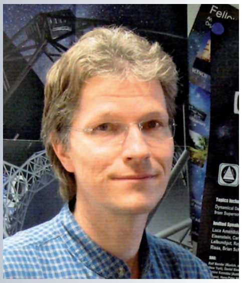
ESO
Karl-Schwarzschild-Strasse 2
D-85738 Garching
Germany
bleibundgut@eso.org

Contents

Bruno Leibundgut

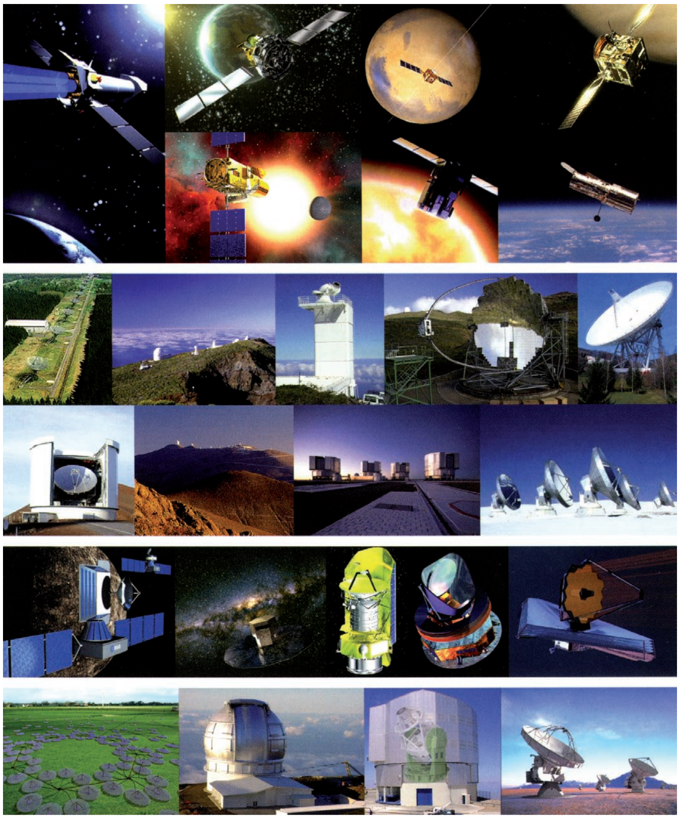
European Southern Observatory



Astrophysics for the next decade

Abstract

Astrophysics has entered a 'golden age' with access to the complete electromagnetic spectrum through a combination of ground- and space-based observatories. Scientific results of the past decades have revolutionised the view of the universe and placed the solar system in a new context. Plans for the observational facilities of the next decade are drawn up defining the future of astrophysics. The current evolution of the existing and planned ESO facilities is used as a case study to address some of the most prominent science questions.



A selection of observing facilities accessible to European astronomers. Taken from the ASTRONET Roadmap (Bode et al. 2008).

1. Introduction

Every generation of astronomers has tried to define the most exciting research topics and to forecast what the new facilities will bring and where they should concentrate their efforts. Planning for the future with the existing telescopes and instruments, and the enabling opportunities of new observatories remains a critical task. Observational astrophysics also depends on large facilities and regular planning on national as well as European levels appears appropriate. The major research themes have been, and still are being, collected in science vision documents, roadmaps, decadal reviews and other planning documents. An incomplete collection includes the European ASTRONET Science Vision (de Zeeuw and Molster 2007), the ASTRONET Roadmap (Bode et al. 2008), the ESA Cosmic Vision (Bignami et al. 2005), the series of working group reports commissioned by ESA and ESO (Exoplanets – Perryman et al. 2005; ALMA-Herschel Synergy – Wilson et al. 2006; Fundamental Cosmology – Peacock et al. 2006; Galactic Populations, Chemistry and Dynamics – Turon et al. 2008), several national decadal reviews in Europe (a list of national plans can be found on the ASTRONET home page: http://www.astronet-eu.org/-Science-Vision-) and other parts of the world, astroparticle roadmaps (e.g. the European ASPERA roadmap: Spiering et al. 2008), and specific publications. An ESO conference on Science with the VLT in the ELT Era was held recently (Moorwood 2009). It is not too surprising that the scientific goals and themes of new facilities often read fairly similar. Examples are the characterisation of dark energy and dark matter, observations of the light from the first objects in the early universe, the objects responsible for the ionisation of the intergalactic material, the formation and evolution of galaxies as well as the formation of stars and planets are present in most science cases.

The full electromagnetic spectrum is now accessible to observations. We are currently in a situation where we can observe photons of energies from a few hundred TeV (corresponding to a wavelength of $1.2 \bullet 10^{-20}$ m) to wavelengths of several meters (or an energy of $1.2 \bullet 10^{-8}$ eV), i.e. over 20 orders of magnitudes can be monitored. The combination of space and ground observatories provides access to the sky never enjoyed before. The ‘spectrum’ is now extended to other particles (‘messengers’) through cosmic ray research, astrophysical neutrinos, the prospect of detecting gravitational waves and discovering dark matter particles in underground laboratories. This combination of fantastic observing capabilities and some of the dramatic discoveries of the past decades have led some to proclaim a ‘Golden Age in Astrophysics’. The International Year of Astronomy 2009 is a fitting celebration of the achievements and the promises of astrophysics, the role it plays in our world view and the universe we live in. Engaging the public’s interest in the world we inhabit and the cosmos engulfing us brings enhanced visibility and responsibility.

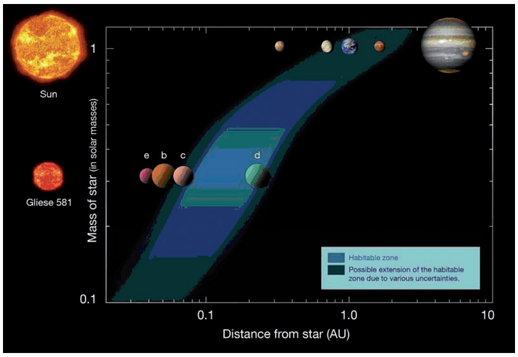
2. Research themes

The most prominent astronomical results over the past decades are leading to new questions. The following sections give a personal view of the achievements of past years and the prospects for the coming decade. Predicting the future is notoriously difficult and I will not venture too far. However, I believe that clear lines of research can be discerned and are the basis for several instruments in development or planning. I will mostly concentrate on the ESO programme for VLT instruments and future facilities.

3. What matters in the universe?

The discovery of dark energy and the long-standing enigma of dark matter remain major puzzles to be resolved. If the past decade is any guidance, then we are expecting large surveys and concerted efforts using many telescopes to achieve a further decrease in the uncertainty on the equation of state parameter of dark energy and to map out the gravitational growth of structure in the universe. The requirement to collect very large samples over large sky areas results in major projects of global scale and distributed efforts. Five main astrophysical methods are currently discussed to further improve our understanding of cosmology: Baryonic acoustic oscillations (BAO), weak lensing, supernovae, galaxy clusters and redshift space distortions. With the exception of distances derived from supernova observations all methods determine a combination of the expansion history and the growth of structure, i.e. dark matter concentrations. Examples of BAO surveys are the 2dF survey with the Anglo-Australian Telescope (Cole et al. 2005) and the Sloan Digital Sky Survey (Eisenstein et al. 2005). These are now followed by the WiggleZ survey (Drinkwater et al. 2009) and the Baryonic Oscillation Spectroscopic Survey (BOSS; Schlegel et al. 2007). One of the first massive weak lensing surveys is part of the Canada-France-Hawaii Telescope Legacy Survey (Hoekstra et al. 2006). The CFHT Supernova Legacy Survey (SNLS), the ESSENCE project and nearby supernova searches have now provided a sample of about 1000 Type Ia supernovae useful for cosmology. A summary of supernova surveys can be found in Leibundgut (2008). Galaxy clusters principally have been based on X-ray surveys and have been followed up from the ground to establish the redshifts, cluster membership and cluster dynamics. Redshift distortions can also yield measurements of the growth rate of mass agglomerations.

All these surveys have made use of 4 m and 8 m telescopes over several years. Telescopes equipped with large multiplex facilities (either wide-field imagers or multi-object spectrographs) have been essential. The commitment of large fractions of observing time has also been critical for the success of such surveys. Due to their small field of view and the massive amount of observing time necessary, it is to be expected that extremely large telescopes will contribute mostly specific information on individual objects. Instruments at 8 m telescopes for wide-field surveys are Suprime-Cam and the FMOS multi-object spectrograph at Subaru. The 4 m LAMOST telescope is in commissioning with a very high multiplex spectrograph and is fully dedicated to wide-field spectroscopy. It will certainly be used for cosmological surveys. Plans for the extremely high multiplex spectrograph VIRUS are in an advanced state for the Hobby-Eberly Telescope (HET) to be used for the HETDEX project (Hill et al. 2008). VIMOS at the VLT has already provided a first measurement of the redshift distortion (Guzzo et al. 2008) and the VIPERS survey is currently being executed (http://vipers.lambrate.inaf.it/).



The planetary system around Gliese 581. The innermost planet has a mass of only 2 M♀. The outermost planet is within the habitable zone around this star. Adapted from Mayor et al. (2009; ESO Press Release 15/09).

An extremely large telescope can make a unique contribution by measuring the temporal change of redshifts and hence directly map the dynamics of the cosmic expansion (Liske et al. 2008). The CODEX experiment on the European Extremely Large Telescope (E-ELT) would be able to perform such a measurement. The fundamental requirement here is the very high spectral resolution and stability (to be achieved with laser combs, Steinmetz et al. 2008), sufficient photon collecting power and a long time line. This is clearly a measurement that is beyond any existing telescope facility.

Further progress could be achieved through a dedicated space mission covering the whole extra-galactic sky. ESA is currently studying EUCLID, which would measure the equation of state parameter of dark energy to 1% accuracy. Such a mission will require ground-based support for calibration.

4. Planets, planets, planets

Our place in the universe can only be understood, if we have a better picture of how the solar system compares to planetary systems around other stars. This has been the most rapidly growing field of astronomy over the past decade and has produced several hundred known exoplanets in about 15 years (Udry and Santos 2007). There are three major ways to detect and characterize exo-planets: radial velocity changes in the parent star, direct imaging and detection of planetary transits as extremely faint eclipses of stars. Three additional methods are discovery by the periodic modulation in a pulsar signal, gravitational lensing by a foreground star (Beaulieu et al. 2006) and the astrometric movements of the parent star. Only one planetary system (with three planets) around a pulsar has been discovered (Wolszczan and Frail 1992). These systems must be extraordinarily rare as it is not obvious how a planetary system can survive the formation of the neutron star. Microlensing measurements have the impediment that it is very difficult to obtain additional information about the parent star or the planet after the lensing event. So far, the optical/infrared interferometers have not been powerful enough to measure the reflex motion in the astrometry of star, although the VLTI might be in a position to do this once PRIMA has been fully commissioned (Delplancke et al. 2003). A complete "discovery tree" for exo-planets can be found in Perryman et al. (2005).

The most important goals for the coming years are the characterization of planetary systems (rather than individual planets), a complete census of the mass distribution of planets, as well as their chemical composition and temperatures. Several planetary systems, i.e. stars which are known to harbour two or more planets, have been found so far. Currently, the measured mass distribution is highly biased as massive planets in short orbits are strongly favoured by the radial velocity method. Only the combination of several discovery schemes and increased sensitivity will provide a more complete picture. The measurement of chemical composition of planets has been done through differential spectroscopy in transiting systems. Direct spectroscopy of planets that can be separated from their host star will provide a significant improvement in the analysis.

A real industry of radial velocity projects has sprung up making use of many telescopes from 1 m to 10 m diameters. The observational requirements here are high spectral resolution and extended time series to measure at least a large fraction of an orbit or several orbits. Since planets at large distance from their host star have large periods, they can only be discovered by patient people. The currently most successful instruments are HARPS at the ESO 3.6 m telescope and HIRES at Keck. HARPS has recently found the least massive planet known with only twice Earth's mass (Mayor et al. 2009). The combination of planet transits with host star radial velocities is especially precious as masses, sizes and mean densities of the planet can be determined. The CoRoT satellite has already found several such planets and their masses have been determined through HARPS measurements (e.g. Moutou et al. 2008). The addition of HARPS North at the William Herschel Telescope will provide a full sky coverage and in particular supply the radial velocity measurements of transiting planets found by the Kepler satellite. The future of the radial velocity method will see the extension to fainter magnitudes with the ESPRESSO instrument on the VLT (Pasquini et al. 2009) and CODEX at the E-ELT.

Direct imaging has mostly been done in the near infrared where the contrast between the host star and the planet is strongest. In particular, young planets are still cooling and are more easily detected in the near-IR. A high spatial resolution calls for adaptive optics (AO) instrumentation on large telescopes or imaging with space telescopes. It is no surprise that all current 8m telescopes have invested in AO. Keck, Gemini, Subaru and the VLT possess the capability to correct for image distortion caused by atmospheric turbulence and all these telescopes have found exo-planets and exoplanetary systems recently (Marois et al. 2008, Lagrange et al. 2008). These observatories are also investing in the next generation adaptive optics systems with several laser guide stars. At the same time several new instruments are developed for direct imaging of planets close to their star.

At ESO the SPHERE (Spectro-Polarimetric High-contrast Exoplanet Research) instrument is being built to directly observe and analyse planets around nearby stars. It will concentrate on young star associations, stars with already known planets from other detection methods and stars younger than 1 Gyr, when the brightness contrast between star and planet is high. A contrast of 14 to 16 magnitudes and very high angular resolution down to 0.1 arcsecond separations plus sensitivity to H≈24 mag are essential for this instrument. In addition, low resolution spectroscopy is included to characterise the planetary atmosphere. SPHERE will contain an optical and a near-infrared channel. Extreme adaptive optics combined with a coronagraph and dual-beam design for accurate image subtraction are employed to achieve the demanding requirements. The optical channel will be equipped with a polarimeter to separate the reflected light close from the star and hence further increase the contrast. A description of the instrument can be found in Beuzit et al. (2006). SPHERE should become available at the VLT in 2011.

A completely different option is to use interferometry for the characterisation of planetary systems. The MATISSE instrument for VLTI is in the preliminary design phase. Through its capability of combining up to four beams, it will be able to directly image planets at mid-infrared wavelengths.

A natural evolution in this field is to explore the increased angular resolution provided by larger telescopes and hence it is no surprise that direct imaging for planetary systems is one of the ELT core programmes. At ESO the EPICS instrument study is exploring the possibilities for the E-ELT.

5. How did stars and planets form?

The very early stages of star formation are hidden in the cores of dense molecular clouds and hence not directly observable at visible or near-IR wavelengths. The transition from the cloud collapse to the initial ignition of the nuclear burning has still not been observed. This field will profit most from the increased wavelength coverage that ALMA offers. The combination of angular resolution – to separate the individual sources in the crowded fields of their birth places – and the sensitivity at mm wavelengths is crucial to detect collapsing clouds and the increased heating of the surrounding gas by the nascent star. As the temperature increases and the surrounding material becomes ionised the object is revealed at progressively shorter wavelengths. The combination of different facilities to map the complete picture of star formation is essential. The disentangling of the different emission sites of the forming star and its environment are critical to improve our understanding of this process. The planetary disks and the later stages of the debris disks hold the signatures of forming planets. The chemistry of such disks is largely unexplored (although see the first results from MIDI at VLTI by van Boekel et al. 2004), but will become accessible with increased angular resolution and extended wavelength coverage. Matching angular resolution at all these wavelengths will yield the full picture. JWST is ideally suited to observe the warm disks and clouds, but the increased angular resolution of the extremely large telescopes will supply further details of the disks and possibly forming planets.

Since large telescopes are essentially diffraction limited in the thermal infrared the achievable angular resolution directly depends on the aperture. The advantage of the 8 m telescopes even over JWST for this type of research is obvious. CanariCam on the GTC will be ideally placed to explore the nearest star formation regions like Orion and Taurus. MATISSE at the VLTI will also be able to map star forming regions in great detail and an unchallenged angular resolution.

ALMA will have the potential to resolve many young circumstellar disks and detect gaps of planets. Combining this spatial information with the knowledge of the chemistry in the disk will provide unique details. The contribution of Thomas Henning has further details on the advances expected in this field in the coming years.

6. The Milky Way - our home

The solar neighbourhood and the structure of the Milky Way remain interesting fields of research. Astrometric missions, like HIPPARCOS and GAIA, are adding the proper motion information to the radial velocities and chemistry of the stars. The study of 14000 F and G stars over nearly two decades has provided a clearer picture about the dynamical evolution of these nearby stars (Nordström et al. 2004). The necessary sample size requires such very long studies. In this case, the objects are sparsely distributed on the sky and needed to be observed individually.

The structure of the Milky Way can only be understood through such coordinated, long-term efforts. The report by the ESA-ESO working group on stellar populations outlines what should be done in the coming years to make best use of the GAIA results combined with ground-based telescopes (Turon et al. 2008). The need for spectroscopy of thousands of stars is stressed in that report. Highly multiplexed facilities or observatories willing to invest large amounts of observing time will be in an excellent position to make such contributions.

The Galactic Bulge remains an active area of research. The exact composition and formation of this important galactic structure, observed through the Galactic bar, are the topic of many ongoing studies. The potential to separate stars according to their proper motion and a better isolation of the bulge stars from the foreground further improves the knowledge on the composition of the Milky Way.

Combining the information from gas flows, the stellar dynamics and the chemical composition of the various components holds the promise to fully disentangle the evolution of the Galaxy. The SDSS has found many dwarf galaxies around the Milky Way and provided clues to understand the growth of our Galaxy and the dark matter distribution around us. At the same time the existence of the densest and most massive star clusters near the centre of the Milky Way (Genzel et al. 2003a) together with high-energy phenomena like the observed 511keV electron-positron annihilation γ-ray line near the centre (Churazov et al. 2005) show that there is still a lot to be learned from this unique region on the sky and in our Milky Way.

7. Our own black hole

The accurate mapping of the innermost stellar orbits has proven beyond doubt that a super-massive black sits at the centre of the Milky Way (Schödel et al. 2002). The detection of infrared flashes from the position of Sagittarius A* (Genzel et al. 2003b) is the first evidence of matter falling into the black hole. This latter detection was only possible through adaptive optics. Multi-wavelength studies show the time behaviour of these flares. They ultimately will allow probing for the rotation of the black hole itself.

Probing the Galactic Centre has been a long-term undertaking and it is easy to predict that this research will continue for several years to come with the largest available telescopes. The exact measurement of the stellar orbits requires several years to map sufficient trajectories. In the future, precession of the peri-bothron (closest approach to the black hole) of the stellar orbits will provide even more details on the structure of the gravitational field around the black hole. Gemini South with the multi-conjugate adaptive optics system GEMS and also Keck with its next generation adaptive optics system NGAO will be well suited for these observations. ESO is developing the adaptive optics facility (AOF), which should provide further improved AO capabilities to the already existing AO-supported instruments NACO and SINFONI. All these observatories also use laser guide star facilities.

The goal now must be to explore the space-time geometry in the strong gravity regime. The black hole at the centre of the Milky Way is the nearest object, where we can hope to study many of the predictions of general relativity in detail. The Schwarzschild radius of the black hole is about 9 microarcseconds as seen from Earth and resolving emission from material on this angular scale should show many of the GR effects. Since the Galactic Centre is hidden behind several magnitudes of optical extinction, the only way to observe it is in the infrared. The resolution required for the above study can only be achieved through interferometry with the VLT unit telescopes. An instrument to explore this parameter space, GRAVITY, is currently in the design phase. It should allow astronomers to astrometrically probe this innermost region of our Galaxy. It may even be possible to determine the astrometry of individual flashes as a function of time. This would provide information on the very last moments of the matter falling into the black hole.

8. How did galaxies form and evolve?

There are four different redshift ranges of interest to track the evolution of galaxies. The galaxy population at $z>3$ needs to be mapped in more detail than is available today. These objects are mostly found through the Lyman-breaks in their spectrum, although one needs to be aware that this represents a selection. At higher redshifts galaxies are found through their Lyman-α emission. At redshift $1<z<2$ there is a population of massive galaxies with old stars. These ‘red and dead’ galaxies seem to have formed and exhausted their gas early. They form a significant fraction of the known mass in galaxies. A summary of the current knowledge of these objects is available in Bergeron (2009).

The build-up of the morphological Hubble sequence over cosmic time is a major topic in this field. The separate tracks of star-forming and passive galaxies need to be followed and possible crossings explored. The galaxies need to be identified in deep, wide-field imaging surveys and followed with massive spectroscopic surveys. Suprime-Cam on Subaru has made major contributions in this field and the upcoming survey telescopes VISTA, VST and later on LSST will provide plenty of objects.

At the moment the only spectropgraphs capable of such massive surveys are mounted on 4 m telescopes. The exceptions are VIMOS on the VLT and FMOS on Subaru, which is currently in commissioning. The large samples to be collected by these spectrographs will help understand the statistics of the different galaxy types.

The characterisation of internal dynamics of these galaxies needs to be explored to understand their evolutionary state. This requires high angular resolution as well as spatially resolved spectroscopy. Integral field spectrographs supported by adaptive optics are essential for this research. HST is a prime resource, but ground-based telescopes with adaptive optics can provide important contributions as well. There are many instruments currently mounted at 8 m telescopes. The VLT offers NACO and SINFONI, both supported by laser guide stars. The first GTC instrument, OSIRIS, with the important tunable-filter mode, which allows covering many galaxies in a field and quickly scan for emission-line objects, should be able to make important contributions. Future VLT instruments for this research will be KMOS as well as HAWK-I and MUSE supported by the adaptive optics facility. Of course, this is also one of the primary science cases of JWST. The future ELTs will provide even higher angular resolution, but will have to restrict themselves to small samples.

Objects at the highest redshifts are the scientific goal of almost all new facilities. The search for Lyman-α emitters and the detailed investigation of the intergalactic medium through the study of quasar absorption lines are the domain of large telescopes. JWST will have the advantage that the infrared background in space is limited to zodiacal light only. Subaru's Suprime-Cam has delivered most of the highest redshift galaxies (see Masanory Iye's contribution) and large sky areas need to be scanned to find these extremely rare and faint objects. LSST and EUCLID will provide many candidate objects, which will need to be followed up by optical and infrared spectroscopy. X-shooter and NACO at VLT, OSIRIS at the GTC, LRIS and DEIMOS at Keck and GMOS on the Gemini telescopes will be the instruments of choice to identify the nature of these objects. In the future AO-supported HAWK-I and MUSE together with KMOS on the VLT, MOSFire on Keck and EMIR on the GTC will provide tools to further investigate this rare population. Bergeron (2009) gives more details for VLT and ELT observations relevant for this field.

9. Fashions and other transient phenomena

Supernovae and Gamma-Ray Bursts (GRBs) have become very fashionable objects. Supernova cosmology (e.g. Leibundgut 2008) has provided evidence for dark energy and the connection of supernovae with the GRBs have sparked strong interest. While there is a lot of interesting physics to be learnt from these most energetic events, one should be careful not to overestimate their importance for astrophysics. Supernova explosions, both types – the core-collapse and the thermonuclear explosions – present some of the most fascinating physics, but at the same time also present some of the most challenging puzzles. It will remain to be seen how much the different observational methods will be able to contribute to these fields. In any case, the introduction of the rapid response mode at ESO (and Gemini) has provided the community with the capability to use 8 m telescopes to observe fast astronomical phenomena with the appropriate speed. In some cases GRBs could be observed within 10 minutes of the γ-ray detection by SWIFT (e.g. Vreeswijk et al. 2007). It is such types of specialisations, which can contribute dramatically to some observational fields.

On the other hand, there are scientific topics, which ‘resonate’ with instrumental capabilities. An example might be the study of active galactic nuclei (AGN) with low-resolution spectrographs at 4 m telescopes. The 8 m telescopes have contributed relatively little to the understanding of AGNs. However, accessing the innermost parts of AGN with interferometric observations, as is currently being done with the VLTI, will open up a new window into these astronomical power houses. The increased angular resolution has allowed the study of the inner torus of AGN_s(Jaffe et al. 2004).

Another spectacular success of 8 m telescopes has been the abundance studies of metal-poor stars (e.g. Cayrel et al. 2004). However, it is not clear in which direction this field is moving. It might well become part of the general studies of the stellar populations and the elemental distributions in our Galaxy described above.

All observatories need to be aware of emerging scientific trends and assess how they can position themselves to make an optimal contribution. ASTRONET is currently investigating how the 2 m to 4 m European telescopes can be coordinated to provide the most efficient resource for astronomy. A global coordination for 8 m telescopes is not planned, but it might be useful to discuss synergies between different observatories as it is done by the 8 m and 10 m telescopes on Mauna Kea.

10. When opportunity knocks

Nature occasionally provides us with unique and singular opportunities. SN 1987A was the nearest stellar explosion for several hundred years and has an uninterrupted observational record with HST and the VLT. This spectacular event continues to be observed with the major telescopes and remains a most interesting astrophysical object (for a summary of what has been learnt from SN 1987A see Fransson et al. 2007).

It is not possible to predict such events but observatories should be prepared to make best use when they occur. Flexible operational modes and the willingness to quickly identify and invest in such opportunities are instrumental for success. As the inauguration of the GTC on La Palma took place all major telescopes were observing Jupiter to follow up on an impact of a large body on the planet. This is now the second time such an impact can be studied in detail after Shoemaker-Levy 9 bombarded Jupiter in 1994. The solar system regularly offers surprising events.

We do not know what nature has in store for us, but we should be prepared to recognise the chance when it arises.

11. Telescopes of the future

The plans for extremely large telescopes need to be seen in context with the existing telescopes. There are now 13 telescopes operating with a diameter of more than 7 metres. Another 22 telescopes with diameters between 3 m and 7 m are available to astronomers. The bulk of the observations continues to come from these telescopes and it will be nearly a decade before any of the ELTs will start operations. The current suite of telescopes remains the basis for observational optical and infrared astronomy in the coming decade. Major additions in this size category will be JWST, LSST, VISTA, LAMOST and the Lowell Observatory's Discovery Telescope.

There are three ELT projects in advanced planning or with the first elements being procured, but they will clearly be outnumbered by the already existing 8 m to 10 m telescopes. The instrumentation on the ELTs will also be limited and will have to suit their strengths – light gathering power and angular resolution. Many scientific topics can very well be continued with the current telescopes and applications, which need large samples or long time series, will be better suited by the 8 m telescopes with state-of-the-art instrumentation.

The 8 m telescopes will remain the work horses of observational astronomy for the coming decade and beyond. They represent a distributed resource, which provides access for many different communities, and have a full instrumentation complement. The instrumentation on the VLT alone nearly covers the full available parameter space in term of wavelength coverage, spectral resolution, spectral multiplex and angular resolution combined with relatively large fields of view. Given this competition, it will be important for the observatories to decide where they want to put their resources and how they can optimally use the strengths of their telescopes. Examples of projects, which will most likely be preferably done with 8 m telescopes, are time series, collection of large samples, wide-field imaging and spectroscopy, and the search for rare objects. The 8 m telescopes will also be well suited to follow many space projects or complement ALMA observations.

The use of 4 m telescopes over the past decade can help to decide which strategies worked well. Several examples of successful specialisation of 4 m telescopes can be mentioned here: the exploitation of the wide-field capability of the AAT to produce the 2dF survey, the deep, wide-field imaging surveys of MegaCam on CFHT, UKIDSS, which made use of UKIRT, or the Mosaic2 camera on the CTIO Blanco telescope have produced important scientific results. The HARPS survey on the ESO 3.6 m telescope has made a clear difference in exo-planet research. It should be noted that these investments always were leveraged with dedication of large amounts of observing time. The time will come where the 8 m telescopes will benefit from such specialisations as well.

As mentioned several times already, there was and still is an important rôle for 8 m telescopes in complementing and enhancing surveys done with 4 m telescopes. The follow-up observations of UKIDSS, VST, VISTA, LSST and PanSTARRS will need a lot of 8 m time. Investigating rare objects found by such surveys in great detail with the large telescopes will be critical. The full exploration of the electromagnetic spectrum means that the 8 m telescopes will supply the optical and infrared photometry and spectroscopy to follow-up sources detected by Herschel, Fermi, XMM/Chandra, JWST and eROSITA. In many cases polarimetry will also be used to further investigate the light emission. Of course, ALMA and the SMA will be strong partners of the 8m telescopes for several decades to come.

12. ESO's next decade

ESO currently operates the La Silla Paranal Observatory, constructs ALMA and designs the E-ELT. It now receives well over 1000 observing proposal per (half-year) scheduling period. This means that ESO is handling over 2000 proposals per year for four 8 m VLT unit telescopes, the VLTI array, APEX, 3.6 m, NTT and the MPG 2.2 m telescope. Overall, it offered 23 different facility instruments plus a visitor focus on these telescopes for Period 84. Six instruments are undergoing upgrades of various forms and there are six VLT instruments in construction, under development or planning. In addition, the laser guide star facility went through a major upgrade programme recently and the adaptive optics facility providing a deformable secondary mirror is under development. Finally, the VLTI will be equipped with the phase referencing system PRIMA. All ESO data become publicly available through an extensive archive. Over 700 refereed publications based on data from ESO telescopes are published every year.

ESO is the European partner in the ALMA project and is responsible for several major deliverables. ALMA will start operations in 2013 with four receiver bands and 66 antennae. ESO is currently building up the ALMA Regional Centre with several nodes in member states.

At the same time ESO is finishing the design study for the European Extremely Large Telescope and pending Council approval will construct this telescope and instrumentation in the coming decade.

13. La Silla Paranal Observatory

The successful operations of the La Silla Paranal observatory remain a top priority for ESO. The VLT had reached its full instrument suite some years ago. In 2009 the first second generation instrument, X-shooter, has been commissioned and will start operating. Hence the VLT provides 11 facility instruments covering the whole optical and infrared electromagnetic spectrum plus adaptive optics support including laser operation. A visitor focus is maintained for highly specialised instruments. In addition, the VLT Interferometer with its auxiliary telescopes is operating about 200 nights per year. It is equipped with two instruments and is being upgraded with the Phase Reference Imaging and Micro-arcsecond Astrometry (PRIMA) facility.

The VLT on Paranal remains the prime observatory for European astronomers in the Southern hemisphere. Instrument upgrades and improvement of the facilities, like the laser guide star shown in this picture, are crucial for the continued success of the observatory.

PRIMA will give allow to observe much fainter sources than is currently possible and should make many interesting objects accessible to interferometry.

The instrumentation programme for the VLT continues with upgrades to existing instruments (e.g. detector upgrades for FLAMES/GIRAFFE, UVES, VIMOS, VISIR), upgrades of optical components (filters, gratings, grisms) and new instruments. In a few years the infrared multi-object spectrograph KMOS will be commissioned. It will be followed by MUSE, which will provide a massive integral field in the optical and will have many astrophysical applications. The planet finder SPHERE will make use of extreme adaptive optics to achieve the best possible angular resolution. The Adaptive Optics Facility will combine an adaptive secondary mirror with multiple laser guide stars to support HAWK-I and MUSE. A dedicated AO instrument is currently under discussion. VLTI is augmented with PRIMA and the future instruments GRAVITY and MATISSE to provide dual-feed fringe stabilisation, microarcsecond astrometry and closure phase observations. Detailed information on the VLT instruments can be found at http://www.eso.org/sci/facilities/paranal/instruments/ and http://www.eso.org/sci/facilities/develop/.

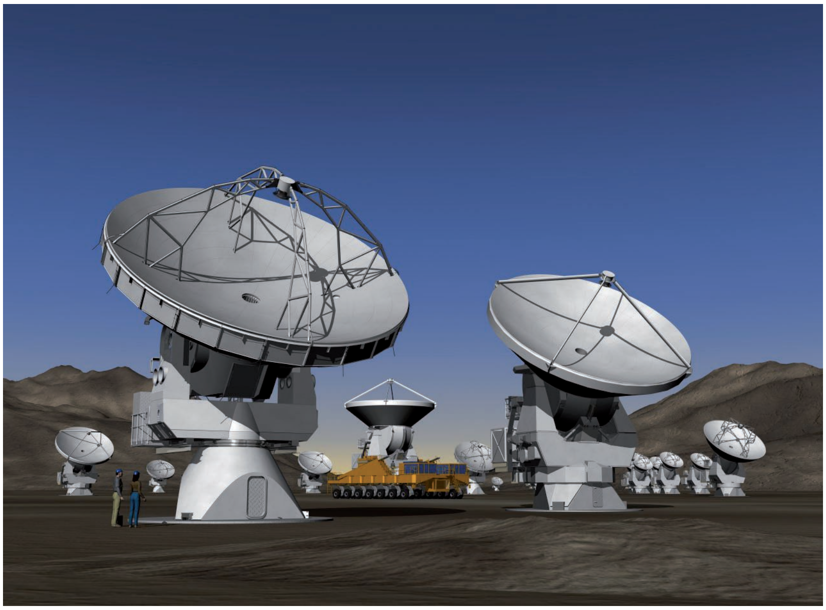
The 3.6 m telescope and the NTT on La Silla continue operations with extended long-term large observing programmes. HARPS is in strong demand and provides the most accurate radial velocity measurements globally. An upgrade to improve the spectral stability further and include a spectropolarimetry mode is ongoing. EFOSC2 and SOFI are the instruments on the NTT and afford access to general purpose projects. They are now in strong demand for multi-year supernova and solar system studies. The NTT also receives visitor instruments regularly for specialised observing methods. The wide-field imager WFI and the high-resolution spectrograph FEROS continue to be offered on the 2.2 m telescope.

In the next year the wide-field telescopes VISTA and VST will start operations and be used for massive public imaging surveys.

14. ALMA

The completion of the construction of ALMA within the next years is another primary goal of ESO. This global observatory is being built by a collaboration of Europe, North America and East Asia. The 66 antennae (50 with 12 m and 16 with 7 m diameter) at an altitude of 5000 meter will open a new window to the universe with the mm and sub-mm capabilities of the antenna array. The science requirements include the detection of carbon monoxide and the forbidden [C II] line in galaxies at a redshift of about 3, the dust emission and gas kinematics in proto-planetary disks and exploration of forming exo-planets. The resolution that ALMA can achieve will be comparable to the one from HST, JWST and AO-supported 8-10 m telescopes. ALMA's science goals are described at http://www.eso.org/sci/facilities/alma/science/goals.html where a link to the community-based design reference science plan can be found.

ALMA will offer four receiver bands at the start, but four more bands are under development. Eventually ALMA will offer a wavelength range from 84 GHz (3.6mm) to 950 GHz (320μm). The flexible array configuration will allow angular resolutions of better than 0.1 arcseconds. ESO provides the European access to this facility and is setting up the support of its community through the ALMA Regional Centre (ARC) and various national nodes. The scientific programme is strengthened through nine additional postdoctoral fellow positions funded by the European Union Marie-Curie scheme.

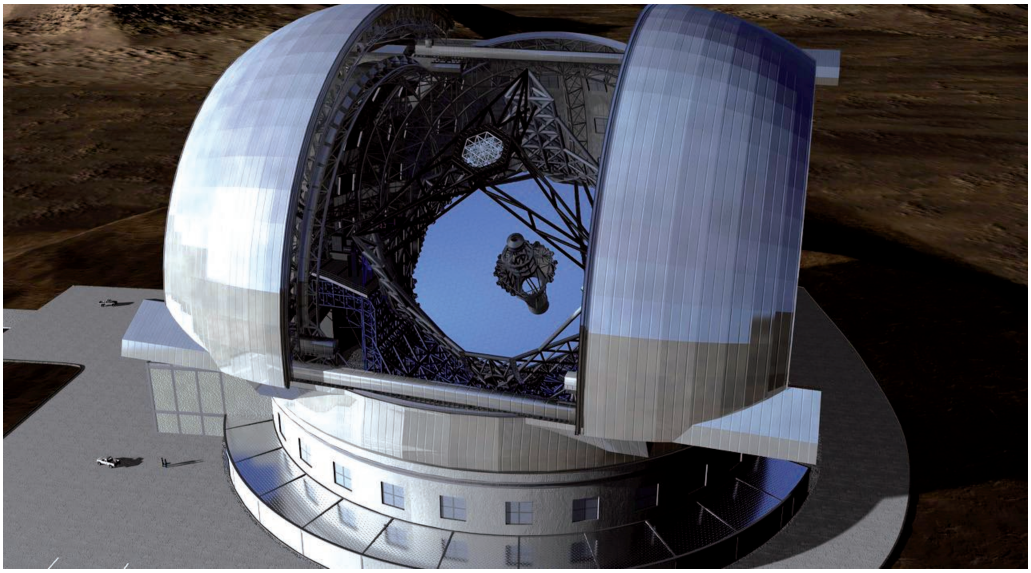


Artist impression of the ALMA observatory on Chajnantor. ALMA operations are planned to start in 2013 making this picture a reality.

ALMA synergy with the VLT and other optical/infrared telescopes is an important element for ESO. The coverage of the spectral energy distribution of many objects between the optical, which is typically dominated by the hot plasma of stars and the emission from cool gas and dust at mm wavelengths, is a very strong tool to disentangle complex and composite objects. Early science with ALMA is planned for late 2011 and full operations for 2013.

15. E-ELT

The detailed design study for a European Extremely Large Telescope of 42 m diameter will be finished in 2010 and a proposal for construction of the E-ELT will be presented to the ESO Council. It is ESO's next big project. The telescope has a revolutionary 5-mirror design which fully incorporates adaptive optics through a deformable mirror and a tip-tilt correction on a separate mirror. The science case for the E-ELT has been developed together with the community through the OPTICON network (e.g. Hook 2009) and will be delivered with the telescope proposal. The major themes are the same as described above. In addition, the E-ELT will have great power to resolve stellar populations beyond the Local Group. Eight possible instrument concepts for the E-ELT are being studied with the community (D'Odorico et al. 2009) together with two adaptive optics modules. There are currently 36 individual institutes from 10 member states involved in the instrument studies.



The E-ELT is the next large project for ESO. The study phase will be finished in 2010.

The E-ELT will strongly depend on synergetic observations with other facilities in space and on the ground. It will be a critical component in the telescope landscape with ALMA, JWST, survey telescopes and the Square Kilometre Array. Of course, the new parameter space accessible with the E-ELT will almost certainly reveal new phenomena, which are inaccessible to current telescopes. Despite the expected discovery potential of the E-ELT, the selection of the interesting objects will happen with the smaller telescopes and the 8 m telescopes will play a critical role for the effective and optimal use of the E-ELT.

16. References

Beaulieu, J.P., et al., 2006, Nature, 439, 437

Bergeron, J., 2009, in The VLT in the E-ELT Era, A. Moorwood (ed.), Heidelberg: Springer, 147

Beuzit, J.-L., et al., 2006, ESO Messenger, 125, 29

Bignami, G., Cargill, P., Schutz, B., Turon, C., 2005, Cosmic Vision: Space Science for Europe 2015-2025, Noordwijk: ESA, BR-247 (ISBN 92-9092-489-6)

Bode, M.F., Cruz, M.J., Molster, F.J. (eds.), 2008, The ASTRONET Infrastructure Roadmap, (ISBN 978-3-923524-63-1)

van Boekel, R., et al., 2004, Nature, 432, 479

Cayrel, R., et al., 2004, A&A, 416, 1117

Churazov, E., et al., 2005, MNRAS, 357, 1337

Cole, S., et al., 2005, MNRAS, 362, 505

Delplancke, F., et al., 2003, Ap&SS, 286, 99

Drinkwater, M., et al., 2009, AAO Newsletter, 115, 3

Eisenstein, D.J., et al., 2005, ApJ, 633, 560

Fransson, C., et al., 2007, ESO Messenger, 127, 44

Genzel, R., et al., 2003a, ApJ, 594, 812

Genzel, R., et al., 2003b, Nature, 425, 934

Guzzo, L., et al., 2008, Nature, 451, 541

Hill, G.J., et al., 2008, in Panoramic Views of Galaxy Formation and Evolution, T. Kodama, T. Yamada, and K. Aoki (eds.), San Francisco: Astronomical Society of the Pacific, Conference Series, 399, 115

Hoekstra, H., et al., 2006, ApJ, 647, 116

Hook, I., in Science with the VLT in the ELT Era, A. Moorwood (ed.), Heidelberg: Springer, 225

Jaffe, W., et al., 2004, Nature, 429, 47

Lagrange, A.M., et al., A&A, 493, L21

Leibundgut, B., 2008, Gen. Rel. Grav., 40, 221

Liske, J., et al., 2008, MNRAS, 386, 1192

Marois, C., et al., 2008, Science, 322, 1348

Mayor, M., et al., 2009, A&A, 493. 639

Moorwood, A., (ed.), 2009, Science with the VLT in the ELT Era, Heidelberg: Springer

Moutou, C., et al., 2008, A&A, 488, L47

Nordström, B., et al., 2004, A&A, 424, 951

D'Odorico, S., Casali, M., Mainieri, V., 2009, in Science with the VLT in the ELT Era, A. Moorwood (ed.), Heidelberg: Springer, 235

Pasquini, L., et al., 2009, in Science with the VLT in the ELT Era, A. Moorwood (ed.), Heidelberg: Springer, 395

Peacock, J., et al., 2006, Report by the ESA-ESO Working Group on Fundamental Cosmology, Garching: ST-ECF (http://www.stecf.org/coordination/esa_eso/cosmology/report_cover.pdf)

Perryman, M., Hainaut, O., Dravins, D., Léger, A., Quirrenbach, A., Rauer, H., 2005, Report by the ESA-ESO Working Group on Extra-Solar Planets, Garching: ST-ECF (http://www.stecf.org/coordination/esa_eso/extrasolar/report.pdf)

Schlegel, D.J., et al., 2007, Bulletin AAS, 39, 966

Schödel, R., et al., 2002, Nature, 419, 694

Spiering, C., et al., 2008, Astroparticle Physics: the European strategy (http://www.aspera-eu.org/images/stories/roadmap/aspera_roadmap.pdf)

Steinmetz, T., et al., 2008, Science, 321, 1335

Turon, C., et al., 2008, Report by the ESA-ESO Working Group on Galactic Populations, Chemistry and Dynamics, Garching: ST-ECF (http://www.stecf.org/coordination/esa_eso/galpops/report.pdf)

Udry, S., Santos, N., 2007, ARA&A, 45, 397

Vreeswijk, P.M., et al., 2007, A&A, 468, 83

Wilson, T., et al., 2006, Report by the ESA-ESO Working Group on Herschel-ALMA Synergies, Garching: ST-ECF (http://www.stecf.org/coordination/esa_eso/alma-herschel/report_cover.pdf)

Wolszczan, A., Frail, D.A., 1992, Nature, 355, 145

De Zeeuw, P.T., Molster, F.J. (eds.), 2007, A Science Vision for European Astronomy: A Strategic Plan for European Astronomy, (ISBN 978-3-923524-62-4)