ARENA - Antarctic Research,
a European Network for Astrophysics

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A Vision

for European Astronomy and Astrophysics at the Antarctic station Concordia, Dome C

In the next decade 2010-2020

Executive Summary

Prepared by the

ARENA *ANTARCTIC RESEARCH, A EUROPEAN NETWORK FOR ASTROPHYSICS*

consortium in fulfilment of the work programme of the EC-FP6 contract RICA 026150

Map produced by the Australian Antarctic Data Centre Stations as listed at http://www.comnap.aq/facilities (September 2009) - Map Catalogue N° 13698

Map of the Antarctic continent with the main research stations

Executive Summary

ARENA, a consortium of European and Australian laboratories gathered in a network funded by an EC-FP6 contract in 2006-2009 has released a roadmap for the development of astronomy and astrophysics on the Antarctic Plateau. This document based on the results of the investigations made by a hundred of experts in atmospheric physics and several relevant fields of astrophysics from 8 countries identifies the science cases that would most benefit from the Antarctic plateau conditions and describes a suite of appropriately designed instrumental projects.
A set of statements and recommendations supporting the creation of an international astronomical observatory offering exceptional conditions at the French-Italian station Concordia at Dome C are drawn out.

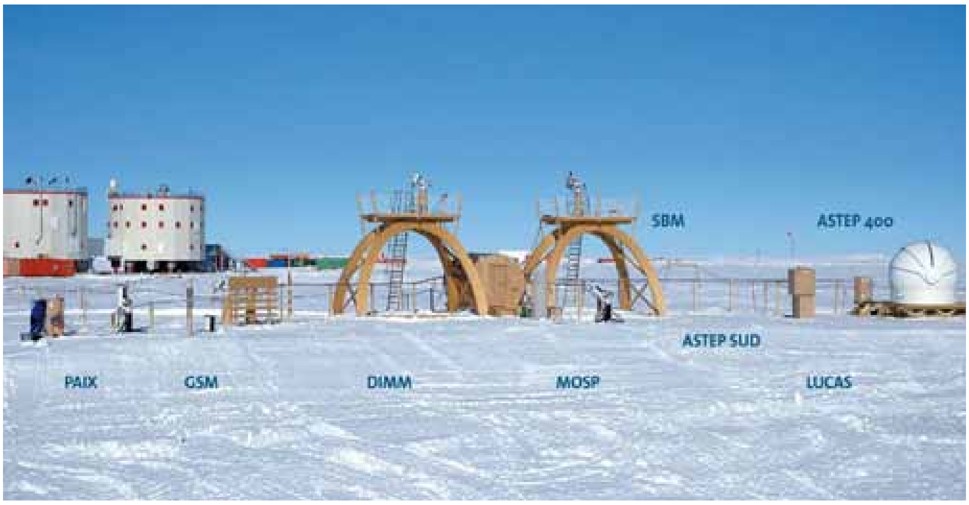


Photo : A. Agabi

The Concordia station and the site testing equipment

Astronomers have always sought the best possible observing conditions. The inner Antarctic continent is the wildest, coldest, and driest desert on earth, offering an almost pristine nature without human contamination, or even faunal or floral presence. It is therefore, in essence, an outstandingly appealing area to explore for the construction of major astronomical facilities of the future. Astronomers have for decades been attracted by this opportunity. Several pioneering attempts have been made to set up increasingly sophisticated instruments over the last 40 years, encompassing a wide range of techniques and scientific goals. The only major astronomical facility so far established is at the US Amundsen-Scott station, right at the geographic South Pole, and named the Martin A. Pomerantz Observatory in tribute to one of the most active astronomers in Antarctica over the last half century.

France and Italy have recently joined the effort: they have built and, since 2005, operate year–round a multidisciplinary station at Dome C called Concordia. Dome C is one of the highest domes on the Antarctic Plateau, located about 1,200km from the coast at a latitude of about –75° and an elevation of 3,202m. Dome C is an extremely promising location for the establishment of the first European astronomical observatory in Antarctica, which could eventually become a major item of an international research infrastructure.

To explore this opportunity in all its aspects, a network, ARENA, was created under the auspices of the European Commission. ARENA has had as a goal the investigation of the scientific prospects and the possibility of implementing an astronomical observatory at Concordia, and to document a suite of instrumental projects that could benefit greatly from the conditions on the Antarctic plateau. ARENA created the impetus necessary to form international consortia in charge of preparing detailed studies (Phase A and B) of at least a couple of the proposed projects; consortia that could possibly undertake their construction before the end of the coming decade, 2010-2020. Preliminary site assessments and atmos-

The 40cm planetary transit telescope ASTEP

pheric modelling by several expert teams, primarily from Australia, France, and Italy, have demonstrated that this region offers exceptional conditions for astronomy mainly thanks to the cold, dry, and calm atmosphere. The atmosphere above the highest spots of the Antarctic continent offers the best conditions on earth to investigate astronomical objects at high angular resolution in the near thermal IR and submillimetre-wave ranges. The high latitude location allows very long continuous night-time photometric observations, which are essential for the study of periodic variability of celestial objects. In several well-identified domains («niches») the Antarctic plateau may even compete with space missions, but at a much lower cost, and with the invaluable bonus of using the most advanced technologies.

The ARENA network has identified 6 particularly promising astrophysical areas with well-defined research programmes. Taking into account the constraints of logistics and environment, the network has been able to outline the top-level requirements for the instrumentation able to address these programmes.
They are, i) wide-field, extremely sensitive imaging and spectro-imaging in the near and thermal infrared (2.3-4µm) with a 2.5m-class telescope (the PLT project), ii) extremely sensitive submillimetre wave imager with a collecting area equivalent to a 25m dish (project AST), iii) near IR interferometry for the detection of exoplanets and exozodiacal light (the ALADDIN project), iv) a set of smaller dedicated instruments (some of them already in the construction phase on-site) for planetary transits (ASTEP), stellar variability, asteroseismology, and infrared imaging photometry (IRAIT), v) cosmic microwave background experiments (the QUBIC project) and, vi) high angular resolution solar measurements (the AFSIIC project).

A series of recommendations have been drawn from the discussions held during the ten workshops and three conferences that took place during the last 4 years.

Site assessment

A large amount of data have been collected with the aim of quantifying the day- and night-time astronomical observing conditions at Dome C. The available data show that the precipitable water vapour is usually below 0.7mm and drops to 0.3mm for 50% of the time, thus offering excellent conditions for submillimetre observations. The extreme cold of the atmosphere means that its thermal emission is greatly reduced. This, in turn, leads to significant savings in the time required to carry out large observing programmes at wavelengths longer than 2µm.

The absence of strong turbulence in the upper atmosphere results in low scintillation and creates favourable conditions for photometric programmes. The median free-atmosphere seeing in the visible is 0".36, but achieving this imaging accuracy in the optical is limited by the presence of a very strongly turbulent boundary layer which extends up to median altitudes of some 40m in winter and up to 400m in summer. The small outer scale of turbulence measured at Dome C, combined with the long coherence time and large isoplanatic angle, is beneficial for high angular resolution techniques at this site. Detailed measurements of the vertical and temporal variation of the atmospheric parameters are now needed, in order to draw robust conclusions about short- and long-term stabilities and trends, and to constrain the specifications of instruments to be deployed at Dome C.

Near-infrared high angular resolution wide-field imaging

Various countries have for some time proposed the construction of a large optical/infrared telescope in Antarctica. The conditions on the Antarctic plateau particularly favour exploitation of the spectral windows not easily accessible from the ground, i.e., in the thermal IR beyond 2.3 µm where observations are normally hampered by the strong thermal background emission of the sky and from the ground. Thanks to the exceptional seeing conditions above the turbulent layer, Dome C is an ideal site to make large-scale, high angular resolution, extremely deep imaging surveys in this wavelength regime.

The **PLT** (Polar Large Telescope) project is the result of extensive discussions between Europeans and Australians to propose a realistic, albeit ambitious, project for such a telescope with a 2.5m aperture. A limited number of programs will be performed aimed at surveying very distant galaxies, dusty SNIa, and extreme stellar populations in the local group, and at characterizing exoplanets by transit and microlensing milli-magnitude photometry. The project will be based on a European-Australian collaboration. A preliminary evaluation of the cost points toward a 11 Meuros telescope and 5 Meuros focal instrument with a Phase B study in 2010-2013 potentially funded by the FP7 and a first light before the end of the decade.

Submillimetre-wave astronomy

Performing ground-based astronomical


Photo : Y. Fantei-Caujolle

The 80cm infrared telescope IRAIT


Photo : Y. Fantei-Caujolle

The 2.5m millemetre-wave telescope COCHISE

observations in the submillimetre part of the electromagnetic spectrum requires, at a minimum, very dry conditions. The Antarctic plateau, a unique «desert» on Earth, is an obvious candidate site.

The atmospheric transmission in the submillimetre windows centred at e.g., 200, 350, 450, and 850 µm has been estimated by the team of CEA-IRFU/Saclay using measurements with a tipper instrument and the MOLIERE radiative transfer modelling code. The 200µm window opens up to better than 20% transmission for 25% of the time. Observations at 350 and 450µm would be possible all year. Theses values of transmission indicate that observing conditions at Dome C are superior to the known sites in Chile or Argentina. The estimated transmission values were used as filters to select science cases. «Cosmic history of star formation, black holes and galaxies», «Origins of stellar masses», «Galactic engines», and «Galaxy clusters in the far Universe and dark energy» were selected as the four main science cases for a submillimetre-wave telescope facility in Antarctica.

One of the functions of the thermal infrared telescope (the Italian IRAIT 80cm telescope) can be as a pathfinding experiment for submillimetre astronomy. It will perform atmospheric and sky-noise measurements with a bolometer array, prepare a catalogue of source calibrators in the far southern sky, and attempt several science observations of the Sun and of star formation.

Finally, this roadmap provides a vision for an Antarctic Submillimetre Telescope (**AST**) project. This could be a large telescope facility consisting of a 25m diameter class, single-dish telescope at Dome C, or an equivalent collecting area achieved with a network of medium-size radio antennas, operating at submillimetre wavelengths and offering unique science possibilities. Its performance at 200, 350 and 450µm would be superior to an equivalent telescope on any of the Andean sites. Furthermore, a single-dish telescope could be used as a Very Long Baseline Interferometry station with the ALMA and other antennas in South America.

Optical and infrared interferometry

Studying the warm inner parts of debris disks, the extrasolar counterparts of the zodiacal dust cloud, is of prime importance to characterize the global architecture of planetary systems. Furthermore, the presence of large quantities of warm dust around nearby main sequence stars represents a possible obstacle for future space missions dedicated to the direct detection and characterization of Earth-like planets. The frequency of the occurrence of bright exozodiacal disks around solar-type stars is currently mostly unknown. As of today, exozodiacal disks have been directly resolved around a small number of main sequence stars, at a sensitivity level of about 1000 times our Solar System zodiacal dust cloud. In this context, the Antarctic plateau could provide the optimal ground-based conditions for an infrared nulling interferometer dedicated to the direct detection of warm dust clouds around nearby main sequence stars.

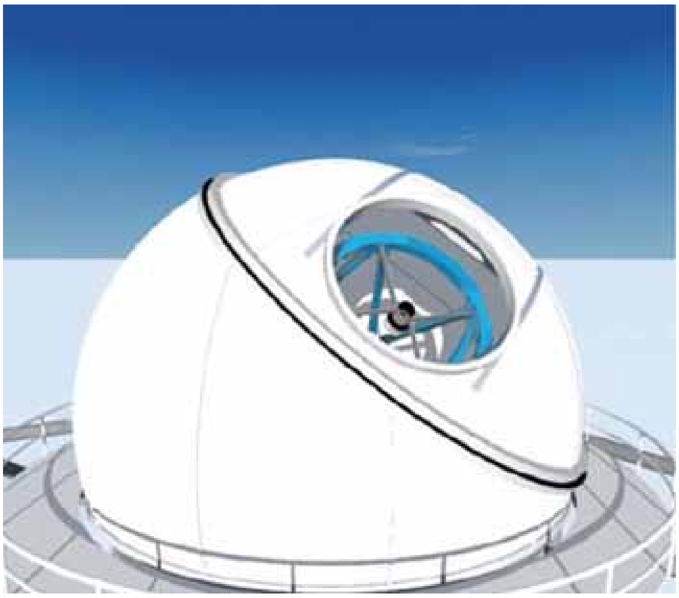
Joint efforts between several European institutes within the ARENA consortium led to the definition of the **ALADDIN** concept. In order to achieve a significantly improved sensitivity with respect to existing instruments, the architecture of the system is specifically focussed and optimised for the purpose: ALADDIN implements the nulling interferometry technique at the focal plane of a two-telescope interferometer mounted on a rotating beam structure. Thanks to the Antarctic environment, such a nulling interferometer coupled to a pair of 1m-class telescopes operated at thermal infrared wavelengths would perform significantly better than a similar instrument working on 8m-class telescopes in a temperate site (e.g., at ESO Paranal).

Long time-series photometric observations

Time-series data are the result of astronomical observations of temporal phenomena; to be valuable such observations typically require one or more of the following conditions:

- Long observing duration in stable conditions, particularly in combination with high duty cycles
- Very good seeing and/or low scintillation
- Observations in spectral ranges that have been little explored to date.

Contributing to all of these requirements, Dome C provides unique opportunities for ground-based observations. Because of the need for long and continuous time coverage, most such observations require a dedicated telescope, typically of sub-1m size. However, there are also scientific cases for which the use of significant time allocations on larger multi-purpose facilities is more appropriate. The major science cases for time-series at Dome C are: detection and characterization of extrasolar planets (transits), asteroseismology, and stellar activity studies. The panel reviewed several projects that were presented:



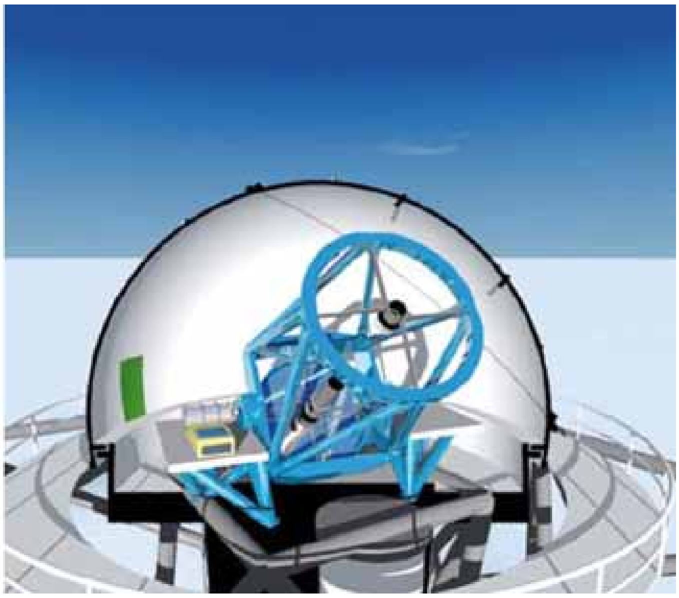


Photo : M. Burton

CAD image of the 2.5m infrared wide-field telescope, PILOT / PLT

• **ASTEP 400**, a 40cm telescope for planet detection, received its first light at Dome C in November 2009. It should provide scientific data rapidly (2010-2011) and thus should be strongly supported by the relevant agencies.
• Of projects in the development phase, **ICE-T** (International Concordia Explorer Telescope), a 2 x 60cm binocular telescope, is graded the top priority instrument for time-series photometry; it is expected to become the reference instrument for stellar activity studies. Its construction is funded, but site-access and operational issues need to be resolved as soon as possible for an anticipated deployment around 2013-2014.
• **SIAMOIS** (Seismic Interferometer Aiming to Measure Oscillations in the Interior of Stars) is the top priority instrument for advanced time-series spectroscopy, and is expected to become the reference instrument for stellar Doppler velocity studies. Its deployment with two small-aperture telescopes is anticipated for 2013-2014. In a second phase, the scientific return can be enhanced to include specific faint targets by feeding the instrument from a 2m-class telescope..
• Finally, **PLT** (Polar Large Telescope) is considered critical for shorter time-series projects requiring a larger and flexible instrument, where open access for the scientific community will be important.

Cosmic Microwave Background

Cosmic Microwave Background (CMB) observations have been extensively developed since the discovery of this radiation in 1965 by Penzias and Wilson. It has been demonstrated that Antarctica is the best place on Earth to study its anisotropies in temperature and polarization. The US M.A. Pomerantz Observatory at the South Pole is essentially dedicated to this research with, today, the largest astrophysical instrument ever built on this continent, the South Pole Telescope (SPT), a 10m aperture millimetre-wave dish and the BICEP polarization experiment. The basic advantage of the polar environment for CMB research is the unique atmospheric stability, particularly of the terrestrial molecular oxygen lines, and the fact that one can observe the same area of the sky over very long periods at almost constant elevation. Dome C appears to be even better because of a lower atmospheric optical depth and lower wind speeds, and thus even better stability (with respect to the South Pole). Moreover, its location 14° in latitude away from the pole allows cross-linked scans and drift removal techniques.

Members of the CMB working group are currently implementing the **QUBIC** experiment through a collaboration between Italy, France, Ireland, UK and the USA. This instrument (formerly called BRAIN) will take advantage of the conditions at Dome C to mainly measure the B-mode of the CMB polarization with a bolometric interferometer, combining the extreme sensitivity of bolometric detectors with the optical purity of interferometers. The project is supported by IN2P3 in France and PNRA in Italy and by the ARENA CMC.

The working group also supports a project for a single millimetre and submillimetre-wave large dish mainly for high angular resolution observations of intra-cluster structures and the study of the different populations of thermal and non-thermal electrons that produce distinct Sunyaev-Zel'dovich effects (SZE) and that could provide new clues on Dark Matter candidates.

Solar astrophysics

The Dome C site where Concordia station is located also offers unique qualities for solar observations, combining excellent seeing, low coronal sky brightness, low water vapour, continuity and an impressive duty cycle (4 months, i.e., 3 times more than at mid-latitudes sites, under excellent observing conditions). This allows both very high angular resolution (<< 0".1) adaptive optics observations and access to the corona, thus providing data on the chromosphere-corona interface that is impossible to obtain from other sites (or indeed from space for many years). These data include direct measurements of the magnetic field in the chromosphere and corona made possible by exploiting the remarkable infrared atmospheric transmission on the Antarctic plateau. Accordingly, primary science cases were defined in both high angular resolution and 2D coronal spectroscopy, and a meso-scale facility has been designed to achieve them.

The project proposed is the Antarctica Facility for Solar Interferometric Imaging and Coronagraphy (**AFSIIC**), a large (by solar astronomy standards) assembly of 3 x Ø500mm (preferably Ø700mm) off-axis SiC telescopes placed above the turbulent layer. With a baseline of 1.4-4m this solar interferometer with coronal capabilities would have a performance superior to any current or planned ground-based telescope, including the 4m-class ATST and EST. It features 2D spectro-imaging, spectro-polarimetry, magnetoseismology, and chromospheric and coronal magnetometry to facilitate a magnetic investigation from the convection zone to the corona. Furthermore it will be the only major solar observing facility in the southern hemisphere, observing when other (northern) teles-

Photo : O. Absil

Artist view of ALADDIN at Concordia

copes will suffer from winter conditions.

ARENA roadmap

Considering the various propositions made by the working groups and on the basis of the present knowledge of the site assessment, the following statements and recommendations are made by the ARENA CMC. We recommend that a process be fostered to lead to the creation of an internationally managed astrophysical station at Dome C aimed at collecting unique data over a wide range of wavelengths from the visible to the millimetre. We strongly recommend continuation of the site quality characterization to confirm the promising results already obtained, and to study their variations with time. Atmospheric parameters that have thus far not been fully studied should be measured and monitored with some urgency. These include: the atmospheric opacity at all wavelengths, the photometric stability, the sky background emission (particularly in the near thermal infrared), the turbulence profile and the outer scale of turbulence. We strongly recommend making these data rapidly available to the community and implementing a regularly updated data-base to archive the data and provide long-term, easy access to them. We strongly recommend using, as far as possible, the same instruments, calibration and data processing in the different polar sites currently under investigation, to enable objective comparison. We express our interest in the exploration of as yet undocumented sites (such as the Antarctic Ridges A and B).

We have identified a wide range of science cases, as detailed above, that would strongly benefit from the unique Antarctic conditions. A suite of appropriately designed instruments is identified; these can be classified into 3 main categories:

• *small instruments,* some of which are currently in the construction phase (IRAIT, COCHISE, BRAIN/QUBIC, ASTEP) or ready to be built (SIAMOIS, ICE-T). They all fit within the present logistics capabilities. Their cost is in the range of a few million euros. For obvious reasons of manpower capacity on site, and to leave room for more ambitious projects, their number should not increase without limit in the future. An international peer-reviewing process to select future projects based on their scientific excellence should be established,

• *mid-size facilities* (mesoscale projects, cost range of a few tens of million euros, (such as PLT or a solar telescope/interferometer) that will need affordable upgrades of the logistics (power supply, transport, e-communication). They will require, however, a very large deployment of personnel to the site over several summer seasons for the construction,

• *large to extremely large projects* that, according to the conclusions of the dedicated ARENA activity NA4 would require a sufficiently large increase in the resources available for logistics that one could not expect them to be deployed in the coming decade (such as ALADDIN, AST, AFSIIC and, a fortiori, KEOPS - the km-scale optical/infrared interferometer array).

For the coming decade and in consideration of the reflections of the different working groups the following recommendations of ARENA are made:

• to continue the site assessment

• to establish a major funding plan in order to run the currently on-going telescopes or instruments (**COCHISE, IRAIT, ASTEP, QUBIC**) and obtain, as soon as possible, high-quality science from them

• to make plans for the rapid implementation of **SIAMOIS** and **ICE-T**

• to start immediately, in 2010, a phase B study for **PLT** on the basis of the phase A studies made by the Australians for PILOT, for first light before the end of the decade.

• to commence phase A studies for:

- a large submillimetre-wave telescope facility (AST) to exploit the extraordinary potential of the site in the THz regime,
- a pathfinder for interferometry in the optical/NIR range (such as ALADDIN),
- an instrument dedicated to high angular resolution astrophysical studies of the Sun (such as **AFSIIC**).

It is unlikely that all these actions will be funded in the next decade. ARENA refrained from ranking these projects, however, leaving the strategic decisions to the national, european, and international agencies that are expressed, for instance, in the body of the ASTRONET recommendations. However, we believe that the only project in the mid-size (cost) range that can effectively be carried out in the next decade is PLT. This project has the potential for wide support from the community and will be made possible only if a strong and sustainable international collaboration is set up around it. We point out that several studies that will be carried out for this project, such as the implementation of a Ground Layer Adaptative Optics (GLAO) device specific to polar conditions, the construction of a stiff tower and the mitigation of frosting, will also be useful for other projects, in particular future optical/IR interferometric and solar projects. Fostering european and international collaborations and aggregating a critical mass of resources have been constantly emphasized by ARENA. The internationalisation of Concordia for astrophysics to the status of a European Research Infrastructure is essential, but it is strongly dependent on the decision to build rapidly at least one significantly ambitious project, now, and to propose an ambitious vision beyond. The Concordia station at Dome C represents a real opportunity for Europe (and collaborators) to develop one of the best astronomical sites on the Earth, operated all year round. Concordia is ready to implement, host, and operate a new generation of mesoscale astronomical instruments capable of major advances in several cutting-edge astrophysical areas during the next decades. The momentum created by ARENA should definitely be sustained though new vigorous actions, such as a better coordination of the site testing operations and data access, the establishment of consortia to submit excellent proposals to the relevant funding calls, and above all the Phase B design study of mesoscale projects.