Cosmology from Antarctica

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ABSTRACT. We are in a golden age of observational cosmology, where measurements of the universe have progressed from crude estimates to precise knowledge. Many of these observations are made from the Antarctic, where conditions are particularly favorable. When we use telescopes to look out at the distant universe, we are also looking back in time because the speed of light is finite. Looking out 13.7 billion years, the cosmic microwave background (CMB) comes from a time shortly after the big bang. The first attempt at CMB observations from the Antarctic plateau was an expedition to the South Pole in December 1986 by the Radio Physics Research group at Bell Laboratories. The measured sky noise and opacity were highly encouraging. In the austral summer of 1988–1989, three CMB groups participated in the "Cucumber" campaign, where a temporary summer-only site dedicated to CMB anisotropy measurements was set up 2 km from South Pole Station. Winter observations became possible with the establishment in 1990 of the Center for Astrophysical Research in Antarctica (CARA), a U.S. National Science Foundation Science and Technology Center, which developed year-round observing facilities in the "Dark Sector," a section of Amundsen-Scott South Pole Station dedicated to astronomical observations. Scientists at CARA fielded several astronomical instruments: Antarctic Submillimeter Telescope and Remote Observatory (AST/RO), South Pole Infrared Explorer (SPIREX), White Dish, Python, Viper, Arcminute Cosmology Bolometer Array Receiver (ACBAR), and Degree-Angular Scale Interferometer (DASI). By 2001, data from CARA, together with Balloon Observations of Millimetric Extragalactic Radiation and Geophysics (BOOMERANG), a CMB experiment on a long-duration balloon launched from McMurdo Station on the coast of Antarctica, showed clear evidence that the overall geometry of the universe is flat, as opposed to being open or closed. This indicates that the total energy content of the universe is near zero, so that the energy needed to originate the material of the universe is balanced by negative gravitational energy. In 2002, the DASI group reported the detection of polarization in the CMB. These observations strongly support a "concordance model" of cosmology, where the dynamics of a flat universe are dominated by forces exerted by the mysterious dark energy and dark matter. The CMB observations continue on the Antarctic plateau. The South Pole Telescope (SPT) is a 10-m-diameter offset telescope that is beginning to measure anisotropies on scales much smaller than 1°, as well as discovering new protogalaxies and clusters of galaxies. Plans are in progress to measure CMB polarization in detail, observations that will yield insights to phenomena in the first second of time.

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INTRODUCTION

Observations of the deep universe have driven the development of Antarctic astronomy. The speed of light is finite, so as we look out in distance, we are also looking back in time. We see the Sun as it was 8 minutes ago, we see the Andromeda galaxy as it was 2.5 million years ago, and we see the most distant galaxies as they were billions of years ago. The farthest we can see is 13.7 billion light years distant, to a time that was only 350,000 years after the big bang, the "surface of last scattering." Before that time, the universe was opaque because photons could travel only a short distance before encountering a free electron. But at that time, the universe had just cooled enough that electrons could be captured into atoms. Space became transparent as a result of the disappearance of free electrons. Most of the photons released have travelled unimpeded to the present day; this is the cosmic microwave background (CMB) radiation (Penzias and Wilson, 1965). At present, the wavelength of the CMB radiation is a factor of 1,000 longer than it was when it was emitted, as a result of the universal expansion. Those wavelengths now lie in the millimeter-wave band, wavelengths that interact with water vapor in the Earth's atmosphere, subtracting signal and adding noise. In order to get the best possible view of the early universe, we need to go to into space or to sites like the Antarctic plateau that have very little water vapor.

This is an account of the history of Antarctic astronomy, the decades-long effort by many people within the Antarctic program to study the CMB from the South Pole. One result of these observations is the solution to one of the great metaphysical problems: the origin of matter. Other results include definitive confirmations of big bang cosmology and insights into the formation of the first galaxies. Still to come in the decades ahead may be insights to major unsolved problems in modern physics.

OBSERVATIONS OF THE COSMIC MICROWAVE BACKGROUND

Cosmology has become a precise observational science in past two decades. Cosmologists describe the universe by a model with roughly a dozen parameters, for example, the Hubble constant, H_0, and the density parameter, Ω. These constants describe and determine the mathematical model of the universe used in cosmology. A decade ago, typical errors on these parameters were 30% or greater; now, most are known within 10%. We can honestly discriminate for and against cosmological hypotheses on the basis of quantitative data. The current concordance model, Lambda–Cold Dark Matter (Ostriker and Steinhardt, 1995), is both highly detailed and consistent with observations. Many of those observations have come from the Antarctic.

The CMB radiation is highly isotropic, meaning that it is almost the same from all directions on the sky. From the first, it was understood that deviations from perfect isotropy would advance our understanding of cosmology (Peebles and Yu, 1970; Harrison, 1970): small deviations from smoothness in the early universe are the seeds from which subsequent structure grows, and these small irregularities in the surface of last scattering appear as small differences, or anisotropies, in the brightness of the CMB in different directions on the sky. Anisotropies in the CMB radiation indicate slight variations in density and temperature that eventually evolve into stars, galaxies, and clusters of galaxies. The physical size of the irregularities in the surface of last scattering can be calculated from the cosmological models, and these predictions can be compared to observations, as we shall see below.

Observations at progressively higher sensitivity by many groups of scientists from the 1970s through the 1990s failed to detect the anisotropy (cf. the review by Lasenby et al., 1999). In the course of these experiments, better observing techniques were developed, detector sensitivities were improved by orders of magnitude, and the effects of atmospheric noise became better understood. The techniques and detectors were so improved that the sensitivity of experiments came to be dominated by atmospheric noise at most observatory sites. Researchers moved their instruments to orbit, to balloons, and to high, dry observatory sites in the Andes and Antarctica. Eventually, CMB anisotropies were detected by the Cosmic Background Explorer satellite (COBE; Fixsen et al., 1996). Ground-based experiments at remote sites also met with success.

After the detection of CMB anisotropy, the next step was to measure its power spectrum. Individual spots on the sky that are slightly brighter or slightly dimmer in the CMB are not of significance in themselves. What matters are the statistics about the angular size and intensity of the anisotropies over large swaths of sky. The power spectrum, which is brightness as a function of spatial frequency, captures this information. The power spectrum was measured by a series of ground-based and balloon-borne experiments, many of them located in the Antarctic. The data were then vastly improved upon by the Wilkinson Microwave Anisotropy Probe (WMAP; Spergel et al.,

2003) and the South Pole Telescope. The Planck satellite mission (Tauber, 2005), launched in May 2009, will provide high signal-to-noise data on CMB anisotropy and polarization that will reduce the error on some cosmological parameters to the level of 1%.

DEVELOPMENT OF ASTRONOMY IN THE ANTARCTIC

The principal source of atmospheric noise in radio observations is water vapor. Because it is exceptionally cold, the climate at the South Pole implies exceptionally dry observing conditions. As air becomes colder, the amount of water vapor it can hold is dramatically reduced. At 0°C, the freezing point of water, air can hold 83 times more water vapor than saturated air at the South Pole's average annual temperature of –49°C (Goff and Gratch, 1946). Together with the relatively high altitude of the pole (2,850 m), this means the water vapor content of the atmosphere above the South Pole is two or three orders of magnitude smaller than it is at most places on the Earth's surface. This has long been known (Smythe and Jackson, 1977), but many years of hard work were needed to realize the potential in the form of new astronomical knowledge (cf. the review by Indermuehle et al., 2006).

A French experiment, Emission Millimetrique (EMILIE; Pajot et al., 1989), made the first astronomical observations of submillimeter waves from the South Pole during the austral summer of 1984–1985. It was a ground-based single-pixel bolometer dewar operating at $\lambda 900\mu$m and fed by a 45 cm off-axis mirror and it had successfully measured the diffuse galactic emission while operating on Mauna Kea in Hawaii in 1982, but the accuracy of that result had been limited by sky noise (Pajot et al., 1986). Martin A. Pomerantz, a cosmic ray researcher at Bartol Research Institute, encouraged the EMILIE group to relocate their experiment to the South Pole (Lynch, 1998). There they found better observing conditions and were able to make improved measurements of galactic emission.

Pomerantz also enabled Mark Dragovan, then a researcher at Bell Laboratories, to attempt CMB anisotropy measurements from the pole. Dragovan et al. (1990) built a lightweight 1.2-m-diameter offset telescope and were able to get it working at the pole with a single-pixel helium-4 bolometer during several weeks in January 1987 (Figure 1). No CMB anisotropies were seen, but the atmospheric calibration results were sufficiently encouraging that several CMB groups (Dragovan et al., 1989; Gaier et al., 1989; Meinhold et al., 1989; Peterson, 1989) participated in the "Cucumber" campaign in the austral summer of 1988–1989. Three Jamesway tents and a generator were set up at a temporary site dedicated to CMB anisotropy 2 km from South Pole Station in the direction of the international date line. These were summer-only campaigns, where instruments were shipped in, assembled, tested, used, disassembled, and shipped out in a single three-month-long summer season. Considerable time and effort were expended in establishing and then demolishing observatory facilities, with little return in observing time. What little observing time was available occurred during the warmest and wettest days of midsummer.

Permanent, year-round facilities were needed. The Antarctic Submillimeter Telescope and Remote Observatory (AST/RO; Stark et al., 1997, 2001) was a 1.7-m-diameter offset Gregorian telescope mounted on a dedicated, permanent observatory building. It was the first radio telescope to operate year-round at South Pole. The AST/RO was started in 1989 as an independent project, but in 1991 it became part of a newly founded National Science Foundation Science and Technology Center, the Center for Astrophysical Research in Antarctica (CARA, http://astro.uchicago.edu/cara; cf. Novak and Landsberg, 1998). The CARA fielded several telescopes: White Dish (Tucker et al., 1993), Python (Dragovan et al., 1994; Alvarez, 1995; Ruhl et al., 1995; Platt et al., 1997; Coble et al., 1999), Viper (Peterson et al., 2000), the Degree-Angular Scale Interferometer (DASI; Leitch et al., 2002a), and the South Pole Infrared Explorer (SPIREX; Nguyen et al., 1996), a 60 cm telescope operating primarily in the near-infrared K band. These facilities were housed in the "Dark Sector," a grouping of buildings that includes the AST/RO building, the Martin A. Pomerantz Observatory building (MAPO) and a new "Dark Sector Laboratory" (DSL), all located 1 km away from the main base across the aircraft runway in a radio quiet zone at a longitude of approximately 90°W.

The combination of White Dish, Python, and UCSB South Pole 1994 (Ganga et al., 1997) data gave the first indication, by 1997, that the spectrum of spatial anisotropy in the CMB was consistent with a flat cosmology. Figure 2 shows the state of CMB anisotropy measurements in May 1999. The early South Pole experiments, shown in green, clearly delineate a peak in CMB anisotropy at a scale $\ell = 200$, or 1°, consistent with a flat universe ($\Omega_0 = 1$). Shortly thereafter, the Balloon Observation of Millimetric Extragalactic Radiation and Geophysics (BOOMERANG)-98 long-duration balloon experiment (de Bernardis et al., 2000; Masi et al., 2006, 2007; Piacentini et al., 2007) and the first year of DASI (Leitch et

FIGURE 1. Mark Dragovan, Robert Pernic, Martin Pomerantz, Robert Pfeiffer, and Tony Stark, with the AT&T Bell Laboratories 1.2 m horn antenna at the South Pole in January 1987. This was the first attempt at a CMB measurement from the South Pole.

al., 2002b) provided significantly higher signal-to-noise data, yielding $\Omega_0 = 1$ with errors less than 5%. This was a stunning achievement, definitive observations of a flat universe balanced between open and closed Friedmann solutions. In its second year, a modified DASI made the first measurement of polarization in the CMB (Leitch et al., 2002c; Kovac et al., 2002). The observed relationship between polarization and anisotropy amplitude provided a detailed confirmation of the acoustic oscillation model of CMB anisotropy (Hu and White, 1997) and strong support for the standard model. The demonstration that the geometry of the universe is flat is a major scientific result from the Antarctic.

SITE TESTING

One of the primary tasks for the CARA collaboration was the characterization of the South Pole as an observatory site (Lane, 1998). It proved unique among observatory sites for unusually low wind speeds, the complete absence of rain, and the consistent clarity of the submillimeter sky. Schwerdtfeger (1984) and Warren (1996) have comprehensively reviewed the climate of the Antarctic plateau and the records of the South Pole meteorology office. Chamberlin (2001) analyzed weather data to determine the precipitable water vapor (PWV), a measure of total water vapor content in a vertical column through the atmosphere. He found median wintertime PWV values of 0.3 mm over a 37-year period, with little annual variation. The PWV values at the South Pole are small, stable, and well understood.

Submillimeter-wave atmospheric opacity at South Pole has been measured using skydip techniques. Chamberlin et al. (1997) made over 1,100 skydip observations at 492 GHz ($\lambda 609 \mu$m) with AST/RO during the 1995 observing season. Even though this frequency is near a strong oxygen line, the opacity was below 0.70 half of the time

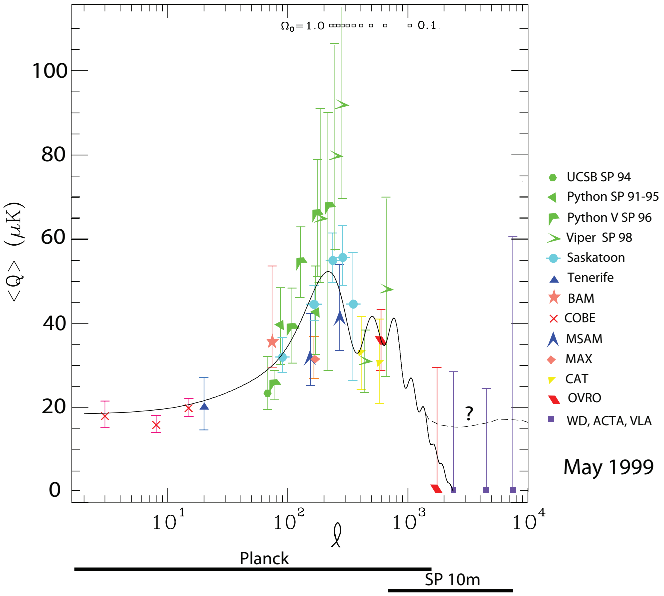

FIGURE 2. Microwave background anisotropy measurements as of May 1999. This was prior to the launch of BOOMERANG, the deployment of DASI, and the launch of WMAP, all of which significantly improved the data. South Pole experimental results are shown in green. Note that the peak at $\ell = 200$ is clearly defined, indicating a flat universe ($\Omega_0 = 1$). Abbreviations are as follows: UCSB SP 94 = a campaign at the South Pole in 1994 by the University of California, Santa Barbara, sponsored by NSF; BAM = Balloon-borne Anisotropy Measurement; COBE = Cosmic Background Explorer; MSAM = Medium-Scale Anisotropy Measurement experiment; MAX = Millimeter Anisotropy Experiment; CAT = Cosmic Anisotropy Telescope; OVRO = Owens Valley Radio Observatory; WD = White Dish; ACTA = Australia Telescope Compact Array; VLA = Very Large Array.

during the austral winter and reached values as low as 0.34, better than ever measured at any other ground-based site. From early 1998, the $\lambda 350 \mu m$ band has been continuously monitored at Mauna Kea, Chajnantor, and the South Pole by identical tipper instruments developed by S. Radford of the National Radio Astronomy Observatory and J. Peterson of Carnegie-Mellon University and CARA. The 350 μm opacity at the South Pole is consistently better than at Mauna Kea or Chajnantor.

Sky noise is caused by fluctuations in total power or phase of a detector caused by variations in atmospheric emissivity and path length on timescales of order 1 s. Sky noise causes systematic errors in the measurement of astronomical sources. This is especially important at the millimeter wavelengths for observations of the CMB: at millimeter wavelengths, the opacity of the atmosphere is at most a few percent, and the contribution to the receiver noise is at most a few tens of degrees, but sky noise may still set limits on observational sensitivity. Lay and Halverson (2000) show analytically how sky noise causes observational techniques to fail: fluctuations in a component of the data due to sky noise integrate down more slowly than $t^{-1/2}$ and will come to dominate the error during long observations. Sky noise at the South Pole is considerably smaller than at other sites, even comparing conditions of the same opacity. The PWV at the South Pole is often so low that the opacity is dominated by the dry air component (Chamberlin and Bally, 1995; Chamberlin, 2001); the dry air emissivity and phase error do not vary as strongly or rapidly as the emissivity and phase error due to water vapor. Lay and Halverson (2000) compared the Python experiment at the South Pole (Dragovan et al., 1994; Alvarez, 1995; Ruhl et al., 1995; Platt et al., 1997; Coble et al., 1999) with the Site Testing Interferometer at Chajnantor (Holdaway et al., 1995; Radford et al., 1996) and found that the amplitude of the sky noise at the South Pole is 10 to 50 times less than that at Chajnantor (Bussmann et al., 2004).

The best observing conditions occur only at high elevation angles, and at the South Pole this means that only the southernmost third of the celestial sphere is accessible with the South Pole's uniquely low sky noise, but this portion of sky includes millions of galaxies and cosmological sources, the Magellanic Clouds, and most of the fourth quadrant of the galaxy. The strength of the South Pole as a millimeter and submillimeter site lies in the low sky noise levels routinely obtainable for sources around the south celestial pole.

LOGISTICS

South Pole Station provides logistical support for astronomical experiments: room and board for on-site scientific staff, electrical power, network and telephone connections, heavy equipment support, and cargo and personnel transport. The station power plant provides about 200 kW of power to astronomical projects out of a total generating capacity of about 1200 kW. Heavy equipment at South Pole Station includes cranes, forklifts, and bulldozers; these can be requisitioned for scientific use as needed. The station is supplied by over 200 flights each year of LC-130 ski-equipped cargo aircraft. Annual cargo capacity is about 3,500 tons. Aircraft flights are scheduled only during the period from late October to early February, so the station is inaccessible nine months of the year. All engineering operations for equipment installation and maintenance are tied to the annual cycle of physical access to the instruments. For quick repairs and upgrades during the austral summer season, it is possible to send equipment between the South Pole and anywhere serviced by commercial express delivery in about five days. During the winter, however, no transport is possible, and projects must be designed and managed accordingly.

In summer, there are about 20 astronomers at the pole at any given time. Each person stays at the pole for a few weeks or months in order to carry out their planned tasks as well as circumstances allow; then they depart, to be replaced by another astronomer. Each year there are four or five winter-over astronomers who remain at the South Pole for a year.

Experiments at the pole use about 20 L of liquid helium per day. Helium also escapes from the station in one or two weather balloons launched each day. The National Science Foundation and its support contractors must supply helium to the South Pole, and the most efficient way to transport and supply helium is in liquid form. Before the winter-over period, one or more (4,000–12,000 L) storage dewars are brought to the South Pole for winter use. The supply of liquid helium has been a chronic problem for South Pole astronomy, but improved facilities in the new South Pole Station eliminate single points of failure and provide a more-certain supply.

Internet and telephone service to the South Pole is provided by a combination of two low-bandwidth satellites, LES-9 and GOES-3, and the high-bandwidth (3 Mbps) NASA Tracking and Data Relay Satellite System TDRS-F1. These satellites are geosynchronous but not geostationary since their orbits are inclined. Geostationary satellites are always below the horizon and cannot be used. Internet service is intermittent through each 24-hour period because each satellite is visible only during the southernmost part of its orbit; the combination of the three satellites provides an Internet connection for approximately 12 hours within the period 1 to16 hours Greenwich local sidereal time. The TDRS link helps provide a store-and-forward automatic transfer service for large computer files. The total data communications capability is about 100 gigabytes per day.

TELESCOPES AND INSTRUMENTS AT THE SOUTH POLE

The Antarctic Submillimeter Telescope and Remote Observatory (AST/RO) was the first radio telescope to be operated year-round on the Antarctic plateau. It was designed as a demonstration of feasibility and a prototype for the telescopes to follow. It was a general-purpose 1.7-m-diameter Gregorian (Stark et al., 1997, 2001) for astronomy and aeronomy studies at wavelengths between 200 and 2000 μm. The AST/RO was located in the Dark Sector in a dedicated building and was operational from 1995 through 2005. It was used primarily for spectroscopic studies of neutral atomic carbon and carbon monoxide in the interstellar medium of the Milky Way and the Magellanic Clouds. Six heterodyne receivers and a bolometer array were used on AST/RO: (1) a 230 GHz receiver (Kooi et al., 1992), (2) a 450–495 GHz quasi-optical receiver (Zmuidzinas and LeDuc, 1992; Engargiola et al., 1994), (3) a 450–495 GHz waveguide receiver (Walker et al., 1992; Kooi et al., 1995), which could be used simultaneously with (4) a 800–820 GHz fixed-tuned superconductor-insulator-superconductor (SIS) waveguide mixer receiver (Honingh et al., 1997), (5) the PoleSTAR array, which deployed four 810 GHz fixed-tuned SIS waveguide mixer receivers (Groppi et al., 2000; Walker et al., 2001), (6) Terahertz Receiver with NbN HEB Device (TREND), a 1.5 THz heterodyne receiver (Gerecht et al., 1999; Yngvesson et al., 2001), and (7) the South Pole Imaging Fabry-Perot Interferometer (SPIFI; Swain et al., 1998). There were four acousto-optical spectrometers (AOS; Schieder et al., 1989): two low-resolution spectrometers with a bandwidth of 1 GHz, an array AOS having four low-resolution spectrometer channels with a bandwidth of 1 GHz for the PoleSTAR array, and one high-resolution AOS with 60 MHz bandwidth. The AST/RO produced data for over a hundred scientific papers relating to star formation and the dynamics of cold interstellar gas in the Milky Way and the Magellanic Clouds. Among the more significant are a submillimeter-wave spectral line survey of the galactic center region (Martin et al., 2004) that showed the episodic nature of starburst and black hole activity in the center of our galaxy (Stark et al., 2004).

Viper was a 2.1 m off-axis telescope designed to allow measurements of low-contrast millimeter-wave sources. It was mounted on a tower at the opposite end of the MAPO from DASI. Viper was used with a variety of instruments: Dos Equis, a CMB polarization receiver operating at 7 mm; Submillimeter Polarimeter for Antarctic Remote Observing (SPARO), a bolometric array polarimeter operating at λ450 μm; and the Arcminute Cosmology Bolometer Array Receiver (ACBAR), a multiwavelength bolometer array used to map the CMB. The ACBAR is a 16-element bolometer array operating at 300 mK. It was designed specifically for observations of CMB anisotropy and the Sunyaev-Zel'dovich effect (SZE). It was installed on the Viper telescope early in 2001, and was successfully operated until 2005. The ACBAR has made high-quality maps of SZE in several nearby clusters of galaxies and has made significant measurements of anisotropy on the scale of degrees to arcminutes (Runyan et al., 2003; Reichardt et al., 2009).

The SPARO was a nine-pixel polarimetric imager operating at $\lambda 450\mu$m. It was operational on the Viper telescope during the early austral winter of 2000. Novak et al. (2000) mapped the polarization of a region of the sky (~0.25 square degrees) centered approximately on the galactic center. Their results imply that within the galactic center molecular gas complex, the toroidal component of the magnetic field is dominant. The data show that all of the existing observations of large-scale magnetic fields in the galactic center are basically consistent with the “magnetic outflow” model of Uchida et al. (1985). This magnetodynamic model was developed in order to explain the galactic center radio lobe, a limb-brightened radio structure that extends up to 1° above the plane and may represent a gas outflow from the galactic center.

The DASI (Leitch et al., 2002a) was a compact centimeter-wave interferometer designed to image the CMB primary anisotropy and measure its angular power spectrum and polarization at angular scales ranging from 2° to several arcminutes. As an interferometer, DASI measured CMB power by simultaneous differencing on several scales, measuring the CMB power spectrum directly. The DASI was installed on a tower adjacent to the MAPO during the 1999–2000 austral summer and had four successful winter seasons. In its first season, DASI made measurements of CMB anisotropy that confirmed with high accuracy the “concordance” cosmological model, which has a flat geometry and significant contributions to the total stress energy from dark matter and dark energy (Halverson et al., 2002; Pryke et al., 2002). In its second year, DASI made the first measurements of “E-mode” polarization of the CMB (Leitch et al., 2002c; Kovac et al., 2002).

Q and U Extra-Galactic Sub-mm Telescope (QUEST) at DASI (QUaD; Church et al. 2003) is a CMB polarization experiment that placed a highly symmetric antenna feeding a bolometer array on the former DASI mount at MAPO, becoming operational in 2005. It is capable of measuring amplitude and polarization of the CMB on angular scales as small as 0.07°. The QUaD has sufficient sensitivity to detect the conversion of E-mode CMB polarization to B-mode polarization caused by gravitational lensing in concentrations of dark matter.

BICEP2/SPUD (Keating et al., 2003; Yoon et al., 2006; Nguyen et al., 2008) is a millimeter-wave receiver designed to measure polarization and amplitude of the CMB over a 20° field of view with 1° resolution. It is mounted on the roof of the Dark Sector Laboratory and has been operational since early 2006. The design of BICEP2 is optimized to eliminate systematic background effects and thereby achieve sufficient polarization sensitivity to detect the component of CMB polarization caused by primordial gravitational waves. These measurements test the hypothesis of inflation during the first fraction of a second after the big bang.

The South Pole Telescope (SPT) is a 10-m-diameter off-axis telescope that was installed during the 2006–2007 season (Ruhl et al., 2004; Carlstrom et al., in press). It is equipped with a large field of view (Stark, 2000) that feeds a state-of-the-art 960-element bolometer array receiver. The initial science goal is a large SZE survey covering 4,000 square degrees at 1.3¢ resolution with 10 μK sensitivity at a wavelength of 2 mm. This survey will find all clusters of galaxies more massive than 3.5×10^{14} $M_\odot$ regardless of redshift. It is expected that an unbiased sample of approximately 3,000 clusters will be found, with over 700 at redshifts greater than 1. The sample will provide sufficient statistics to use the density of clusters to determine the equation of state of the dark energy component of the universe as a function of time. The SPT has made a first detection of galaxy clusters using the SZE (Staniszewski et al., 2009) and a first measurement of arcminute-scale CMB anisotropy (Lueker et al., 2010). The SPT has also discovered new class of galaxies that are unusually bright at millimeter wavelengths (Vieira et al., 2010).

THE ORIGIN OF MATTER IN A FLAT UNIVERSE

The discovery by Antarctic telescopes that the universe has a flat geometry was the final step in solving one of the great problems in metaphysics: the origin of matter. The Friedmann metric is the solution to the Einstein field equations that describes the big bang. The Einstein equations describe gravity as a non-Euclidean geometry, where space is a manifold with an intrinsic curvature, so that the sum of the angles of a triangle between three points in space-time do not necessarily add up to 180°. The force of gravity on a freely falling body is manifested in a trajectory that follows a geodesic curve in a curved space. In the Friedmann solution, all of space is uniformly filled with material, whose density changes as the universe expands and evolves. (The Friedmann metric is fundamentally different from the Schwarzschild metric that describes black holes: the Schwarzschild metric describes a static space that is a vacuum everywhere except at a single singular point where all the mass is concentrated.) Three different spatial geometries are possible in Friedmann models: closed, flat, and open.

The closed geometry is, at any given instant in time, a three-dimensional hypersphere. That means that if you instantly draw a straight line in any direction, it will circle around the hypersphere and come back at you from the opposite direction. The sum of the angles of a triangle are more than 180° (bigger triangles more than little ones), and the circumference of a circle is less than 2π times the radius (bigger circles to a greater extent than little ones). The volume of the hypersphere is finite at all times, and so the universe is finite at all times. A Friedmann model that is finite in space must also be finite in time: the hypersphere starts small, expands to a finite maximum extent, and then shrinks back to zero size after a finite lifetime.

The open geometry is, at any given instant, an infinite three-dimensional hyperboloid. That means that given a line and a plane in that space, there exists more than one other plane (in fact, an infinite number) that pass through that point but nowhere intersect the first plane. The sum of the angles of a triangle is less than 180°, and the circumference of a circle is more than 2π times the radius. The volume of the hyperboloid is infinite at all times, and so the universe is infinite at all times, except at the singular instant of the big bang. A Friedmann model that is infinite in space must also be future-eternal: the hyperboloid expands forever.

The flat geometry is, at any given instant, an infinite three-dimensional Euclidean space that follows Euclidean rules for geometric entities. With time, however, the entire space expands or contracts homogeneously, perhaps at a variable rate. It is an intermediate case between closed and open and can be thought of as a closed geometry with an extremely large radius of curvature or an open geometry with an extremely flat hyperboloid. The flat Friedmann model just barely expands forever, which means that it recollapses only after an infinite time has gone by.

The difference in the geometry of triangles in the three cases provides an observational test that is sensitive to the geometry. The physical size of the anisotropies on the surface of last scattering can be calculated. The angular size that they appear to us depends on the geometry since the angles of the 13.7 billion light-year-long triangle between us and the two sides of a feature are distorted by the geometry. Figure 3 shows actual BOOMERANG data, in comparison to computer simulations of the appearance of CMB anisotropies in the three cases. The geometry of our universe is very nearly flat.

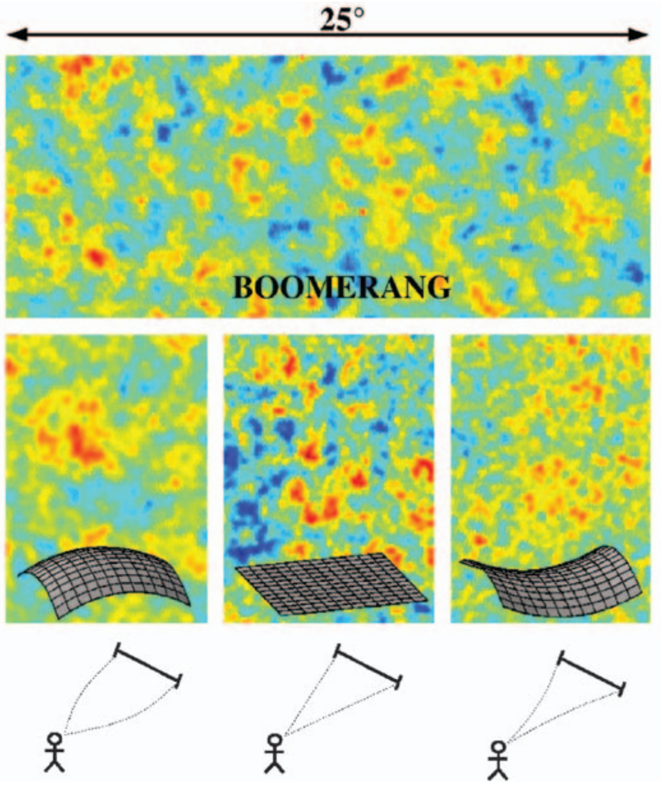

FIGURE 3. Data from the BOOMERANG experiment, showing a picture of CMB anisotropies in an actual map of the sky in the top panel. The middle three panels show computer simulations of the expected anisotropies in three cases: (left) a closed universe, (middle) a flat universe, and (right) an open universe. The drawings at the bottom illustrate how features on the surface of last scattering would appear to have different angular sizes, depending on the effect of geometry on the photon paths. The flat model clearly fits the data best.

This result is highly significant because the energy content of the universe is different in the different geometries. As Einstein showed, energy and matter can be converted, one into the other. All the material of the universe has positive energy. The gravitational field, however, has negative energy. Consider, for example, a weight attached to a rope that has been hauled up to the ceiling. The weight plus the Earth has a particular gravitational field strength. If we lower the weight to the floor, we find that the gravitational field has increased. But in the process of lowering the weight, we can extract energy, for example, by attaching the rope to run a pulley on an electrical generator. By increasing the gravitational field, we can extract energy: the gravitational field must therefore have negative energy. Landau and Lifshitz (1962) show that in the closed and flat cases, the gravitational energy of the universe as a whole exactly balances the positive energy of all the material, so that the total energy content of the universe is zero. This is not true in the open universe case, where the positive energy of the matter exceeds the negative energy of the gravitational field. At the start of our universe, no material and no energy were needed; matter is created by the separation of positive and negative energies.

CONCLUSIONS

Even in the era of CMB satellites, ground-based CMB observations are still essential for reasons of fundamental physics. The CMB radiation occurs only at wavelengths longer than 1 mm. The resolution of a telescope (in radians) is equal to the observed wavelength divided by the telescope diameter. To work properly, the overall accuracy of the telescope optics must be a small fraction of a wavelength. Observing the CMB at resolutions of a minute of arc or smaller therefore requires a telescope like the SPT that is 10 m in diameter or even larger, with an overall accuracy of 0.1 mm or better. There are no prospects for an orbital or airborne telescope of this size and accuracy in the foreseeable future. There is, however, important science to be done at high resolution, work that can only be done with a large ground-based telescope at the best possible ground-based sites.

Observations from the Antarctic have brought remarkable advances in cosmology. Antarctic observations have definitively demonstrated that the geometry of the universe is flat. These observations were made possible by excellent logistical support offered for the pursuit of science at the Antarctic bases. Cold climate and lack of water vapor provide atmospheric conditions that for some purposes is nearly as good as space, but at greatly reduced cost. Antarctica provides a platform for innovative, small instruments operated by small groups of scientists as well as telescopes that are too large to be lifted into orbit. In future, Antarctica will continue to be an important site for observational cosmology.

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