Astronomy on Antarctic Plateau

Lifan Wang[1,8], Roger Angel[2], Michael Ashley[14], Xuelei Chen[3], Xiangqun Cui[1,16], Darren Depoy[8], Longlong Feng[1,5], Yipeng Jing[17], Eamonn Kerins[10], Jon Lawrence[14], Lucas Macri[8], Shude Mao[10], Anna Moore[13], Carlton Pennypacker[12], Nick Rattenbury[10], Reed Riddle[13], Zhaohui Shang[1,15], George Smoot[12], John Storey[14], Nick Suntzeff[8], Tony Travouillon[13], Jun Yan[1,3], Donald York[11], Xiangyan Yuan[1,16], Xinmin Zhang[4], Wei Zheng[9], Zonghong Zhu[7]

[1] Chinese Center for Antarctic Astronomy, [2] University of Arizona, [3] Nanjing Institute of Astronomical Optics Technology, [4] Institute of High Energy Physics, Beijing China, [5] Purple Mountain Observatory, Nanjing, China, [6] Beijing University, [7] Beijing Normal University, [8] Texas A&M University, [9] Johns Hopkins University, [10] University of Manchester, UK, [11] University of Chicago, [12] Lawrence Berkeley National Laboratory, [13] California Institute of Technology, [14] University of New South Wales, [15] Tianjing Normal University, [16] National Astronomical Observatory of China, [17] Shanghai Astronomical Observatory

Summary: The Antarctic plateau provides many exciting possibilities for astronomical observations. The next decade may see a significant astronomical buildup on the Antarctic Plateau. Dome A and Dome C are currently the two most promising sites. These high points on the plateau have unique properties for astronomical observations. Two of these arise from the extreme cold: the column density of water vapor is lower than at any other site, thus opening unique windows at infrared and submillimeter wavelengths; and the ambient temperature, and thus the thermal background emission of telescope mirrors, is lower than at any other site. Two more advantages arise from the unique character of the atmospheric turbulence: the atmospheric boundary layer is extremely thin, only tens of meters, which opens the possibility of wide field, high resolution imaging by either adaptive correction of the thin ground layer or by raising the telescope above the boundary layer; the wind speeds at all levels of the atmosphere are low, which is highly favorable for adaptive correction. It will likely be possible to form diffraction limited images over a good fraction of the sky down to visible light wavelengths three times HST resolution for an 8 m telescope. Dome A, being the highest and coldest point in Antarctica, is especially promising based on the results of recent theoretical models and site surveys. More comprehensive site monitoring should be planned for the next decade.

Based on existing data, the site has certain areas of astronomical observations can already be planned with little risks. Wide field near-IR imaging, for example, relies critically on the thermal background and the low temperature at Dome A makes it an ideal site. Another key area is likely to be exoplanet imaging and spectroscopy in the *L*-band, where the combination of super-diffraction limited AO correction and the very low thermal background will enable very high contrast imaging at very close inner working angle, for example 0.15 arcsec for an 8 m telescope.

1. Introduction

For many years the Antarctic plateau has been recognised as offering an outstanding opportunity for astronomy (e.g., Storey 2005). The high altitude, low temperatures, minimal free-atmosphere turbulence, and a very thin surface layer combine to produce observing conditions that are unrivalled elsewhere on the planet.

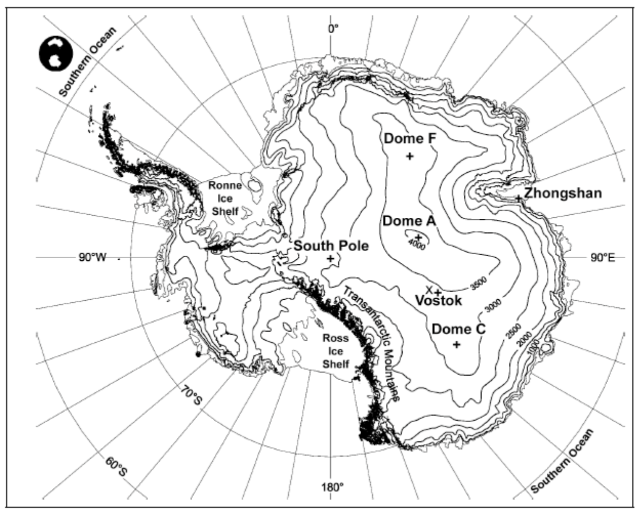

Fig. 1.— Map of Antarctica showing the Chinese coastal station Zhongshan and the high plateau stations South Pole, Dome C, Dome F, Vostok, and Dome A. "X" marks the current position of the south geomagnetic pole. Basic map courtesy of the Australian Antarctic Data Centre.

Site testing spanning more than a decade, first at the South Pole and more recently at Dome C and Dome A, has quantified the gains that an Antarctic observatory can enjoy (e.g., Storey et. al. 2007; Yang et al. 2009). While there are technical and logistic challenges to be overcome, the success of major projects such as the South Pole Telescope (Ruhl et al. 2004; Staniszewski et al. 2008) has demonstrated that these challenges are not insurmountable, and that the expected gains can be realised in practice.

Figure 1 shows the location of the existing stations on the Antarctic plateau: South Pole, Dome C, Vostok and Dome F (operated by the US, France/Italy, Russia, and Japan respectively) plus the new site of Dome A (being recently developed by China). Mountaintops are often the preferred locations for an observatory. At higher elevations, less atmosphere remains above the telescope, the precipitable water vapour will be less, and the temperature will be colder. However, at temperate sites higher elevations are also windier and often very difficult to access. On the Antarctic plateau the advantages of a higher elevation increase even faster with altitude, as the low temperatures mean that the scale height of the atmosphere is less than at temperate sites. In addition, because the wind patterns are predominantly katabatic (Parish & Bromwich 1987, 2007), the surface wind speeds decrease as the altitude of the site increases. This, combined with still lower temperatures, implies that the stable boundary layer will be even thinner at Dome A than at Dome C. Finally, because the topography of the Antarctic plateau is very smooth, access to the highest sites – though more challenging – is by a straightforward extension of the well-established traverse techniques used to reach the existing Antarctic plateau stations such as Dome C and Dome A.

For all these reasons, the highest point on the plateau, Dome A, has been considered for many years to represent the *ultimate observing site* on the plateau, and hence the Earth (Harper 1989; Gillingham 1991). The advantages are expected to be particularly strong in the infrared/sub-millimetre part of the spectrum, where the high altitude and low water vapour content can be expected to offer unparalleled transmission (Lawrence 2004; Yang et al. 2009).

2. Scientific Goal

Practically all observational astronomy programs can benefit from the excellent observing conditions provided by Antarctic Plateau. This has been explored in great detail in the past three years by the ARENA network (http://arena.unice.fr). The ARENA network focuses on programs at Dome C, but most of these studies are also applicable to Dome A which has perhaps even better observing conditions than Dome C in some aspects. The following area has been identified by the ARENA consortium as potentially important for an astronomical observatory at Dome C:

- Wide field optical/infrared imaging and spectroimaging surveys
- Submillimeter astronomy
- Interferometry
- Long time series observations including planetary transits, asteroseismology and microlensing
- Cosmic Microwave Background
- Solar astrophysics, high resolution observations, magnetoseismology and coronagraphy

While the European approach is more systematic in evaluating the scientific potential at Dome C, the team led by China is more focused on areas that maximize the scientific output in the near term. The effort concentrates on two major directions: Wide field optical/IR surveys and spectroscopy and sub-millimeter astronomy. Site survey instruments and proto-type telescopes are being constructed by the China-Australia-US collaboration and will be installed in the next two years.

These efforts and those that are currently going on at Dome A have the same goal: To build one or more astronomical observatory at Dome C or Dome A for the next decade that will answer many of the most important questions in today's astronomy.

3. Space vs Antarctic Plateau

To some degree the Antarctica plateau is the closest match to space on the surface of the Earth. Site surveys at Dome C show atmospheric boundary layers of only 30 meters and the recent survey of Dome A confirmed the theoretical expectation that the boundary layer at Dome A is even thinner. Natural seeing of around 0.3 arcseconds can be achieved above the boundary layer. The air is found to be very quiet at Dome A, with typical wind speed less than 10 m/sec. The winter temperature is typically -70 degrees which makes it the coldest spot on the Earth and the best sites for infrared and sub-millimeter observations. Compared to space, the Antarctic Plateau can provide comparable image qualities in the optical and near-IR. Diffraction limit images in the near-IR are possible with no or only low order active optics correction. Compared to space, one major disadvantage at the Antarctic sites is the stronger sky background and atmospheric absorption in some wavelength ranges. A carefully designed system can effectively avoid these disadvantages and maximize the potential of the site.

Dome A and C, though difficult to access compared to Hawaii and Chilean sites, involve much less demanding and less expensive logistics than launching telescopes into space. . Regular yearly services can be expected for Dome A and C whereas space telescopes require instruments to be designed with no or minimal services. Dome A/C also allows construction of telescopes with larger apertures than can be done from Space. For instance, in the infrared or sub-millimeter wavelength range, telescopes larger than 30 meters can be planned that allows sharp images to be taken in the infrared and sub millimeter.

As we venture deeper into the territory of the Antarctic plateau, the Dome A/C sites will become more and more accessible. In 1996, a French-Italian team established a summer camp at Dome C. The new all-year facility, Concordia Station, became operational in 2005. In Jan 2009, a Chinese team built the Kunlun station at Dome A, and there are plans to upgrade Kunlun Station to a winter over station in the coming 3-5 years. Astronomical observation is a major scientific drive for both stations.

4. A Wide Field Telescope at Dome A for the Next Decade

4.1. Sensitivity

Although useful for practically all astronomy programs, the Antarctic plateau, especially the Dome A site, is ideal for performing wide-field high spatial-resolution surveys. We will focus here, as an example, on a 4-meter wide field optical/IR telescope - the Antarctic Wide Field Telescope (AWFT). The natural seeing above the atmospheric boundary layer is likely to be around $\sim 0''.2$ in the near-IR. With simple tip-tilt corrections, it is possible to do a wide area survey at diffraction limited resolution on a 4m telescope.

As an example, we show in Figure 2 the sensitivity in K-band for such a telescope. Also shown in the Figure is the maximum magnitude of a Typical SNIa at different redshift. The sensitivity is summarized in Table 1.

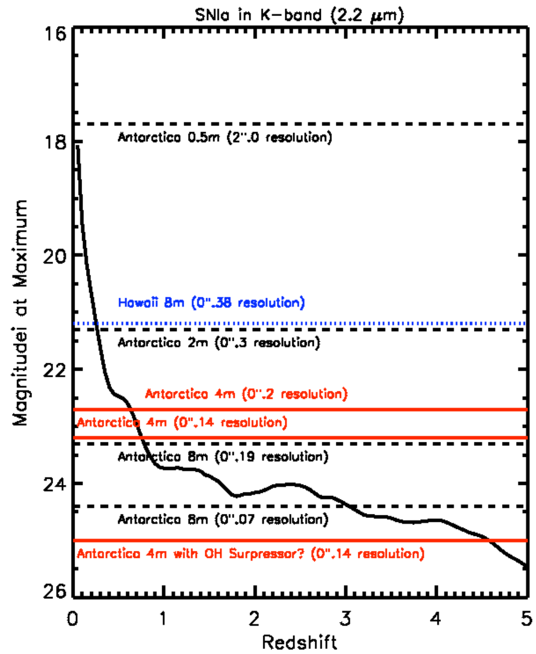

Fig. 2.— Sensitivities of telescopes on different sites. From top to bottom, the horizontal lines are for a 0.5 meter telescope at Dome A, an 8 meter telescope at Mauna Kea, Hawaii, a 2 meter telescope at Dome A, a 4 meter telescope at natural seeing at Dome A, a 4 meter telescope at diffraction limited seeing at Dome A (achievable through simple tip-tilt correction), an 8 meter telescope at Dome A, an 8 meter telescope at diffraction limit at Dome A, and a 4 meter telescope at Dome A but with OH suppressor. Also plotted is the magnitude at optical maximum for a typical SNIa at different redshift. It can be seen that a 4-meter has the potential to reach the first generation of Type Ia supernovae.

4.2. Sciences with a Wide Field Telescope at Antarctica

With tip-tilt and no OH suppressor, it takes only 1 hour for our hypothetical AWFT to reach $K(AB) = 26$, which is 0.4 magnitude deeper than the depth of UltraVISTA in K-band. The UltraVISTA program plans to observe an area less than 1 square degree and use about 1000 hours in several bands in the near-IR using the ESO VISTA telescope[1]. AWFT can easily survey about 5000 sq degree and deeper than UltraVISTA.

This allows for some exciting science programs to be carried out. Most noticeably:

[1] http://www.eso.org/sci/observing/policies/PublicSurveys/sciencePublicSurveys.html

- The first generation of stars and galaxies can be probed by AWFT, out to redshifts beyond 10.

- A wide area survey will allow better constraints of cosmological parameters through improved usage of weak lensing, galaxy clustering, and supernova studies. The near-IR coverage will also help other wide field survey programs such as LSST to calibrate galaxy photo-z, thus strengthening LSST sciences.
- Identify interesting targets for JWST and the next generation of extremely large telescopes.
- Star formation studies.
- Exoplanet search. In the near-IR and at resolution of 0.2 arcsec, the galactic bulge can be monitored continuously during the Austral winter. This is ideal for planet searches which requires both time coverage and the ability to observe crowded fields through dense dust clouds.

5. Wide Field Astronomy on Different Sites

Compared to wide field astronomy on different sites, a major advantage at Dome A/C is the excellent seeing condition there and the potential of reaching wavelength ranges beyond the thermal infrared. For point sources, Dome A/C are especially advantageous as sharper images enable deeper images even when the sky background is of comparable brightness. For diffuse targets such as galaxies, the advantage is less obvious in the optical wavelength range, but may still be significant in the thermal IR wavelength range due to the much lower temperature in Antarctica.

Space offers best observing conditions but the cost of launching a telescope into space is much higher. The full electromagnetic wavelength range is accessible in space, which makes X-ray, UV, and Far IR observations very attractive. However, to get high resolution images at around 3 μm, one needs to build a telescope of around 4 meters, which may become very expensive for a wide field survey telescope.

6. Sub-millimeter Astronomy

The low precipitable water level at Dome A/C opens new atmospheric windows in the sub-milimeter wavelength range. Observations around 500 μm will be possible regularly from the ground.

Table 1: Point Source Limiting magnitude (Vega) for a 4-meter telescope at Dome A.

Band	Resolution	Limiting Mag (1hr, S/N=10)	Resolution	Limiting Mag (1hr, S/N=10)
R	0".063	27.3	0".23	26.7
J	0".08	24.4	0".24	23.3
H	0".10	23.2	0".20	22.4
K	0".14	23.3	0".20	22.7

Scientific programs related to interstellar clouds, star formation, and cosmology will benefit from this development. See http://mcba11.phys.unsw.edu.au/ plato/ for more details.

7. Summary

The Antarctic plateau is rapidly becoming more accessible to scientific research. Site surveys at Dome A/C have so far confirmed the expectation that they are ideal sites for astronomical observations. Many astronomical programs are now being considered by the Europeans and Chinese for Dome A and Dome C, respectively. A wide field telescope with at least 4 meter in aperture at Dome A is particularly attractive as somewhere to begin the astronomical buildup at Dome A. One may expect diffraction limited images in the 0.1 arcsecond range from the natural seeing condition provided by Dome A. However, we emphasize here that the example given in this white paper should not be mistaken as the best the Antarctica plateau can provide. An 8 m telescope for example, in the L-band with a deformable secondary will be hugely powerful for exoplanet imaging and spectroscopy. It would also yield diffraction limited images at optical wavelength with 3x Hubble resolution. We note that 8m is today's standard aperture, production methods are mature. In the diffraction limit, signal to noise goes as D^2, an 8 m at Dome A can reach a mind boggling depth of K(AB) = 29th magnitude with an S/N ratio of 10 in a single one hour exposure with OH suppression. Such a telescope will be the ultimate telescope to probe the darkest corners of the Universe.

The Antarctic Plateau is likely to be the ultimate site for astronomy in the next decade. It is important for US astronomers to maintain a significant role in these programs.

REFERENCES

Harper, D.A. 1989, Infrared astronomy in Antarctica", in Astrophysics in Antarctica, Amer. Inst. Phys. Conf. Proc., 198, 123.

Gillingham, P.R. 1991, Proc. ASA, 9, 55

Lawrence, J.S. 2004, PASP, 116, 482

Parish, T.R., & Bromwich, D.H. 1987, Nature, 328, 51

Parish, T.R., & Bromwich, D.H. 2007, Monthly Weather Review, 135, 1961Ruhl, J., et al. 2004, Proc. SPIE, 5498, 11

Staniszewski, Z., et al. 2008, ApJ, submitted, eprint (arXiv:0810.1578)

Storey, J.W.V. 2005, Antarctic Science, 17, 555

Yang, H. et al. 2009, PASP, in press