Appendix 1 – Science Case

Introduction

The European Southern Observatory (ESO) is the world's foremost intergovernmental organisation for ground-based astronomy.

Through ESO membership Australians will be opening up the Universe to human understanding with the best instrumented large optical and infrared telescopes in the world, the highest resolution stellar interferometer, the world's first large infrared survey telescope, a globally unique millimetre telescope array of unprecedented power and, by 2018, the world's largest optical/infrared telescope. ESO shares Australian astronomers' concentration on astronomical observations from the southern hemisphere.

Membership of ESO will allow Australian astronomers to take part in the most exciting and important discoveries in the exploration and understanding of the Universe at a time when only global cost sharing can support research facilities of the scale and technology required to advance the frontiers of knowledge.

History of Australian astronomical facilities

Over the last half of the 20th century Australia has been fortunate to enjoy state of the art astronomical facilities. This has ensured that discoveries of international significance have continued to be made in large numbers and that research training has been first class. The earliest member of the set of the world's top ranked telescopes was the ANU's Mount Stromlo 74 inch telescope. Completed in 1957 with optics from the U.K., this telescope was used extensively for measurements of the chemical composition of stars using its fine high resolution spectrograph. The new world class facility of the 1960s was the Parkes radio telescope with its innovative surface support and large collecting area. This was the decade of discovery of quasars, and Parkes has enjoyed a long productive lifetime discovering the southern hemisphere's pulsars and mapping the distribution of galaxies in neutral hydrogen. Parkes was built with funding from U.S. organisations and the Australian government.

In 1974 the mutual interest of Australian and U.K. astronomers in southern hemisphere astronomy led to the construction of the Anglo-Australian Telescope (AAT), sharing with a U.S. facility in Chile the title of the world's largest optical telescope in the South (4 metres). The AAT developed technological leadership in multi-object spectroscopy and Australian and U.K. astronomers were first to measure the density of the Universe in redshift surveys that exploited this instrumentation.

The Australia Telescope Compact Array, or ATCA, opened in 1988, is a set of six 22 metre diameter dishes. These antennas sit on a wide gauge rail track, so that they can be moved into different arrangements to get the best possible images of the sky. Until the opening of ALMA, the ATCA is the only telescope of its kind in the southern hemisphere. If the ATCA had not been built, says former ATNF Director, Professor Ron Ekers, "radio astronomy [in Australia] would have slowly declined … [making] a smaller and smaller contribution to the world scene". With the ATCA, rather than becoming a backwater, Australia has maintained its position in radio astronomy. Today the telescope has observing programs related to most of the big areas of the field: the Cosmic Microwave Background, 'dark matter' and gamma-ray bursters, for instance. None of these subjects were the hot topics when the telescope was being planned but, as usual, the most exciting research is what is not foreseen. The designers of the telescope went for high resolving power – ability to see detail – both for its own sake and so the Australia Telescope would complement the new infrared, optical and X-ray telescopes coming on stream, as well as the U.S. Very Large Array (VLA), the major radio telescope in the Northern Hemisphere. The ATCA was fully funded by the Australian government, featured a very high fraction of Australian industrial content and was a bicentennial project.

Optical/infrared telescope technology progressed further during the 1990s with the development of 8 metre mirrors with active optics support systems. After an ARC Discipline Strategy Review Australia joined the Gemini Observatory project which constructed an identical 8 metre class telescope in each hemisphere, one in Hawaii and one in Chile. As a site, Chile has the advantage of higher mountains than Australia, lessening the effect of atmospheric turbulence on optical images. Originally asked to be a 10% partner in the project, Australia initially demurred, eventually having to settle for a 6% share. The ANU has built two state of the art instruments for the Gemini telescopes. The Gemini telescopes (with Australian astronomers on the team) are already noted for the discovery that the stellar and chemical maturity of massive galaxies is reached remarkably early in cosmic time.

This leads us to the present day and Australian participation in two state of the art international projects, the Square Kilometre Array radio telescope and the 30 metre class optical telescopes dubbed “Extremely Large Telescopes” or ELTs. The lessons of the historical development of Australian astronomical facilities are these:

- It is essential to be involved in internationally front rank new technology development projects. State of the art facilities open the windows for discovery.
- The cost of these new facilities is such that international partnership is a requirement. The partnership share should be appropriate for the maintenance of co-leadership in the discipline.
- Decadal reviews of astronomy are needed to prioritise new large scale projects.
- Government funding is expected to be dependent on a high level of local industry involvement.
- Access should be shared by astronomers from all Australian universities and research organisations, based on the scientific merit of proposals.
- The Australian public enthusiastically supports Australian research discovery in subjects that appeal to the imagination and excite interest in science and technology in young people.

The European Southern Observatory

Purpose

ESO, the European Southern Observatory, is the foremost intergovernmental astronomy organisation in Europe and the world's most productive astronomical observatory. ESO provides state-of-the-art research facilities to astronomers and is supported by Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Italy, the Netherlands, Portugal, Spain, Sweden, Switzerland and the United Kingdom. Several other countries have expressed an active interest in membership, including Brazil, which recently signed a formal accession agreement with ESO.

ESO's main mission, laid down in its 1962 founding Convention, is to provide state-of-the-art research facilities to astronomers and astrophysicists, allowing them to conduct front-line science in the best conditions. The annual member state contributions to ESO are approximately 135 million Euros and ESO employs around 700 staff members. By building and operating a suite of the world's most powerful ground-based astronomical telescopes enabling important scientific discoveries, ESO offers numerous possibilities for technology spin-off and transfer, together with high technology contract opportunities, and is a dramatic showcase for industry.

Operations

Whilst the Headquarters (comprising the scientific, technical and administrative centre of the organisation) are located in Garching near Munich in Germany, ESO operates, in addition to the Santiago Centre, three unique observing sites in Chile.

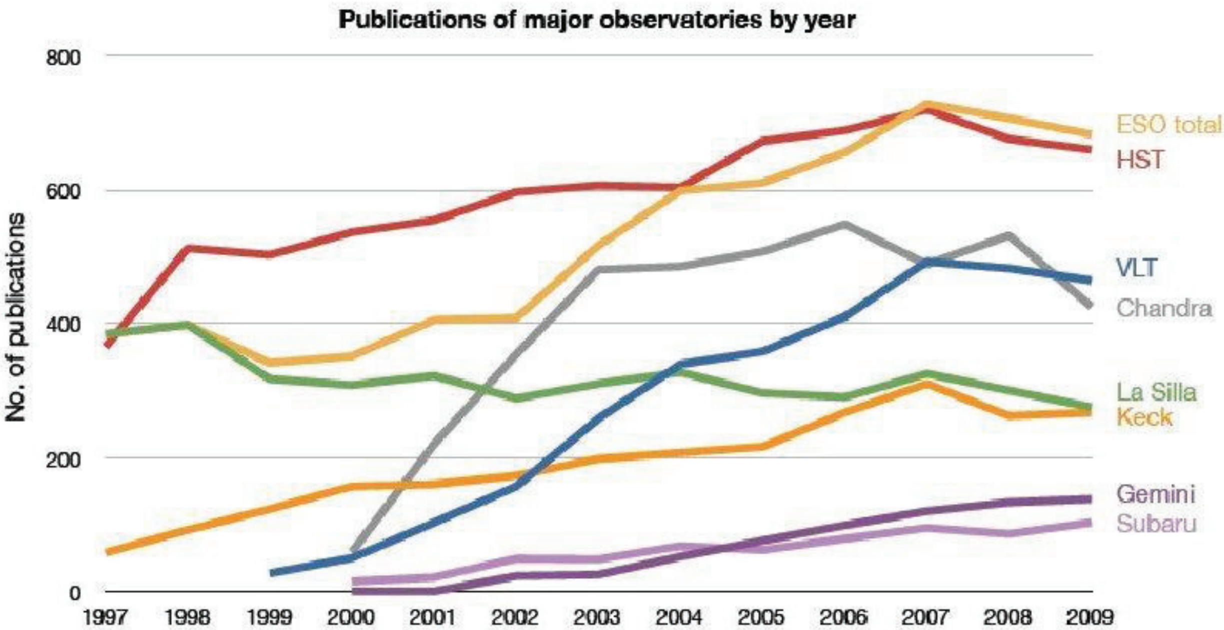
At La Silla, ESO operates several medium-sized optical telescopes, including the most successful low-mass exoplanet hunter.

The Very Large Telescope (VLT), the world's most advanced visible-light astronomical observatory, is located on the 2600 metre high mountain of Paranal, which also hosts the VLT Interferometer and two survey telescopes, the VST and VISTA. The third site is the 5000 metre high Llano de Chajnantor, near San Pedro de Atacama. Here a submillimetre telescope (APEX) is in operation, and a revolutionary telescope – a giant array of 12 metre submillimetre antennas (ALMA) – is being constructed in collaboration with North America, East Asia and Chile.

ESO is currently planning a 42 metre European Extremely Large optical/near-infrared Telescope, the E-ELT, which will become "the world's biggest eye on the sky". The chosen site for the E-ELT is Cerro Armazones adjacent to Paranal.

With ESO's telescopes, astronomers tackle key questions that challenge our minds and our imagination. Astronomy is the study of origins. It is also the study of grandiose events. And great mysteries. Most of all, however, it is humankind's boldest attempt to understand the world in which we live.

Each year, about 2000 proposals are made for the use of ESO telescopes, requesting between four and six times more nights than are available. ESO is the most productive ground-based observatory in the world, which annually results in many peer-reviewed publications: in 2009 alone, more than 650 refereed papers based on ESO data were published. Moreover, research articles based on VLT data are in the mean quoted twice as often as the average.



Strategy

ESO's strategy is to build and operate astronomical facilities of a scale larger than individual nations can develop for themselves. This role is by definition complementary to the national effort of countries such as Australia, which operates as national facilities the Australia Telescope Compact Array and the Anglo-Australian Telescope. There is also no confusion with the role of university facilities.

This strategy has been successfully executed since 1990 in the development of Paranal Observatory and ALMA (in collaboration with NRAO and NAOJ).

The history of ESO is described on its website. The assessment of ESO by the 2010 decadal survey of the US National Academies of Science is as follows:

"With the founding of European Southern Observatory (ESO) and its La Silla Observatory, Europe achieved near parity with the U.S. *public observatories* in the 1980's. The few other (non-ESO) OIR facilities in Europe still tend to be nationally funded and there has been a gradual de-emphasis on institutionally operated observatories. Overall, the European model has evolved toward collective public investment in shared major facilities, major investments in new instruments and data systems, and high levels of user support. In the 1990's Europe achieved full parity with the *combined public-private* U.S. OIR system, through the construction of the Paranal Observatory and its four 8-meter VLT telescopes. In some areas, such as high-resolution stellar spectroscopy, integral field spectroscopy, and data archiving, ESO has now established clear international leadership; the U.S. retains a lead in infrared detectors and high contrast imaging."

VLT and VLTI science

The four Unit Telescopes of the VLT on Cerro Paranal. In the foreground are the four auxiliary telescopes of the VLTI. Credit: ESO

Introduction

Australian astrophysicists and astrobiologists are working today on the fundamental physics of the Universe, the formation of galaxies, 'activity' in galaxies (due to supermassive black holes), the formation of stars and planets and the origin of life in the Galaxy. There are over 500 members of the Astronomical Society of Australia engaged in this research throughout the university system and the two supporting national facilities. These researchers need the best tools to do the job – in globally competitive research it is essential to be working with state of the art technology. The world's best optical and infrared telescopes in the southern hemisphere, where Australian astronomers tend to concentrate their efforts, are ESO's four 8 metre VLT telescopes (Very Large Telescope array). This is not because of anything fundamentally different between ESO's telescopes and Gemini's (Australia has been a member of the Gemini partnership since 1999), but ESO's suite of instruments on the VLT exceeds Gemini in its range of resolutions and wavelength coverage.

In addition, in stellar astrophysics ESO has built the global state of the art facilities for stellar interferometry, which was pioneered by Australian astronomers. With the VLTI ESO has an impressive lead in interferometric technology over the rest of the world, and Australian astronomers from Sydney University are well placed to capitalise on this. The VLTI is intended to achieve an effective angular resolution of 0.002 arcsec at a wavelength of 2 µm.

Optical spectroscopy

Notable achievements in optical spectroscopy in recent years include insights into galaxy evolution, recognition of the largest redshift Gamma Ray Bursters, investigation of the physical conditions of the intergalactic medium and chemical analysis of stars formed early in the history of the Universe. In galaxy evolution spectroscopic surveys reaching redshifts of 2 are showing that massive galaxies are fully formed at early times. This includes full chemical enrichment to solar metallicity. It is not really surprising, as massive galaxies, like massive stars, have relatively short dynamical timescales. A further recent discovery is that elliptical galaxies are denser and more compact at redshift 2. High resolution spectroscopy of quasars is providing an ever-improving probe of the cosmic web of gas, allowing questions to be addressed including: how intergalactic matter is assembled into galaxies; to what degree galaxy feedback regulates and enriches the intergalactic medium; and where and when these processes occur as a function of cosmic time. High resolution spectroscopy of the earliest stars is showing a remarkable diversity of chemical signatures, indicating a variety of processes contributing to the stellar first generation.

ESO's VLT provides a variety of optical spectrographs of varying resolution and multi-object capability to suit these scientific areas. FORS provides low to moderate resolution spectroscopy of a modest number of objects in a 7 arcmin field. High resolution is the role of the echelle spectrograph, UVES, which can service up to eight objects with the FLAMES fibre feed. FLAMES can also observe up to 130 objects simultaneously with the GIRAFFE medium resolution spectrograph. High capacity, low resolution multi-slit spectroscopy is provided by VIMOS, which has four 7 x 8 arcmin fields. The first second-generation VLT instrument has just been commissioned, XSHOOTER, which covers the whole 360-2000 nm wavelength region in a single exposure.

Infrared spectroscopy

Spectroscopy in the infrared on 8 metre telescopes has opened up a range of topics in the last decade. These include:

- protoplanetary disks, the circumstellar environment of stars in the formation process,
- brown dwarfs, the lowest mass stars and the highest mass planets,
- the stellar population of regions of low mass star formation,
- the physics of massive star formation regions,
- the chemistry of asymptotic giant branch stars,
- the ages of stars orbiting the Milky Way's 3 million solar mass central black hole,
- high velocity winds in star forming galaxies at redshift 2,
- star formation in the vicinity of Active Galactic Nuclei, and
- the physical conditions close to supermassive black holes.

On the VLT there is a high resolution infrared spectrograph, CRIRES and an integral field unit spectrograph, SINFONI with an optional adaptive optics feed. Low resolution spectroscopy is provided by the ISAAC instrument. One of ESO's second generation VLT instruments is KMOS which will deploy a suite of 24 integral field units.

Adaptive Optics

The effect of atmospheric turbulence on the wavefront of astronomical sources can be corrected over a finite field of view by shaping a small deformable mirror in the telescope optics in response to information from a bright star in the field. Adaptive optics (AO) opens up the diffraction limit in the infrared, where the corrections are spatially and temporally achievable (0.05 arcsec at 1.6 metre wavelength). Real performance is measured by the

Strehl ratio, the image peak intensity divided by the diffraction limited peak. In the absence of a natural guide star, laser guide stars are projected into the field.

Applications of adaptive optics are very general, including most critically imaging of objects in the solar system, resolution of star clusters, astrometry of stars orbiting the Galactic Centre and imaging of high redshift galaxies. Imaging of exoplanets, where the requirement is for highly efficient contrast with the host star's light, is termed Extreme Adaptive Optics. Another area of development is Multi-Conjugate Adaptive Optics, in which a vertical profile of the atmospheric turbulence is measured, allowing AO correction of a field of, say, 2 arcmin with an adequate Strehl ratio.

ESO has deployed adaptive optics, and both natural guide star and laser guide star systems are in regular use. ESO's exoplanet science is performed using NaCo and ESO is currently working on SPHERE, an upgraded instrument for exoplanet research using Extreme AO. ESO has also demonstrated a working multi-conjugate AO system.

The VLT Interferometer

Australian astronomers are the pioneers of the development of stellar interferometry. Applications of this technology include:

- Accurate angular diameter determinations.
- Double-lined spectroscopic binaries for accurate masses and testing of evolutionary models — including pre-main sequence stars.
- The mean diameters and distances of Cepheid variables.
- The shapes of rapidly rotating stars.
- Limb-darkening studies.
- Circumstellar environs — dust, disks, and winds.
- Multi-wavelength observations of hot massive stars, including modelling envelopes.
- 10 µm observations of a compact emission region at the Galactic centre.
- Observations and simple modelling of dusty tori in Active Galactic Nuclei, revealing a hot embedded dust component.

The VLTI, with its four 1.8 metre Auxiliary Telescopes and four 8.2 metre Unit Telescopes, has no peer as the world's foremost infrared interferometer. Its growing productivity makes it a significant component of the scientific prowess of ESO.

Instrument Development Program

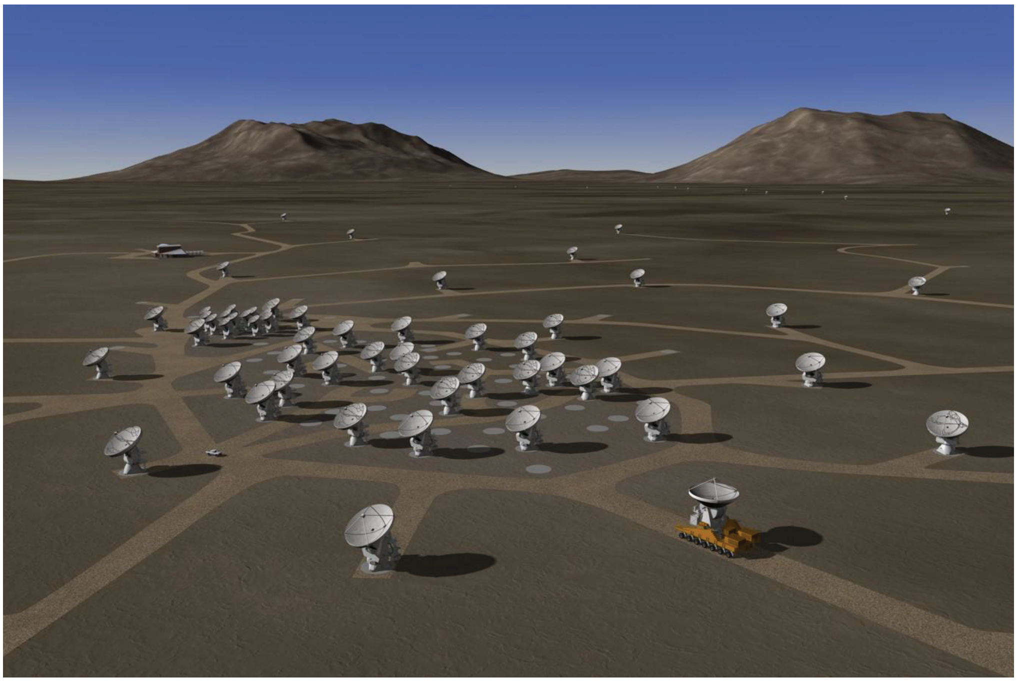
The Multi Unit Spectroscopic Explorer (MUSE) is a second generation instrument in development for ESO's VLT. It is a panoramic integral-field spectrograph operating in the visible wavelength range. It combines a wide field of view with the improved spatial resolution provided by adaptive optics and covers a large simultaneous spectral range. MUSE couples the discovery potential of an imaging device to the measuring capabilities of a spectrograph, while taking advantage of the increased spatial resolution provided by adaptive optics. MUSE splits the adaptive optics corrected field of view into 24 sub-fields. Each of these sub-fields is fed into an Integral Field Unit spectrograph.

MUSE will feature a Wide Field Mode with a field of view covering 1 x 1 arcmin and a Narrow Field Mode with a field of view of 7.5 x 7.5 arcsec.

MUSE will be optimised for the study of:

- Formation of galaxies:
  - high redshift Lyman alpha emitters
  - fluorescent emission and the cosmic web
  - reionisation
  - feedback processes and galaxy formation
  - ultra-deep surveys using strong gravitational lensing
  - resolved spectroscopy at intermediate redshifts
  - Sunyaev-Zeldovich effect
  - late forming population III objects
- Nearby galaxies:
  - supermassive black holes in nearby galaxies
  - kinematics and stellar populations
  - interacting galaxies
  - star formation in nearby galaxies
- Stars and resolved stellar populations:
  - early stages of stellar evolution
  - massive spectroscopy of stellar fields
  - the Milky Way and the Magellanic Clouds
  - the Local Group and beyond
- Solar system:
  - Galilean satellites, Titan
  - surface heterogeneities of the small bodies
  - temporal changes in the gas giant planets

ALMA science



An artist's impression of the ALMA array at Chajnantor, the Atacama site. Credit: ALMA (ESO/NAOJ/NRAO)

The first truly global telescope project is the Atacama Large Millimetre Array (ALMA). ALMA is under construction at Chajnantor in northern Chile by ESO, NRAO (North America) and NAOJ (East Asia). It is composed of at least 66 high-precision 12 metre diameter antennas at a site 5000 metres above sea level, a site which offers the exceptionally dry and clear sky required to operate at millimetre and submillimetre wavelength. The antennas will have reconfigurable baselines ranging from 15 metres to 18 km. Resolutions as fine as 0.005 arcsec will be achieved at the highest frequencies, a factor of ten better than the Hubble Space Telescope.

The quality of the observing site, combined with the unprecedented combination of sensitivity, angular resolution, spectral resolution and image fidelity made possible with ALMA, will enable astronomers to carry out transformational research in a wide variety of astronomical areas. The wavelengths covered by ALMA range from 0.3 mm to 3.6 mm (frequency coverage of 84 GHz to 950 GHz) – this range is essential for probing the first stars and galaxies, directly imaging the disks in which planets are formed, and probing the energy output from luminous starburst galaxies.

Through membership of ESO Australian astronomers would benefit from involvement in this research. Australia brings to the table the ATCA which has a larger field of view at 7-12 mm than ALMA has at 3 mm, plus the ability to observe a lower frequency range (1-50 GHz) than ALMA. We cannot penetrate to shorter wavelengths because of Australia's low altitude. We also bring to the table world-class receiver construction skills, which will be important as ALMA proceeds beyond its initial complement of wavelength capabilities.

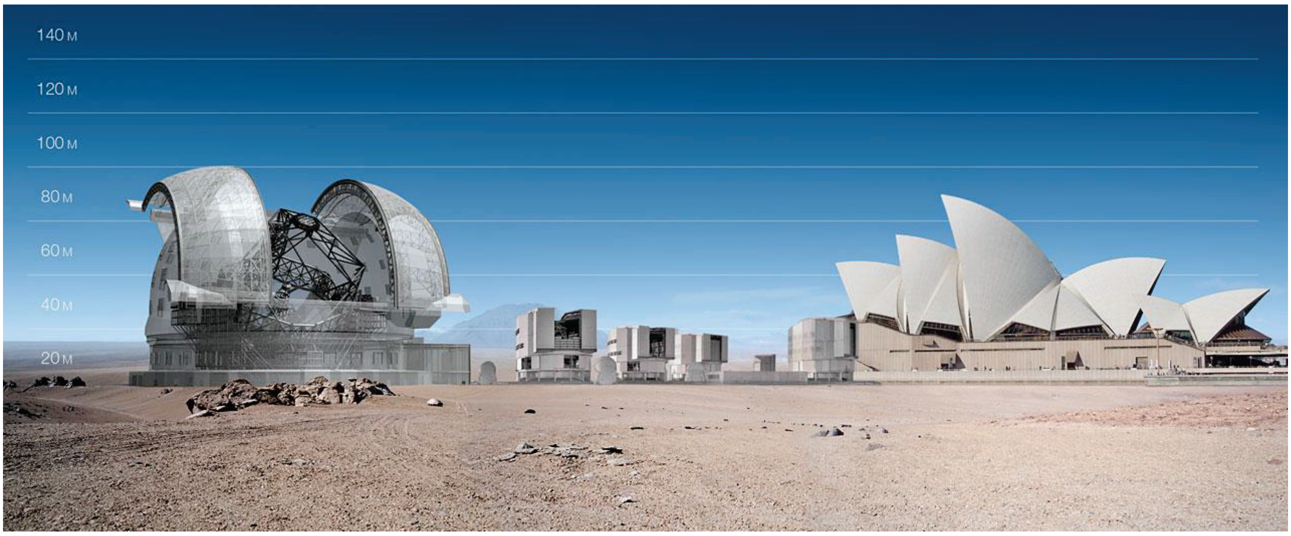
This remarkable instrument will be able to:

- image the redshifted dust continuum emission from evolving galaxies at epochs of formation as early as z = 10. ALMA is an ideal instrument for investigating the origins of galaxies in the early universe, with confusion minimized by the high spatial resolution;
- use the emission from CO to measure the redshift of star-forming galaxies throughout the universe. The large instantaneous total bandwidth of ALMA will make possible blind surveys in order to establish the star-forming history of the universe, without the uncertainties inherent in optical and UV studies caused by dust extinction;
- probe the cold dust and molecular gas in nearby galaxies, allowing detailed studies of the interstellar medium in different galactic environments, the effect of the physical conditions on the local star formation history, and galactic structure. The resolution of ALMA will reveal the kinematics of obscured active galactic nuclei and quasars on spatial scales of 10-100 pc, and will be able to test unification models of Seyfert galaxies;
- image the complex dynamics of the molecular gas at the centre of our own Galaxy with unprecedented spatial resolution, thereby revealing the tidal, magnetic, and turbulent processes that make stellar birth and death at the Galactic Centre more extreme than in the local Solar neighbourhood;
- study star formation in the Magellanic Clouds under different chemical conditions from the Milky Way;
- reveal the details of how stars form via the gravitational collapse of dense cores in molecular clouds. The spatial resolution of ALMA will allow the accretion of cloud material onto an accretion disk to be imaged, and will trace the formation and evolution of disks and jets in young protostellar systems. For older protostars and pre-main sequence stars ALMA will show how planets form, sweeping gaps in circumstellar and debris disks;
- uncover the chemical composition of the molecular gas surrounding young stars, including establishing the role of the freeze-out of gas-phase species onto grains, the re-release of these species back into the gas phase in the warm inner regions of circumstellar disks, and the subsequent formation of complex organic molecules. ALMA will have the large total bandwidth, high spectral resolution, and sensitivity needed to detect the myriad of lines associated with heavy, pre-biotic molecules such as those which may have been present in the young Solar System;
- image the formation of molecules and dust grains in the circumstellar shells and envelopes of evolved stars, novae, and supernovae. ALMA will resolve the crucial isotopic and chemical gradients within these circumstellar shells, which reflect the chronology of the invisible stellar nuclear processing;

ALMA will complement the Square Kilometre Array which will have similar resolution at longer wavelength (30 mm-4 metres) and wider field of view. Whereas ALMA will see the molecular gas and dust of the Universe, a primary focus of SKA will be neutral hydrogen.

An ALMA antenna en route from the Operations Support Facility to the plateau of Chajnantor for the first time. The ALMA transporter vehicle carefully carries the state-of-the-art antenna, with a diameter of 12 metres and a weight of about 100 tons, on the 28 km journey to the Array Operations Site, which is at an altitude of 5000m. Credit: ALMA (ESO/NAOJ/NRAO)

E-ELT science



A national icon juxtaposed with the VLT and the E-ELT. Credit: ESO

ESO has carried out phase A and phase B studies of a 42 metre optical/infrared telescope, the European Extremely Large Telescope (E-ELT), which will be the world's largest optical/infrared telescope. ESO Council approval for construction is pending. A site has been chosen for the E-ELT at Cerro Armazones, 15 km east of the VLT at Cerro Paranal and so there will be logistical economies from this proximity.

The E-ELT will study of 'first light' (the first stars to form in the Universe), high redshift supernovae and the variation of the parameters of fundamental physics. The E-ELT will also require work in difficult and innovative technologies to image terrestrial exoplanets (i.e. earths around nearby stars).

The scope of the scientific goals of ELTs is illustrated by the following list of projects:

- Characterizing the dark matter in the Universe by analyzing the dynamics of dwarf spheroidal galaxies – small, faint galaxies which are completely dominated by dark matter.
- Describing the dark matter distribution at redshift 3 by measuring the power spectrum of baryons over numerous lines of sight illuminated by galaxies.
- Obtaining the shape of the Galaxy's dark matter halo by measuring the orbits of stars in the Galactic centre.
- Investigating dark energy by probing the supernova Hubble diagram to high redshift.
- Detecting any variation of the fundamental physical constants with cosmic time.
- Discovering the primordial stellar systems responsible for the reionization of the Universe by detecting the He II 164 nm line whose strength is the marker for these objects.

- Investigating the intergalactic medium during the epoch of reionization. There are strong synergies with the James Webb Space Telescope (JWST) and ALMA in this area.
- Resolving galaxies during their peak epoch of growth at redshifts 2-4 and understanding their dynamics, star formation processes, chemical enrichment and exchanges with the intergalactic medium.
- Surveying the demographics of supermassive black holes in nearby galaxies and testing for the evolution of supermassive black holes out to redshift 1.5.
- Measuring the chemical composition of the earliest generation of stars.
- Learning the star formation and chemical enrichment history in nearby galaxies. The Virgo cluster is a laboratory of galaxy morphology and red giant branches in these galaxies are accessible to ELTs.
- Probing the physical conditions in protostellar cores and the inner parts of protoplanetary disks. There are synergies with JWST and ALMA in this investigation of star formation.
- Detecting earth-mass planets in the habitable zone of M stars and searching for oxygen in their atmospheres.
- Imaging giant planets in regions of star formation.

VISTA science

VISTA – located at ESO's Cerro Paranal Observatory in Chile. Credit: VISTA

The Visible and Infrared Survey Telescope for Astronomy (VISTA) is a 4 metre-class wide field survey telescope, equipped with a near infrared camera (1.65 degree diameter field of view) containing 67 million pixels of mean size 0.34 arcsec and available broad band filters at Z, Y, J, H, Ks and some narrow band filters. The telescope has a fast f/1 primary mirror giving an f/3.25 focus to the instrument at Cassegrain. VISTA is located at ESO's Cerro Paranal Observatory on its own peak about 1500 metres from the four VLTs and the VST.

There are six public surveys in progress:

- Ultra-VISTA aims to image one patch of the sky (the COSMOS field) over and over again to unprecedented depths. The science goals of Ultra-VISTA include studying the first galaxies, the stellar mass build-up during the peak epoch of star formation activity, and dust obscured star formation.
- The VIKING survey will image the same 1500 square degrees of the sky in Z, Y, J, H, and K to a limiting magnitude 1.4-magnitudes deeper than the UKIDSS Large Area Survey. The near-infrared data will be used for accurate photometric redshifts, an important step in the weak lensing analysis and the observation of baryon acoustic oscillations. Other science drivers include the hunt for high redshift quasars, galaxy clusters, and the study of galaxy stellar masses.
- The VISTA Magellanic Survey will image 184 square degrees of the Magellanic System, i.e., the Large Magellanic Cloud, the Small Magellanic Cloud, the Bridge, and the Magellanic Stream in the Y, J, and Ks wavebands. The survey will be used to study resolved stellar populations, the star formation history of the system as well as to trace its three-dimensional structure.

- VISTA Variables in the Via Lactea will target the galactic bulge and a piece of the adjacent plane. The total area of this survey is 520 square degrees and contains 355 open and 33 globular clusters. A catalogue with a billion point sources including a million variable objects is expected. These will be used to create a 3-dimensional map of the Bulge. Other science drivers include the ages of stellar populations, globular cluster evolution, as well as the stellar initial mass.
- The VISTA Hemisphere Survey will image the entire approximately 20,000 square degrees of the Southern Sky. The resulting data will be about 4 magnitudes deeper than 2MASS and DENIS. The 5000 square degrees covered by the Dark Energy Survey (DES) will also be observed in H-band. The main science drivers of the VHS include: examining low mass and nearby stars; studying the merger history of the Galaxy; measuring the properties of Dark Energy; and searches for high redshift quasars.
- VIDEO – VISTA Deep Extragalactic Observations Survey is a 15 square degree Z, Y, J, H, Ks survey to study galaxy evolution as a function of epoch and environment to redshift of about 4, using active galactic nuclei, galaxy cluster evolution, and very massive galaxies. The width and area of VIDEO are in between the wide but relatively shallow VIKING survey and the small, but very deep, Ultra-VISTA.

The synergies of VISTA with ASKAP are extremely strong. ASKAP is a facility in which Australia has invested well over $100 million already; membership of ESO will add value to this.

Some of the ASKAP Survey Science Projects that would benefit from follow-up by VISTA are:

- Evolutionary Map of the Universe (EMU). VISTA will measure stellar masses of these galaxies.
- Widefield ASKAP L-Band Legacy All-Sky Blind Survey (WALLABY). VISTA will complement SkyMapper magnitudes.
- An ASKAP Survey for Variables and Slow Transients (VAST). VISTA will provide deep IR reference frames.
- The Galactic ASKAP Spectral Line Survey (GASKAP). VISTA will penetrate the dust in the Galactic Plane.
- Deep Investigations of Neutral Gas Origins (DINGO). VISTA will measure stellar masses of these galaxies.
- Compact Objects with ASKAP: Surveys and Timing (COAST). VISTA will provide complementary IR survey data.

SKA Synergies with ESO

It is the nature of astrophysics that information from multiple wavelengths is more likely to solve a problem or make a discovery than observations in the radio or optical alone. The team that is able to muster optical resources to follow up on an SKA project is likely to go off with the prize. For this reason Australian membership of ESO is a highly desirable supplement to the SKA in terms of scientific return on investment.

There are several scientific areas where optical follow-up to SKA observations by the E-ELT or other ESO facilities will be needed. Indeed ASKAP, which will be operational before the SKA, will also require optical and millimeter follow-up of the kind available through ESO. Areas of interest for SKA follow-up include:

- **Epoch of Reionization:** The SKA and ELTs will be complementary in the investigation of the physics of *first light* in the Universe. The SKA will show the structure of the neutral hydrogen gas. ELTs will identify the sources of ionization.
- **Galaxy Evolution:** Galaxies are machines for turning gas into stars. After galaxy formation it is important to trace the life of galaxies over billions of years of cosmic evolution. The SKA will trace neutral hydrogen evolution both in mass density and dynamically; ALMA will do the same for CO; ELTs will trace the star formation history by measuring the recombination lines emitted when stars form and ionize their environment. The powerful adaptive optics unique to ELTs will be vital for this purpose.
- **Star Formation:** The SKA is expected to probe the physics of star formation, including the launching of jets of matter outflowing from new stars. The full physical investigation will require the use of ALMA and the VLTI, both of which are only possible through membership of ESO.
- **Extrasolar planets:** The SKA will be able to detect the radio emission from Jupiter like planets. The full explosion of knowledge about other solar systems will come from a coordinated program of optical Doppler surveys, transit surveys and microlensing surveys, culminating in direct detection using the extreme adaptive optics capabilities of ELTs.
- **Pulsars:** The SKA will advance pulsar science with a larger census and more accurate timing. One of the goals of the ELTs is to detect optical emission from neutron stars, measuring the effective temperature of the thermal radiation and thus the radius. This will be a major advance in studying the equation of state at nuclear densities.

Several of the ASKAP Survey Science Projects would also benefit from follow-up observations by ESO facilities. Some of the synergies of ASKAP with VISTA have been listed in an earlier section, and there are also strong synergies in the area of galaxy evolution as discussed above for the SKA. The ASKAP WALLABY HI emission-line survey will detect large numbers of gas-rich galaxies in the local universe, and follow-up CO observations of some of these galaxies with ALMA will enable the first large and co-ordinated study of atomic and molecular gas in galaxies, providing important pathfinder science for SKA. The ASKAP DINGO survey will detect HI emission in more distant galaxies, and follow-up CO observations of these galaxies will be important to disentangle the relationship between gas supply and star-formation rate in these more distant systems.

Other ASKAP projects where follow-up ALMA observations would be useful include:

- The First Large Absorption Survey in HI (FLASH). VLT IFU images will measure the masses of the black holes which generate the radio continuum emission. FLASH will also identify several hundred HI-selected galaxies in the very distant universe (spanning several billion years of cosmic time to an epoch when the universe was less than half its current age), providing a unique galaxy sample for further study with ALMA. Polarization Sky Survey of the Universe's Magnetism (POSSUM). ALMA will provide high frequency measurements of polarized sources.
- The Commensal Real-time ASKAP Fast Transients survey (CRAFT). Follow-up by SkyMapper, AAT and VLT will be required.
- The High Resolution Components of ASKAP: Meeting the Long Baseline Specifications for the SKA (VLBI). VLBI sources will be followed up with VLT.
- Compact Objects with ASKAP: Surveys and Timing (COAST). The E-ELT will be capable of detecting pulsars optically and measuring their stellar radii.