar clouds in the process of star formation and their interaction with supernovae and H II regions.

The physical state of high-latitude translucent clouds. Ingalls (1999), and Ingalls *et al.* (2000) studied CO toward molecular clouds near the Sun but out of the plane of the Milky Way, and found conditions indicating that much of the emission originates in tiny ($\sim$ 2000AU) cold (8K) fragments within the $\sim$ 100 times larger CO-emitting extent of a typical high-latitude cloud.

Cloud formation and turbulence in the Carina region. Zhang *et al.* (2001) made large-area ($3\,\mathrm{deg}^2$) , fully sampled maps of CO and C I in the Carina molecular cloud complex. They present evidence that the spiral density wave shock associated with the Carina spiral arm is playing an important role in the formation and dissociation of the cloud complex, and also maintaining the internal energy balance of the clouds in this region by feeding interstellar turbulence.

The ${}^{12}\mathrm{C}/{}^{13}\mathrm{C}$ *ratio measured in* C I. Tieftrunk *et al.* (2001) made measurements of the ${}^{12}\mathrm{C}/{}^{13}\mathrm{C}$ abundance ratio from observations of the ${}^3P_2 \rightarrow {}^3P_1$ transitions near 809 GHz. They determined intrinsic ${}^{12}\mathrm{C}/{}^{13}\mathrm{C}$ ratios of of 23 ± 1 for G 333.0-0.4, 56 ± 14 for NGC 6334A and 69 ± 12 for G 351.6-1.3. The enhancement of ^{13}C towards G 333.0-0.4 may be due to strong isotope-selective photodissociation of the chemical precursor ^{13}CO, outweighing the effects of chemical isotopic fractionation; towards NGC 6334 A and G 351.6-1.3 these effects appear to be balanced.

Physical state and dynamics of galactic center gas. Ojha *et al.* (2001), Staguhn (1996), Staguhn *et al.* (1997), Kim *et al.* (2002), and Martin *et al.* (2004) used AST/RO observations of CO and C I to determine the thermodynamic state of dense gas within a few

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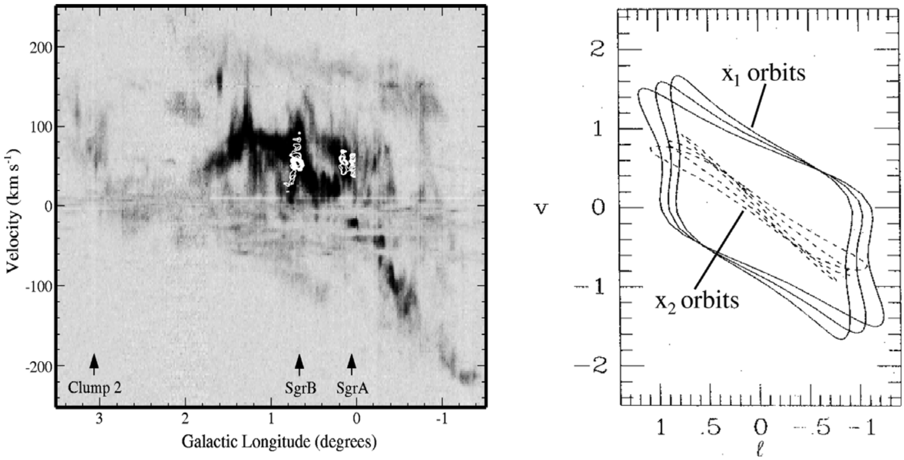

Figure 3. Carbon Monoxide in the Galactic Center Region. Left: the gray scale is $J = 4 \rightarrow 3$ CO, and the white contours are $J = 7 \rightarrow 6$ CO, shown in a longitude-velocity diagram. The nearly horizontal absorption features are foreground spiral arms. Right: Theoretical calculation of x_1 and x_2 closed orbits from Binney *et al.* (1991). Note the faint CO parallelogram tracing the x_1 orbits and the brighter, denser material on x_2 orbits.

kiloparsecs of the Milky Way center. Much of this gas is located on closed x_1 and x_2 orbits (Binney *et al.* 1991; Figure 3). The gas that has accumulated on x_2 orbits is nearly at a density that will cause tipping into instability, where the ring of gas will coagulate into one or two giant ($\sim 10^7$ M$_\odot$) clouds that undergo starburst (Stark *et al.* 2004).

Dense molecular gas in the Magellanic Clouds. Stark *et al.* (1997b), Bolatto (2001), Bolatto *et al.* (2000a,b), Kim, Walsh, & Xiao (2004), Kim *et al.* (2005), Bolatto, Israel, & Martin (2005), and Kim (2006) mapped star-forming regions in the Magellanic Clouds to determine their physical properties and kinematics. Temperatures as high as 300 K occur within these clouds, which have extended photo-dissociation envelopes compared to galactic clouds.

Terahertz observations. Two Terahertz detector systems were installed on AST/RO as guest instruments: the Terahertz Receiver with NbN HEB Device (TREND) was a heterodyne receiver with a LASER local oscillator (Gerecht *et al.* 1999, 2004, Yngvesson *et al.* 2002); and the South Pole Imaging Fabry-Perot Interferometer (SPIFI, Swain *et al.* 1998, Bradford *et al.* 2002). The principal difficulty in Terahertz operation was that when engineering teams could be brought in during the Austral summer, the sky was not transparent enough even for testing, so an untried system would be left for the winter-over scientists to attempt first light during brief winter periods of marginal Terahertz weather. Nevertheless, 205 μm N II was detected (Oberst *et al.* 2006) and mapped in the Eta Carina region (Oberst *et al.* 2011).

5. Conclusion

AST/RO site testing contributed to the characterization of the South Pole as an observatory site, showing the high transparency and stability of the millimeter-wave sky and the possibility of ground-based Terahertz observations. Routine observations over a decade enhanced our knowledge of submillimeter-wave spectroscopic line emission from interstellar gas, the nature of star formation, and the dynamics of the Galaxy. The AST/RO project demonstrated the feasibility of operating a state-of-the-art high-frequency radiotelescope at the South Pole during the Antarctic winter, and thereby laid the foundation for the instruments to come.

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