

A white paper on the technological challenges and logistical needs of the Antarctic astronomy and astrophysics community

Input to the *“Practical Guide to Enabling the 20-Year Antarctic Science Roadmap”*.

Introduction to the science and the instrumentation

In developing this paper we began with the key astrophysical questions identified in the Horizon Scan:

Question 69: What happened in the first second after the Universe began?

Question 70: What is the nature of the dark Universe and how is it affecting us?

- and also, because as it is clearly related to the search for life on other planets,

Question 47: How do subglacial systems inform models for the development of life on Earth and elsewhere?

From there, hypothetical instruments and experiments were conceived that would be capable of answering these questions. The technological challenges that currently stand in the way of such instrumentation were identified, and these are listed below. Similarly, the necessary logistical arrangements to deploy and operate the instrumentation were defined, and these are also presented below.

What happened in the first second after the Universe began?

While we understand much of what happened in the early evolution of the Universe (after about the first 10^{-43} seconds) there are many fundamental questions that remain, including some seemingly irreconcilable paradoxes. It was in this first second that the initial constituents and the structure of the Universe were determined, and this information was imprinted onto the Cosmic Microwave Background. Antarctica offers unique opportunities to study the Cosmic Microwave Background using millimeter-wave telescopes, both from ground based telescopes at the South Pole and on the high plateau, and from balloon platforms launched from McMurdo.

What is the nature of the dark Universe and how is it affecting us?

Although (or perhaps because) astronomy is one of the oldest sciences, we are only beginning to realize just how little we know. Most of what is around us remains unobserved and unknown. Dark matter makes up some 27% of the universe, while dark energy represents another 69%. “Normal” matter, which we mostly think we understand, makes up a mere 4% – although even this includes ultra-high energy particles whose origin is completely unknown, neutrinos that are poorly understood, and cold atomic gas that until very recently has eluded detection.

To answer this question, unknown physics must be explored and observations made at frequencies (energies) hitherto inaccessible. Future instruments will include enhanced neutrino detectors such as IceCube-Gen2, new approaches to allow neutrino detection at yet higher energies, terahertz observatories on the high plateau, and instruments on balloon platforms launched from McMurdo. Another line of attack on this multi-faceted problem is through high-resolution optical and infrared imaging of galaxies, whose distortion as a result of gravitational lensing betrays the presence of unseen dark material. The remarkable atmospheric conditions on the high plateau may offer the only opportunity to resolve this puzzle within the next two decades.

At South Pole, full characterisation of the invisible high-energy neutrino sources requires an extended array of in-ice optical and radio detectors accompanied by surface arrays for vetoing and for cosmic ray studies. On the high plateau, the full complement of future facilities includes large single-dish terahertz telescopes, multi-antenna terahertz interferometers, and wide-field optical/infrared telescopes of 2.5 – 25 metre diameter.

Questions related to the development of life.

The diversity of forms that life can take is illustrated by the many unique Antarctic species, found even in inhospitable locations such as sub-glacial lakes. Interestingly, within our own solar system there are several examples of large water bodies located beneath a frozen crust. For example, Jupiter's moons Ganymede and Europa are both believed to have vast oceans of water beneath their surfaces, and results from the *New Horizons* space mission in 2015 strongly suggest that Pluto may have a similar structure. Twenty years ago, no planets were known outside the solar system. Now, over 1700 planets around other stars have been confirmed, and in twenty years' time, studies of the atmospheric composition of these extra-solar planets should be routine, with the major goal of detecting the presence of extra-terrestrial life. This is an extraordinarily difficult technological challenge, beyond present-day capability. Future facilities that take advantage of the superb observing conditions on the high plateau may well make it possible within two to three decades. Such facilities include optical and infrared interferometers consisting of at least ten 4 metre diameter telescopes distributed over baselines of 10 km or more.

Technological challenges to be addressed

Common

These are the pressing technological issues that must be resolved in order to address at least two of the science/instrumentation areas described above.

- Energy efficient high performance computing hardware.
- Large data storage devices able to withstand the low atmospheric pressure on the high plateau, and possible cold-soaking.
- Low power consumption cryocoolers capable of maintaining instruments at 4K and below.
- Renewable energy technology such as wind turbines able to operate efficiently on the high plateau, with low wind-speeds, low atmospheric pressures, and very low temperatures.
- Development of a diesel power pack at the tens of kW level that has low particulate emission, and can operate unattended for 1 to 2 years.

Balloon platforms

- Light, low-power, reliable cryocoolers.
- Improved power systems (solar arrays, batteries etc.).
- Corresponding improvements in the ability to dump waste heat.
- Continuous improvement in light-weighting technology.
- Enhanced pointing systems for improved in-flight pointing stability.

- Increased mission length (> 2 months is desirable to be able to undertake cartographic surveys).
- Improved flight pattern forecast and predictability.
- Research into expanded launch capabilities for example, a turntable able to respond to wind changes.
- Alternative real-time data recovery systems.

Millimetre-wave receivers (for studies of the Cosmic Microwave Background)

- Continuous improvement in the sensitivity and number of detector pixels that can be deployed in the focal plane.
- Technology development aimed at foreground characterization (e.g., multi-wavelength detectors).
- Development of novel interferometric telescopes.

Terahertz technologies for dark gas observations

- Such technologies include quantum-limited multi-pixel detectors, improved local oscillators, and inexpensive fabrication techniques for large mirrors.

Neutrino detection

- Extension of the energy range and sensitivity of detectors by an order of magnitude or more.

Optical/infrared telescopes

A key issue with optical/infrared telescopes in Antarctica is that the science drives us towards a telescope that is too large to deploy until the engineering risks have been retired through a series of pathfinder experiments. Identifying funding sources for such pathfinders is a critical challenge.

Large single-dish telescopes will require novel telescope designs (e.g., segmented mirrors), in order to be transportable to remote locations. Technologies to facilitate this might include off-axis mirrors, lightweight (carbon fibre?) mirrors, and high precision inertial pointing systems.

- Techniques for the construction of ~30m high towers capable of supporting multi-tonne telescopes (“Engineered ice” is one possibility here).
- Cold-deformable (adaptive optics) systems.
- Efficient anti-frosting and frost-preventing systems for mirrors and lenses
- Beam-transport technologies for interferometers, e.g., through optical fibres at the short wavelength (<5 micron) end of the band, and using evacuated pipes at longer wavelengths.
- Technological advances in mid-infrared photonics and fibres to match current near-infrared capabilities.

Other enabling technologies not unique to an Antarctic telescope include extreme adaptive optics, and specialised algorithms for speckle control and ultra-high contrast imaging.

Logistics needs

Common requirements

The greatest challenges to be faced are the ever-growing energy requirements and the need for greatly increased data transfer rates. For example, future neutrino experiments at South Pole are anticipated to need off-continent data transfer of 1000 GB/day (compared to 150 today), while 24-hour coverage will be important for future Cosmic Microwave Background experiments.

South Pole station

As stated above, electrical power and data-transfer rates are key challenges. As extended neutrino detector arrays are deployed, delivering hundreds of watts of power to the array stations up to 10 km away remains problematic. As detectors grow to occupy areas of up to 1000km², autonomous power systems may provide the only solution.

High plateau sites

Future logistic support of experiments on the high plateau might be done in a number of (non-exclusive) ways. Existing stations (Domes A, C, and F) can further develop their support capabilities, autonomous field observatories such as Ridge A might continue to grow as fully-fledged robotic stations, and one or more new high-plateau sites could be opened up. However it is done, key requirements are:

- Greatly improved communication infrastructure, with broadband Internet access of at least a few Mbps.
- Air access and traverse capability. Specifically, there is need for larger payloads that can be carried in a Twin Otter, and traverse of many tonnes of equipment and fuel to locations such as Ridge A.
- Access to cranes for installation of facilities.
- Power generation at the several tens of kW level.
- Laboratory and workshops facilities for testing and repair, either on site or at an accessible support station.
- Summer access to the observatories for personnel.
- A temperature-stabilised beam combining room, preferably underground.
- Underground/above-ground pipes and vacuum on kilometre scales to route light from telescopes to a central beam-combining location.

Balloon platforms

- Continued support for the Long Duration Balloon facility by NASA/NSF.
- Continued data analysis support from NASA.
- Improved balloon communications and telemetry.
- Dedicated recovery strategy and resources.
- Continued support for logistics (e.g., construction of a third high-bay at McMurdo).
- Secured helium transportation (Should a helium recovery system be implemented? What is the future world-wide availability of helium?)
- Support and logistics for telescope calibration sources.

- Support for NASA in demonstrating Ultra-Long Duration Balloon (ULDB) capabilities (e.g., with larger payloads).

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