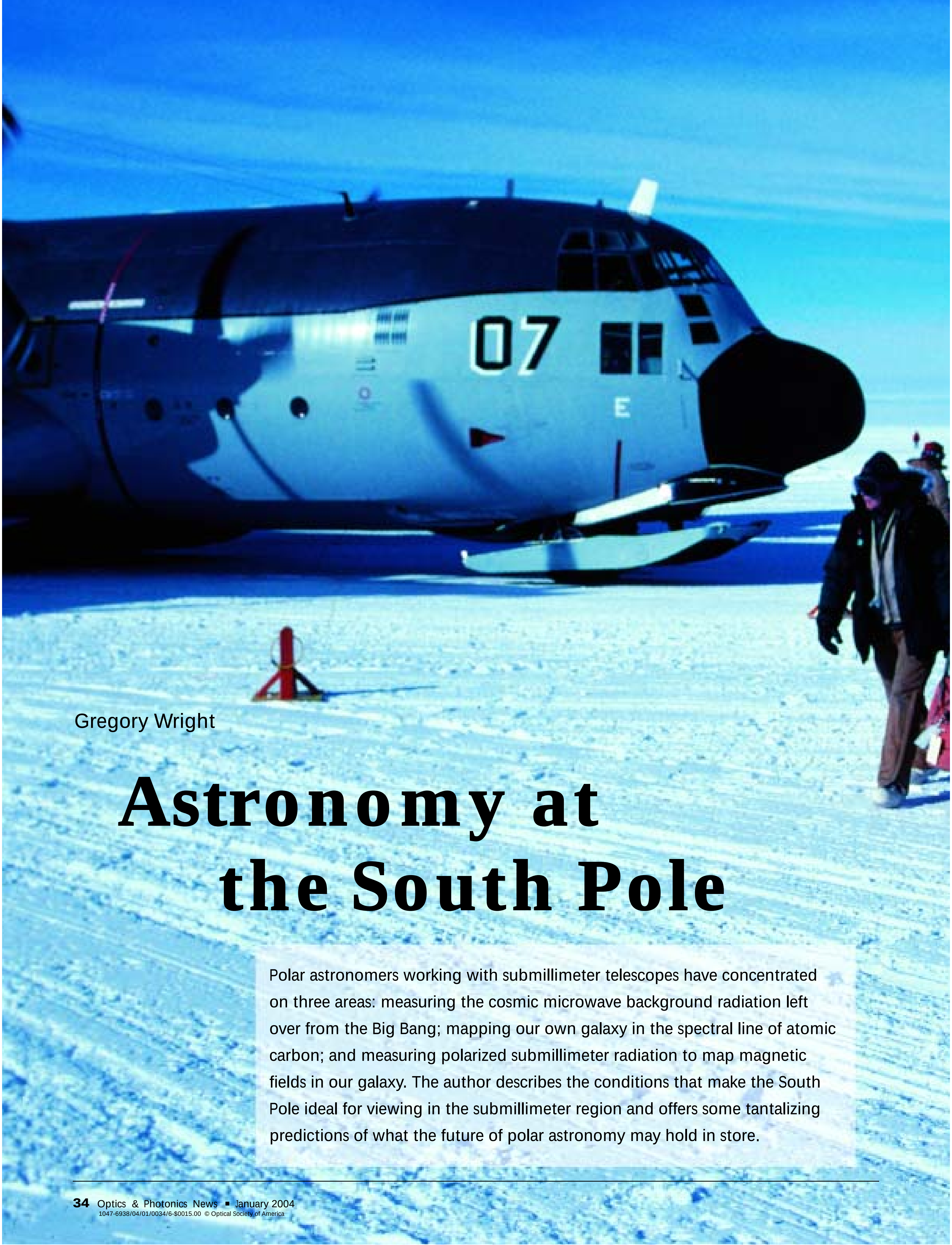

Gregory Wright

Astronomy at the South Pole

Polar astronomers working with submillimeter telescopes have concentrated on three areas: measuring the cosmic microwave background radiation left over from the Big Bang; mapping our own galaxy in the spectral line of atomic carbon; and measuring polarized submillimeter radiation to map magnetic fields in our galaxy. The author describes the conditions that make the South Pole ideal for viewing in the submillimeter region and offers some tantalizing predictions of what the future of polar astronomy may hold in store.

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For most astronomers, it's a short walk from breakfast to work at the telescope. But for the astronomers based at the Amundsen-Scott South Pole Station, where several telescopes are situated within a few hundred yards of the pole, the walk to work crosses a dozen time zones. (Sensibly, the astronomers who work at the station have decided to keep their watches set to a single time, that of the U.S. Antarctic Program's logistic base in Christchurch, New Zealand.)

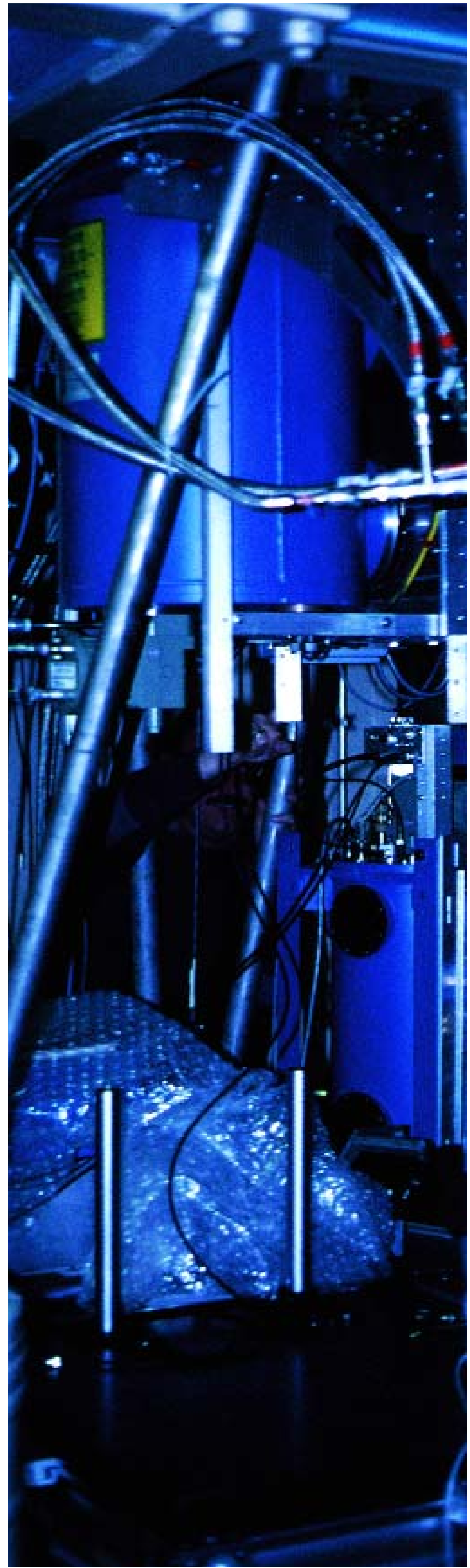
Founded in 1956 as part of the preparations for the International Geophysical Year, the South Pole station has been continuously occupied since then. The scientific work carried out there was originally limited primarily to meteorology and geophysics, but as early as 1962, Martin Pomerantz of the University of Delaware suggested that the pole might be the best site on Earth for ground based astronomy.

As it turns out, he was right: the South Pole did turn out to be the best site for some types of ground based astronomy, although not for those conducted at visible wavelengths. The polar atmosphere, because of its extreme dryness, is partially transparent to millimeter and submillimeter radiation. Near sea level, no radiation at these wavelengths reaches the ground from space. Even on the mountaintop sites that have been traditionally favored, observation at millimeter and submillimeter wavelengths is difficult. The polar plateau is one of the few places where the atmosphere is clear enough to make the use of a submillimeter telescope a scientifically rewarding endeavor.

The expansion of astronomy at the South Pole began in 1986, when a one meter aperture horn antenna was erected by Mark Dragovan and Tony Stark, then of Bell Laboratories. The antenna used

Ginny Figlar, National Science Foundation

The Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) was the first permanent observatory at the pole.

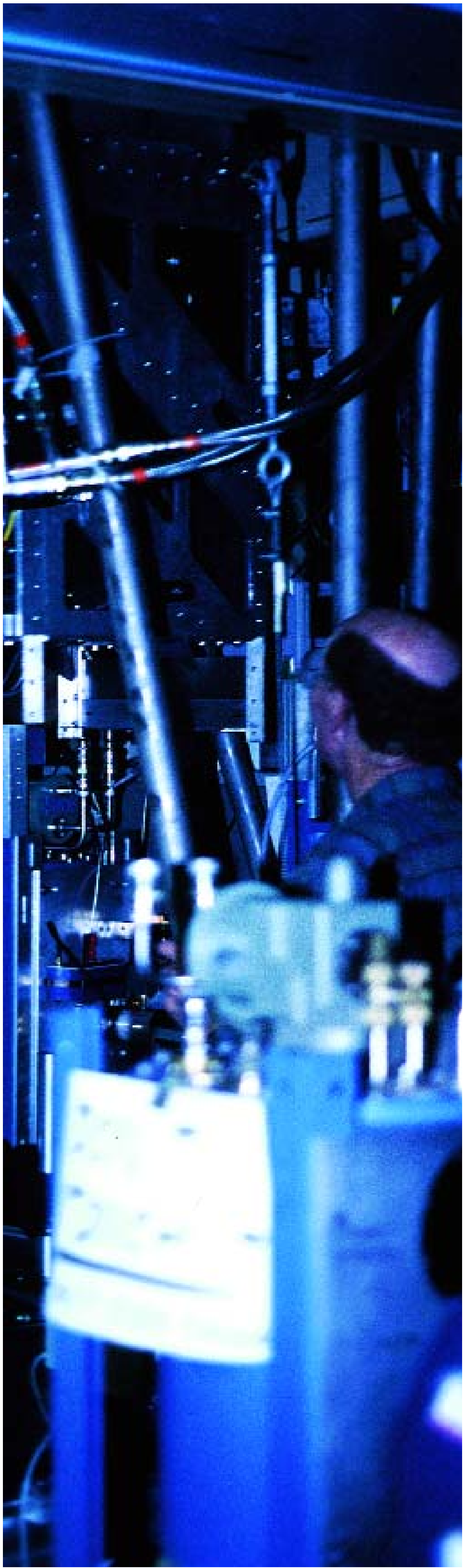


a bolometer detector to search for anisotropy of the cosmic microwave background radiation. The project was conducted only during the brief austral summer. Two years later, three groups converged on the pole for a summer campaign of microwave background measurements. While these efforts were scientifically productive, it was difficult to assemble a sizeable amount of data working exclusively in the summer. The instruments had to be assembled and taken down each year, a factor which cut down on the opportunities for data collection. And the astronomers could not take advantage of the extraordinarily good conditions predicted to occur during the six month long polar night.

These efforts produced some interesting results, but more importantly they taught astronomers interested in working at the pole two lessons. The first was that temporary, summertime-only projects could not obtain much data given the time necessary to set up and take down the instruments. The second was that a campaign of site testing should be carried out to discover how clear transmission through the polar atmosphere was and which wavelengths should be observed from the pole. The site survey effort, now more than a decade old, has produced convincing data that the pole is the best known site for submillimeter astronomy and ground based microwave background measurements.[1]

The first permanent observatory at the South Pole was proposed by Tony Stark and his collaborators in the late 1980s. The Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) was designed to operate at submillimeter wavelengths, in the presence of key spectral lines and where it was predicted that the atmosphere would be transparent enough to allow efficient observation. The AST/RO telescope sits atop the first building constructed in what is called the Dark Sector, which lies across the snow skiway used by the airplanes that deliver all necessary supplies to the pole station. The area is called the Dark Sector because it is isolated from the radio and infrared emissions of the main station. The astronomical facilities at the Dark Sector are about a mile away from the main station and about three-quarters of a mile from the geographical pole.

Three telescopes are currently running at the pole: AST/RO, now in its



Josh Landis, National Science Foundation

(*Left*) The AST/RO telescope receiver. (*Above*) The building that houses AST/RO.

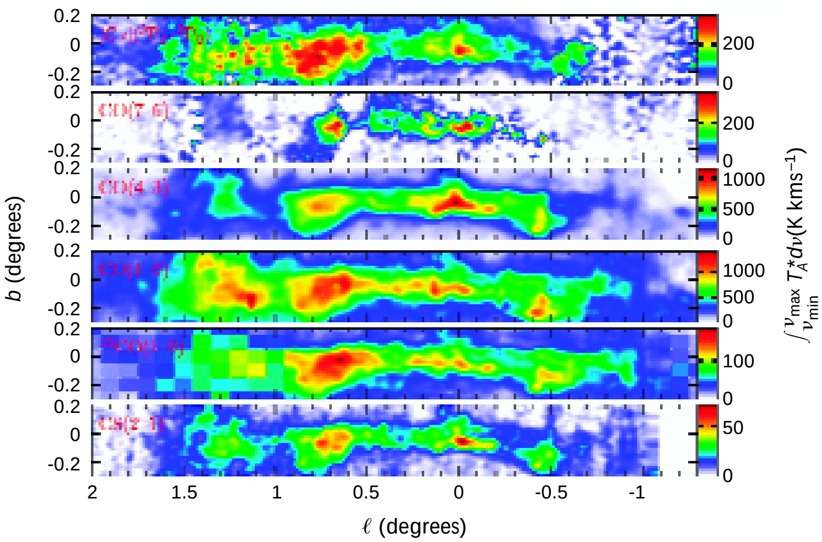
ninth year of operation; the Degree-Scale Anisotropy Instrument (DASI), a millimeter wave interferometer that measures the cosmic microwave background radiation; and Viper, a two meter millimeter wave dish used for both microwave background measurements and tracing galactic magnetic fields by looking at polarized submillimeter radiation.

What is it about the pole?

Astronomers are attracted to the pole because it is high, cold and dry. The South Pole station is located 9,300 feet above sea level atop a glacier that is two miles thick. The mean annual temperature is -56 degrees F; during the winter, the temperature drops to as low as -117 degrees F. The highest measured temperature is +7 degrees F; ice cores taken near the pole indicate that the temperature has not been above freezing for thousands of years. In addition, above the pole the lower scale height of the atmosphere results in a lower than usual barometric pressure: the average pressure is equivalent to that of a 10,500 foot elevation in the temperate latitudes; the lower pressure means that there is less obscuring atmosphere to look through. Low pressure is especially important for submillimeter observation, in which the atmospheric transparency is determined by the pressure broadened wings of the very strong 557 GHz water vapor line. The wings of this line set the atmospheric transparency at frequencies as low as 100 GHz.

Polar air is extraordinarily dry. The precipitable water vapor—the thickness of liquid water that would cover the surface if all the water vapor in the atmosphere were condensed—is only a millimeter or two during the polar summer and as little as 200 micrometers in the winter. By comparison, even in winter the precipitable water vapor over land in temperate latitudes is usually several centimeters.

Less obvious but equally if not more important is the fact that, during periods of clear weather, the polar atmosphere is stable: variations in atmospheric transparency are low. In mid-latitudes transparency changes rapidly, even on high mountaintops. This leads to “sky noise” that limits the sensitivity of observations. The stable atmospheric transparency at the pole allows long observations with concomitant high sensitivity.



Example of AST/RO observations. The upper three maps are the center of our galaxy in the spectral lines of atomic CI (492 GHz), CO (J = 7->6) (810 GHz) and CO (J = 4->3) (460 GHz). The lower three panels are the low excitation carbon monoxide and carbon monosulfide lines.

The focus of polar astronomy

Polar astronomers have concentrated on three main areas: measuring the cosmic microwave background radiation left over from the Big Bang; mapping our own galaxy in the spectral line of atomic carbon; and measuring polarized submillimeter radiation to map magnetic fields in our galaxy.

AST/RO, a 1.7-meter diameter off-axis Gregorian telescope designed to map the galaxy in the spectral lines at atomic carbon, was the first permanent observatory at the pole. Its instrumentation consists of three heterodyne receivers that use superconducting tunnel junction mixers. The receivers operate in the atmospheric windows at 230 GHz, 460 to 492 GHz and 810 GHz. The submillimeter spectral lines of atomic carbon are important because they regulate how fast gas clouds in interstellar space can cool and thus how fast these clouds can collapse to form stars. As a gas cloud contracts under its own gravity, the gas compresses and begins to heat up. Heating causes collisional excitation of carbon atoms and carbon-containing molecules, especially carbon monoxide (CO), which is very stable in interstellar space. These excited atoms and molecules radiate copiously at submillimeter wavelengths, carrying off the heat of gravitational contraction.

An example of AST/RO observations is shown above. The upper three maps are the center of our galaxy in the spectral lines of atomic CI (492 GHz), CO (J = 7->6) (810 GHz) and CO (J = 4->3) (460 GHz). The lower three panels are the low excitation carbon monoxide and carbon monosulfide lines. By tracing these species, especially atomic carbon and the highly excited carbon monoxide spectral lines, the mechanisms that generate and distribute molecular gas can be deduced. As mentioned above, atomic carbon and carbon-containing molecules play a central role in the energy balance of interstellar gas clouds and, in ways not yet fully understood, determine the distribution of stellar masses.

DASI, an interferometer with all its individual receiving elements on a common mount, measures the cosmic microwave background on angular scales of about a degree. Unlike most astronomical interferometers, it doesn't use the separation of its receiving elements to synthesize a large aperture with fine angular resolution. Instead, it uses separated elements to help decorrelate atmospheric effects. The result is that DASI can detect variations in the microwave background that are only a few parts per million of the total sky emission caused by the atmosphere.

DASI's original measurements helped confirm the simplest model of the Big Bang when it "saw" the second and third "acoustic peaks" in the spatial power spectrum of the microwave background. These peaks are caused by the random temperature and pressure variations present in the early universe as it expanded. More recently, DASI detected polarization of the microwave background. Polarization may open a new window on the physics of the early universe. These observations may, however, be confused by foreground sources that emit polarized radiation. (For example, many active galactic nuclei are sources of polarized radio emission.) Polarization is being studied by groups around the world and is a key component in the plans for a next generation instrument at the pole.

The Submillimeter Polarimeter for Antarctic Remote Observing (SPARO) is one of several instruments that have used the Viper telescope. It recently found evidence of polarized continuum emission near the center of our galaxy. The polarized emission is used to trace the magnetic fields near the massive black hole believed to be at the galaxy's core.

Why not optical astronomy?

Given that the sky over the pole is often so clear, why not use it as a base for optical astronomy? It turns out that while the antarctic atmosphere can be exceptionally transparent, the small fluctuations of the refractive index of air which cause the twinkling of stars is more pronounced at the pole than one would expect. The South Pole Infrared Explorer (SPIREX) telescope was operated at the pole in the mid-1990s, and while it did return some interesting science (especially by recording the impact of multiple fragments of the Shoemaker-Levy comet on Jupiter), it also confirmed that polar "seeing"—as astronomers call it—is not as good as one might hope.

The reason is understood to be the peculiar atmospheric conditions that reign over the polar plateau. In the equatorial latitudes, air in the lower atmosphere is warmed and rises toward the stratosphere. Over the poles, the air at high altitudes cools, sinking back toward the ground. In Antarctica, this causes the katabatic wind, which rolls downhill from the coldest parts of the plateau. (If you've been at the base of a glacier you may have felt a katabatic wind coming off it, as the air over the ice cools and flows downhill. This is the same phenomenon that occurs over the pole, albeit on a smaller scale.)

During the polar night, radiative cooling produces a strong temperature inversion near the ground. It's not uncommon for the air temperature a couple of meters above the surface to be twenty or more degrees Celsius colder than it is fifty meters up. The combination of the surface temperature inversion and the katabatic wind spoils optical seeing over the pole. The wind stirs the inversion layer, pushing bubbles of cold air higher and warm air lower. The air temperature irregularities are directly responsible for the refractive index variations that give rise to poor seeing.

It is tantalizing to note that not far above the inversion layer, the temperature is quite stable and the seeing is presumably very good. Measurements (made by micro-thermometers carried by balloons) of the small scale temperature variations show that the atmosphere is very uniform only a hundred meters above the surface. One of the best places on Earth to put an optical telescope might be within a few hundred feet (although unfortunately in an inconvenient direction!) of the pole.

There is also hope that the optical seeing might be better higher up on the polar plateau, where the katabatic wind is less intense. Measurements made from the new joint French-Italian station at Dome C, higher up on the polar plateau than the Amundsen-Scott South Pole Station, will be able to test this hypothesis.

The AST/RO telescope is situated in the Dark Sector, which is isolated from the radio and infrared emissions of the main station. An artificial penguin, positioned strategically at the base of a sign, causes visitors to the Dark Sector to do a double-take.

The future of South Pole astronomy

The AST/RO telescope, which continues to operate, will be augmented with a new hot electron bolometer mixer receiver (and associated far infrared laser local oscillator) that will work at frequencies as high as 1,400 GHz. The receiver, built by researchers at the University of Massachusetts campuses in Amherst and Lowell, may result in the highest frequency radio observation possible from the ground. The terahertz region is barely accessible at the best sites; at higher frequencies, the atmosphere is opaque until one reaches the infrared in the 10-μm region. DASI continues to map the polarization of the cosmic microwave background to help us better understand the conditions in the universe about 500,000 years after the Big Bang.

The South Pole Submillimeter Telescope (SPST), now under design, will carry polar astronomy into the next generation. It will be an 8–10-meter class instrument that accommodates bolometer receivers with many thousands of detector elements. The telescope optics are optimized for a wide field of view, with up to 30,000 usable beams at a 200-μm wavelength.

The goals of SPST are to continue to map microwave background radiation and to explore the era of galaxy formation. As the galaxies formed, copious amounts of gas and dust were produced and warmed by the first generation of stars. The far infrared radiation from these galaxies has now been red-shifted by the universe's expansion into the submillimeter and millimeter wave bands. The 158-μm spectral line of singly ionized carbon may be the brightest point in the spectrum of a galaxy, making it a cosmic signpost that marks the epoch of galaxy formation. SPST will have the sensitivity and resolution required to discover many young galaxies, and thus to illuminate one of the least understood eras in the history of the universe.

With all this going on, astronomy at the South Pole has a bright—if chilly— future.

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Reference

1. J. J. Peterson, S.J.E. Radford, P.A.R. Ade, R.A. Chamberlin, M.J. O'Kelly, K.M. Peterson and E. Schartman, Stability of the Submillimeter Brightness of the Atmosphere Above Mauna Kea, Chanjnantor and the South Pole, Publications of the Astronomical Society of the Pacific, 115, 383-8 (March 2003).

Note: The official South Pole Web site, www.spole.gov, has been unavailable for much of 2003 because of malicious network activity. However one can find a wealth of unofficial information, both contemporary and historical, at www.southpolestation.com. The latter site is not affiliated with the National Science Foundation or its contractors.