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Optical and infrared astronomy in the 21st century – the continuing revolution

CATHERINE CESARSKY and RICHARD WEST

European Southern Observatory, 2 Karl-Schwarzschild-Strasse, D-85748
Garching, Germany. E-mail: ccesarsk@eso.org, rwest@eso.org

For some decades, astronomy and astrophysics have undergone a technological and conceptual revolution. Supported by ever more powerful telescopes and instruments on the ground and in space, the volume and quality of new insights is incredible, both in terms of physical understanding of individual celestial objects and the grand evolutionary scheme. New and powerful observational facilities such as the ESO Very Large Telescope (VLT) are opening new horizons, from the nearby solar system to the corners of the Milky Way galaxy in which we live and, not least, towards the vast expanses in time and space of the remote and early Universe. The next generation of ultra-sensitive optical-infrared telescopes such as Herschel and ALMA will be ready within this decade and concepts are being elaborated for the construction of super-giant telescopes like the 100 m optical/IR OWL, the 'Overwhelmingly Large telescope'. With these impressive developments, and in a true spirit of exploration, astronomers can now look forward to great research opportunities, in a resounding manifestation of the continuous drive towards a better understanding of our cosmic surroundings and of our own origins, so characteristic for enlightened humankind of every age.

The revolution of astronomy

The science of astronomy and astrophysics is truly in the middle of a revolution. Progress is taking place at a very rapid pace and on an extremely wide front, based on observational and theoretical studies of all known types of objects in the Universe. Investigative goals that were distant dreams just a few years ago are now being realized in a spirit of genuine joy of exploration. The volume and quality of new insights that have been acquired during just a single generation of astronomers is incredible, both in terms of detailed physical understanding of the objects themselves and, not least, of the grand evolutionary scheme in which they partake.

There are several reasons for this impressive advance. One is certainly the intensifying multidisciplinary interaction with the resulting cross-fertilization. Another, no less important, is the availability of new, extremely powerful research tools, especially a new cohort of very large ground-based telescopes and advanced space observatories, equipped with state-of-the-art new instrumentation. The reasons why astronomers are so keen to create these large facilities are threefold.

- Large telescopes gather a great amount of radiation and see finer detail in a given time.
- Space observatories can avoid some constraints that limit ground-based telescopes. They see radiation that does not reach the surface of the Earth because of absorption by the Earth's atmosphere.
- The telescope gathers the radiation but it is the instrumentation in the focal plane that analyses such properties as its flux, spectral composition, and time variation.

The size of the telescope and its location provide the means to gather the radiation, and determine what the astronomer can investigate. The performance of the instrumentation that analyses the radiation is the key to the production of new science.

Astronomy and technology

Science and technology go hand in hand in most empirical sciences. However, few of these can claim such a long-lasting and intimate relationship as is the case within astronomy and astrophysics. As long as five millennia ago, impressive sighting aids like Stonehenge and other megalithic monuments were constructed at great expense by advanced societies at the fringes of continental Europe. Younger structures of similar type are found in other parts of the world, demonstrating a common interest in the stars by many ancient cultures. Observers at these first astronomical facilities kept good records of celestial phenomena such as solstices and eclipses and laid the foundations for long-term documentation of the motion of heavenly objects. In fact, they established the positional databases for the first, empirical attempts to describe cosmic regularities and eventually to predict recurrent natural phenomena.

As technology advanced over the centuries, inventive craftsmen designed increasingly accurate astronomical position-measuring instruments. Some were produced in small editions to serve the needs for reliable terrestrial and nautical navigation. Astronomy entered the 'modern' age in the second half of the 16th century, when ingenious technicians and industrious observers – such as Tycho Brahe – advanced the achievable measuring accuracy by leaps and bounds. A few years later, Galileo Galilei's first crude telescopes changed our view of the Solar System and the Milky Way and, soon thereafter, well-equipped astronomical observatories were constructed in many European countries, with the Paris Observatory as a prime example. Their instruments made the measurement of positions and motions more precise but also revealed new things about the nature of celestial objects and, together with the application of physical interpretation, this was the birth of astrophysics.

In the following three centuries, increasingly sophisticated instrumentation extended the range of the observational horizon. Accurate measurements of the changing positions of the stars led to the discovery of stellar motions by Edmond Halley (also known for the computation of cometary orbits) and introduced the concept of a dynamic Universe (1718). The giant metal mirrors of William Herschel allowed a first 'map' of our discus-shaped Milky Way system (~ 1800). Friedrich Bessel (1837) introduced the trigonometric method of measuring distances beyond the Solar System by means of stellar parallaxest. Following Joseph Fraunhofer's application of the spectrograph to the spectra of the Sun and stars (1817), it became possible to study the composition of celestial bodies in terms of their temperature, density and composition.

The construction of larger optical telescopes – the Lick 1 m refractor in 1889, the 2.5 m Mt. Wilson reflector in 1915 and the Palomar 5 m telescope in 1948 – was coincident with the development of the registering of images and spectra on photographic plates. The new discoveries, together with the rapid progress in physics and related disciplines, radically changed our knowledge of the Universe. Among the milestones were the comprehensive mapping at the correct scale of the Milky Way Galaxy (around 1900), the discovery of the existence of extra-galactic systems (1924) and the universal expansion law (1930), as well as the first identification of the main internal energy-producing fusion processes in stars (1938). The advent of computers made it possible to tackle, in the 1960s, the complex theoretical problem of stellar evolution and this soon led to a detailed understanding of the life of stars, from birth by contraction of an interstellar cloud of gas and dust to the return of processed material to interstellar space as the stars died.

New spectral windows were opened by radio antennae in the 1930s, rocket-borne X-ray detectors from the 1940s, and later with satellite-based gamma-ray, X-ray, ultraviolet, optical, infrared and millimetre-wave sensitive telescopes. Entirely new types of objects were discovered in this process. In scale they range from asteroids in the outer solar system (the Kuiper belt, 1994), to exo-planets orbiting other stars (1995), neutron stars, which emitted bursts of radio waves as pulsar*s* (1967) and black holes in the centres of galaxies, which appeared as quasars (1963). On the largest scales, it became possible to measure approximate values of the basic cosmological parameters, such as the age of the Universe, its mean density and expansion rate. Theoretical considerations predicted a sponge-like structure for the Universe, composed of super-clusters of galaxies separated by voids. This was confirmed with detailed and accurate maps of the galaxies. The existence of exotic components such as dark matter and dark energy was proposed (see the accompanying article by Liddle).

In the 21st century, with powerful new observational and computational tools, we find ourselves at the beginning of a heroic era full of promise for fundamental discoveries. As in the past, some of these will be predicted but there will be those that are unexpected. Astronomers carry out large-scale projects devised to perform analyses of enormous numbers of objects, for example to determine the positions and types of large numbers of galaxies to map the cosmic structure. As they examine all the members of a large survey, they also detect individual unusual objects. Such objects may be rare because they are freakish cases, which are created from dramatic combinations of phenomena, but may be like the Rosetta Stone, which carried both hieroglyphic and Greek inscriptions of the same text and became the key to deciphering the hieroglyphics. Objects may also be rare because they are transitory phases in the long lifetime of evolution of the objects under consideration – rarer than the long-sought flower that lasts a day in the lifetime of a century-old plant. In either case, new physical insights can often be won from these ‘pathological’ or ‘missing link’ cases.

In what follows, we shall look closer at the current situation and the special circumstances that point towards a successful continuation of the present achievements. For this, we will dwell for some time at one of the front-line facilities, the Very Large Telescope (VLT). It is a worthy representative of the new generation of astronomical tools that will continue for many years to provide the basis of accurate data for fundamental astrophysical investigations. However, a series of next-generation projects are already underway, in space and on ground.

Current optical/infrared telescopes

Observations made with telescopes include taking images and recording spectra. Recent progress in the practice of astronomy has taken various directions.

- Larger ground-based telescopes are able to collect more light. They see fainter objects that are further away, further back in time (due to the light travel effect), and closer to the Big Bang. They see greater spectral detail and changes in shorter intervals of time.
- Better detectors have been built, some detecting close to 100% of the

incident radiation. In the infrared region, new detector technology has been driven by military investment and has made enormous advances. The new detectors have less background noise, faster read-out of the data and larger surfaces to give more pixels in the images collected.

- Instruments have been designed with the ability to record simultaneously the radiation from a large number of objects. This greatly enhances the observational efficiency. In addition, optical and infrared satellite observatories have made observations from outside the Earth's atmosphere with an undisturbed view of the Universe.

Our own organization, the European Southern Observatory, specializes in the production and operation of ground-based telescopes that gather optical light and infrared radiation. The technologies are similar to a certain degree and astronomers have come to lump the techniques and the results together under the term 'Optical/IR Astronomy.' The Optical/IR waveband region remains the most widely exploited window on the Universe. On the ground, it is mainly concerned with objects of moderate temperatures (a few hundred K up to, say a few hundred thousand K). This range includes planets and comets in the solar system and outside, around other stars, as well as dust and gas clouds, normal stars and galaxies. Taking their terminology from the study of history, astronomers describe the period between the events of the Big Bang that formed matter and the epoch at which light from the stars within galaxies burst out into space as the 'Dark Ages' of the Universe. In astronomy as in history, we would like to know what happened in the Dark Ages. From space, longer wavelength infrared radiation may be observed (it is absorbed by molecules such as water in the atmosphere). Cooler objects may be observed from space, with temperatures ranging upwards of a few kelvins, including the Cosmic Microwave Background (the cooled remnants of the cosmic fireball from the Big Bang), and dust in interstellar space far from the radiation of stars, or deep within dense protective clouds.

The Universe is full of stars and galaxies. Some stars and galaxies are more worth observing than others for the new contribution to science they might provide, and some ways of observing are more productive than others. The astronomer uses experience and insight to choose what to observe and how, and applies these skills for observing time, making a proposal for the use of a particular telescope in the chosen investigation. If the proposal is successful in the competition, data gathering sessions at the telescopes take place and the data are prepared for interpretation ('data reduction'). Finally, the astronomer interprets the data, inferring the physical and chemical conditions of the observed objects, often with distance and age estimates. New scientific thinking is necessary to relate what has been learned to what is already known. Perhaps what has been learned is exactly what has been predicted in the proposal. This brings a pleasant mood of self-congratulation. Even more excitingly (and rather often), the Universe proves to be cleverer than the astronomer and is different from what has been expected.

The early image of an astronomer was that of a lone scientist making his own equipment and spending long night-time hours using it. Galileo and Tycho come to mind as examples of such a stereotype. In contrast, modern astronomical work often involves a team of many scientists with different backgrounds, concentrating for relatively short night-time bursts of observing activity after long years in which highly specialized engineers have developed and now operate high-technology equipment. In this sense, astrophysics is moving in the same direction as other disciplines, e.g. elementary particle physics, the human genome project.

There has been a sudden burst of activity building large telescopes. The Mt Palomar telescope in California was built in 1948 and, at 5 m aperture, remained the largest telescope for 25 years. In size but not in efficacy it was surpassed by the Soviet 6 m telescope in 1973. Between 1993 and 2003, no less than 16 telescopes will have been built in the range between 6.5 metres and 10.5 metres aperture. This burst arises from new techniques in making telescopes. Large telescopes are made mainly from mirrors rather than lenses. Lenses larger than about a metre in diameter strain and distort too much when held at the edge, but mirrors can be supported from the rear surface. However, even mirrors reach engineering limits when they are several metres in diameter. They bend under their own weight, and they expand and contract when they change temperature. The new breakthrough is in control engineering, which frequently measures (perhaps several times a second) to where the mirror has moved, computes how it ought to be and pushes it back into position. As a result, it is possible to make large mirrors that are thin and that bend rather readily. These are lighter and do not need such a massive supporting structure and can be temperature controlled more easily. An alternative stratagem is to use an array of small mirrors that are equivalent to a single large one. Bending motions, or the shift of one mirror relative to another, can be controlled by servo control referenced to a laser beam.

The ground instruments are fully complemented by space instruments. In space, unhindered by the turbulence in the earth's atmosphere, it is easier to obtain sharp images. It is also possible to observe infrared radiation in wavebands that are absorbed by the atmosphere.

Working mainly in the optical domain, the 2.4 m NASA/ESA Hubble Space Telescope (HST) has been extremely productive during the past decade, once the initial optical problem (incompatible mirrors in the telescope assembly) had been rectified. With its now-excellent image quality, the HST has revolutionized many research fields, limited only by its comparatively small mirror size, which was set essentially by the size of the cargo bay of the Space Shuttle that launched it.

Recently, there have been exceedingly fertile collaborations between the HST and its larger brethren on the ground. In these projects, a reconnaissance of a complicated field of faint objects, or the detail in a single object is first made with the HST. The initial observations are then followed up from the ground. Perhaps the ground-based observations may be a little blurrier than the space ones, but they can be made with bigger telescopes and accumulated for longer. This means that the observations capture more photons and hence it is possible to investigate even quite faint objects at higher spectral resolution than HST can achieve.

Europe enjoys an excellent position in space infrared astronomy. In 1983, the UK and the Netherlands participated with the USA in the first infrared astronomy satellite telescope, IRAS, to survey the whole sky. In 1995, the European Space Agency flew the first infrared space observatory, ISO, for a more detailed study of the infrared objects found by IRAS. IRAS and ISO have brought completely new information on the process of star formation and the interstellar chemistry in the regions where stars are born or die. They have also led to profound changes in our understanding of the evolution of galaxies, showing that galaxies go through extremely intense, brief episodes of star formation, probably triggered by tidal effects as one galaxy passes near another. As the stars are formed in immense clouds of dust, the ultraviolet and optical radiation emitted by the new stars is absorbed by the dust. The galaxies may therefore be rather dim as seen in optical light, but the dust is warmed and re-radiates the starlight in the infrared. IRAS has discovered the existence, in our local Universe, of the brightest of these objects, the Ultraluminous Infrared Galaxies. ISO showed that such objects, and therefore such starburst episodes, were more frequent in the past, presumably when galaxies were closer together, interacting more often, and contained more unused star-formation material. The corollary is that to study the state of galaxies in the early Universe and find out about conditions at that epoch it is necessary to find and understand ultraluminous infrared galaxies.

The new ground-based facilities are distinguished by their advanced technology. At some locations, major gains in observational efficiency have been obtained by altering scientific procedures – almost a form of social engineering! The telescope operators have introduced scheduling methods that optimize the data gathering process, taking into account both internal factors (current state of the telescope/instrument) and external factors (atmospheric conditions). This has freed the astronomers from the process of operating the equipment and making judgements about the suitability of conditions for the scientific observations, and replaced them with professional telescope and instrument operators, typically versatile astronomers and engineers. The research astronomer has moved from the position of the single-handed captain of a small boat, struggling with the wheel

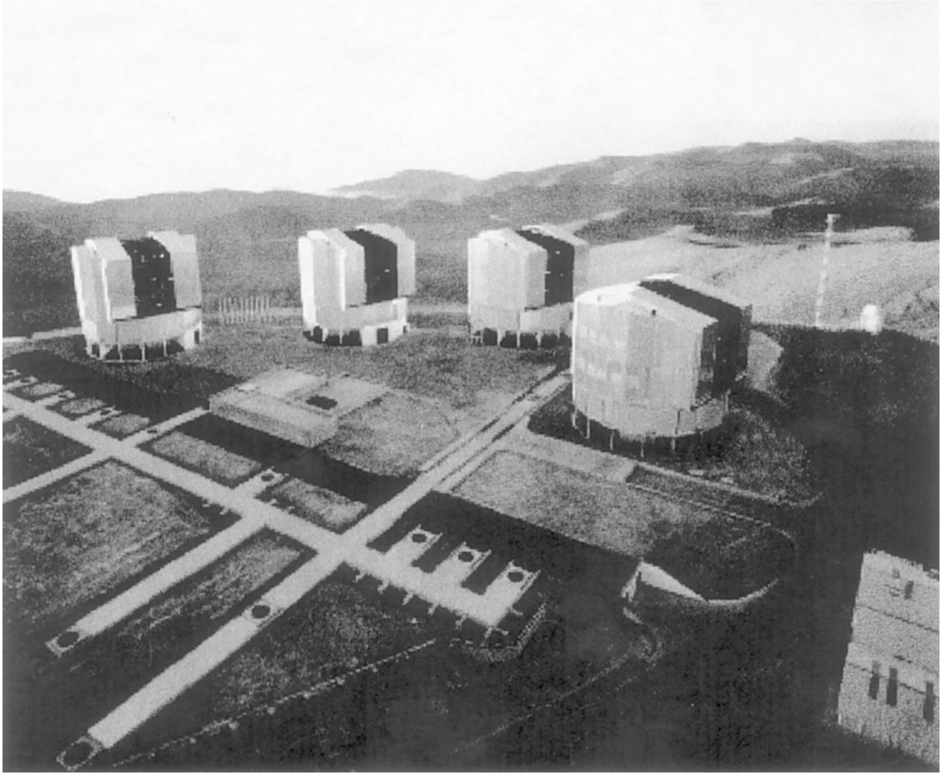

Figure 1. (a) The ESO Very Large Telescope (VLT) at Paranal. The four telescopes can be used individually but are also connected together by tunnels through which the light from each can be gathered to a single point to make a telescope with the discrimination of detail of an equivalent telescope with a 200 metre diameter mirror. (b) Kueyen (a local Chilean Indian word for 'The Moon') is one of the four VLT Telescopes. Its 8.2 m diameter mirror is held at the bottom of the girder-work structure and dwarfs the person below it. Starlight reflects back up to the small mirror at the top of the girder work and then down into the scientific instrument held under the main mirror. The computer-controlled system that supports the telescope's mirror compensates for any movement in the girder-work support structure.

and the sails, to the captain of the Starship Enterprise, commanding the fundamentals but letting others to carry out the appropriate actions in the best way.

The ESO Very Large Telescope

The ESO Very Large Telescope (VLT) is one of a new generation of extremely powerful astronomical facilities. It represents the current engineering and

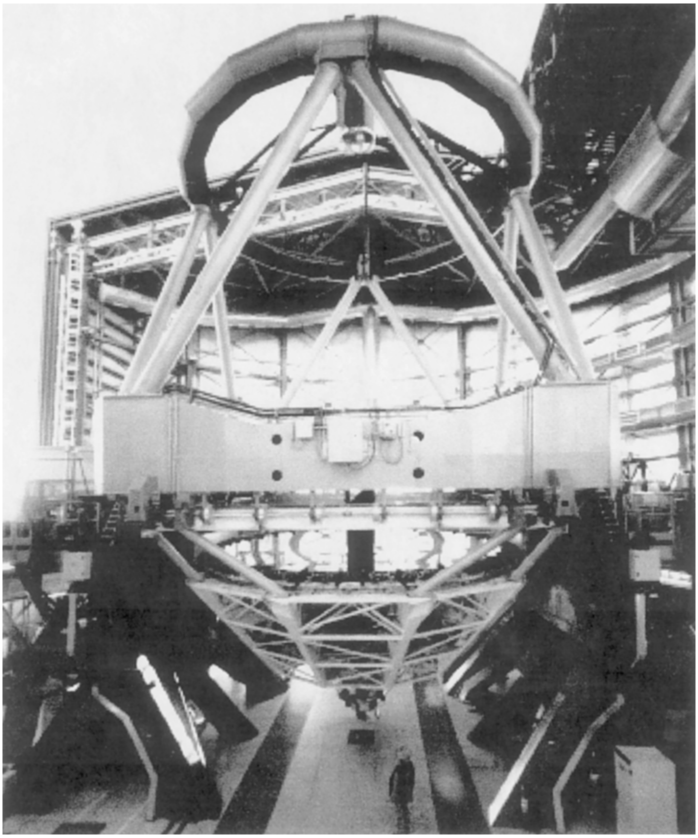

Figure 1. (b)

scientific state of the art and includes many novel features that will serve as a basis for further developments in this century; thus, the overall VLT concept, its technological base and the resulting scientific capabilities has a direct bearing on future projects. VLT is a telescope with the equivalent aperture of 16 m. It is actually made up of an array of four 8.2 m telescopes, positioned near one another in a trapezoidal array, surrounded and complemented by a number of smaller telescopes that could be moved from place to place (Figure 1). A unique feature of the VLT is the possibility of combining the beams from these telescopes coherently, making an interferometer that would mimic the spatial resolution of a telescope with a mirror size equal to the enclosed area in which all the telescopes lie – about 200 m in diameter.

The search for the optimal site in Chile for the VLT commenced in 1983. Cerro Paranal, some 1200 km north of Santiago, was found to have a large number of clear nights, excellent 'seeing' (the astronomer's term for the sharpness of the images and lack of atmospheric blurring) and, in particular, low atmospheric water vapour content and hence a transparent sky for infrared observations. An area of approximately 725 square km around Paranal was donated to ESO by the Chilean government. Construction started in 1991; 'first light' for the first 8.2 m telescope was achieved in May 1998. The other three telescopes followed in 1999–2000 and today all four telescopes are conducting 'routine' observations for research programmes selected by an Observing Programme Committee from numerous proposals emanating from the entire world. After a first demonstration (March 2001), beams from two of the large VLT telescopes were combined into the VLT Interferometer in October 2001.

The four telescopes were named in a competition by Chilean schoolchildren in the Mapuche language. These indigenous people live mostly in the area south of Santiago de Chile. The winning essay was submitted by 17-year old Jorssy Albanez Castilla from Chuquicamata near the city of Calama. The telescopes are known as Antu (pronounced *an-too*; The Sun), Kueyen (*qua-yen*, as in 'quake'; The Moon), Melipal (*me-li-pal*; The Southern Cross) and Yepun (*ye-poon*; Venus), respectively.

Breaking with earlier traditions and entering new engineering territory in ground-based astronomy, the VLT concept was based on a comprehensive model of the entire installation, with close coupling between optical controls, and structural design configurations. This model even includes various environmental effects, including wind loading of the structure, turbulence in the atmosphere, and seismic disturbances. The VLT sees a comparatively wide field-of-view, has high throughput, radiates little infrared radiation of its own into the beam, and points and tracks accurately as stars rise and set.

Outstanding image sharpness was of the highest priority for the VLT and was already achieved by the time of 'first light.' The VLT 8.2 m primary and 1.1 m secondary mirrors are continuously controlled by an 'Active Optics' system, a revolutionary concept that compensates for the variable action of gravity as the telescope frame moves. It was first developed at ESO in the 1980s and successfully tested on its 3.5 m New Technology Telescope (NTT). The VLT is also equipped with Adaptive Optics (AO), a technique developed to eliminate the undesirable image-smearing effects of atmospheric turbulence. In this technique a special instrument measures the distortion that the atmosphere makes of a control star in nearly the same direction as the object of interest. The instrument uses this information to deform a mirror in the optical beam to compensate for the distortion and to make a more perfect image. In case there are no suitable control stars near to objects of particular interest, one of the telescopes will host a sodium laser that produces an artificial control star that glows in the sodium layer of the atmosphere above the telescope.

Each telescope has three focal stations so that a dozen instruments can be mounted quasi-permanently in a stable environment. It is possible to switch rapidly from one to another as the need changes (for example, as the sky conditions change during the night). The instruments will be modified, upgraded, and eventually replaced, maintaining state-of-the-art technology and following the evolving scientific needs. The lifetime of each scientific instrument is expected to be in the range of 7 to 12 years. As a matter of policy, one focal station will be kept available for new, experimental instruments, to keep the interval between technological advance and astronomical application as short as possible.

The data are all calibrated and stored in a long-term archive. It can be analysed with specialized software developed for the purpose. Since the data are taken in response to a specific request, they remain private for the use of the requesting team of astronomers for a year but are then made public for everybody. A joint archive, which includes data from the VLT and from the Hubble Space Telescope, as well as other ESO telescopes, has been set up at the ESO Headquarters at Garching. This archive is part of a Virtual Observatory for research using existing data, as opposed to newly gathered data from a real telescope. The EC-supported Astrovirtel project was begun in 2000 and constitutes a test-bench for this revolutionary concept.

To feed objects of interest into the VLT, two survey telescopes are being built to sift large numbers of stars and galaxies for rare and interesting cases for further study. The VLT Survey Telescope (VST) and the Visual-IR Survey Telescope for Astronomy (VISTA) are soon to be installed close to the VLT. With three smaller Auxiliary Telescopes, which move on tracks on the observing platform, the VLT can be combined as the VLT Interferometer (VLTI). This gives an angular resolution equivalent to a telescope with up to 200 m diameter. This corresponds to 2 m at the distance of the Moon. In principle, VLTI could not only distinguish an astronaut on the Moon, it could recognise him or her.

The first of the four VLT Telescopes was available on 1 April 1999, and as of 2001 all telescopes are available. Already the VLT has made significant scientific advances, providing exploratory excursions into those vast unknown territories that can only be charted in detail by the following generation of super-giant telescopes such as ALMA and OWL (see below). The following is a list of some VLT highlights of the first two years (further details on http://www.eso.org/outreach/press-rel/).

- VLT measured the size and rotation of the nucleus of Comet Wirtanen, to help design the ESA mission, Rosetta, which will attempt to land on it.
- It measured the lithium-6 isotope in a star with a planetary system. This material is thought to be the result of the star eating some of its planets,

like Chronos and his children (see accompanying articles by Encrenaz and Schneider).
- It imaged the extremely faint bow-shock around an isolated neutron star moving through interstellar material in space.
- It measured the mass (200 million solar masses) of the black hole in the nearby Centaurus A galaxy (see the accompanying article by Charles).
- It used cunning techniques to view the far side of the Sombrero Galaxy.
- It determined the composition of very distant intergalactic clouds to find that they were not entirely pure hydrogen, direct from the Big Bang.
- It made a large-scale investigation of the images of 100 000 distant galaxies, measuring the gravitational lens distortion of the images by the mass between us and them, leading to a new estimate of the total mass density of the Universe.
- VLT has determined the age of the Universe from measurements of stellar radioactivity (see the accompanying article by Clementi and Gratton).

Next steps

Astronomers advance their science both by seizing technological developments and extending their observational capability, and by identifying crucial, developing scientific areas in which there are pregnant questions. The most significant science comes when new questions demand the advances that technology is poised to offer. We are reaching to the limits of the optical Universe. These most distant limits are because of the time light must travel from the earliest epochs of the Universe. Because of the expansion of the Universe, the furthest objects are receding fast and are strongly reddened by the cosmic Doppler shift, thus we need to view these objects in red or infrared light. As it happens, the most luminous galaxies in the early Universe are very dusty and their star light is absorbed and re-emitted as infrared radiation anyway. To see into the Dark Ages demands better access to telescopes that can see the infrared. It is easy to be confused when images of separate objects overlap, particularly when galaxies, say, are crowded together at the far horizon of the Universe. So we need the sharpest possible images, or equivalent (or better) measurements through interferometers.

For several reasons, fulfilling these ambitions is not cheap. Infrared technology is sophisticated and observations in the far infrared must be from space. Bringing together people who know the most about the emerging technology together into a single project is not an easy management task. Interferometers have many telescopes, spread over a wide area, but need to be coordinated. Big, for astronomers, is beautiful, but is expensive.

It is clear that the next major advances in observational optical/infrared astronomy are going to be on a global scale, affordable only in global projects. Europe is poised to play its part in these projects and to lead some. Building on the experience of large-scale complex multinational projects such as the VLT, Europe has the capability to carry out even more complex projects in the future.

Herschel

ESA's Herschel Space Observatory (formerly known as FIRST – Far InfraRed Space Telescope) will be bigger and better than any of its predecessors. Moreover, it will observe at wavelengths never covered before. It will be located 1.5 million km away from Earth, farther than any previous space telescope. Due for launch in 2007, Herschel is one of the Cornerstone missions of ESA's Horizons 2000 programme and will cost approximately 460 million euros. Herschel will be the first space facility ever developed covering the far infrared to the submillimetre range of the spectrum, some of which wavelengths are never before observed. The main scientific emphasis, mission requirements and technological needs for Herschel were discussed for the first time during the first half of the 1980s. Construction started in early 2001. An Ariane-5 launcher will launch Herschel in 2007, together with Planck, a mission to study the Cosmic Microwave Background radiation. The two spacecraft will be separated early after launch and will operate independently.

Herschel will be located in the direction away from the Earth. In this way, the telescope can look out into space away from the Sun, the Earth and the Moon, all of whose heat would dazzle the telescope and warm the instruments to unacceptable levels. No clear successor to Herschel has yet been identified.

ALMA

Even though it takes us a little beyond the purpose of this article, we now want to mention a project that extends the scope of optical/IR astronomy towards radio-astronomy. We do so because it is fully complementary in tasks and scientific objectives to the other projects described here. The Atacama Large Millimetre Array (ALMA) is the name for the merger of a number of major millimetre array projects (European, American and Japanese) into one global project. This is the largest and most expensive ground-based astronomy project planned for the next decade. ALMA is basically science-driven and, among the

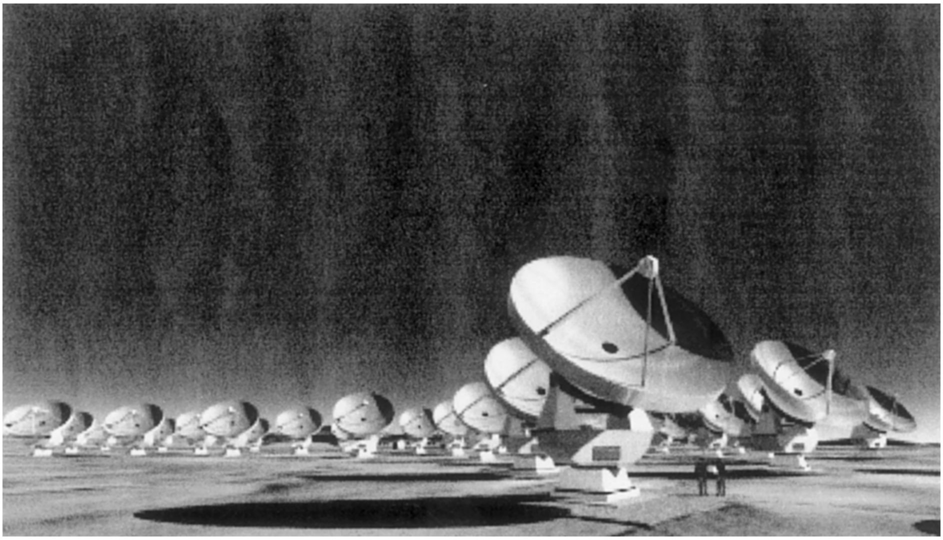

Figure 2. An artist's impression of the Atacama Large Millimetre Array (ALMA) at Chajnantor (altitude 5000 m). Its 64 dishes are 12 m in diameter and spread over a desert plain of 10 km. The dishes act in concert and receive millimetre waves, which are long infrared waves with radio-like properties. The dishes feed them to a single detector system.

many new opportunities, it will detect and study the earliest and most distant galaxies, at the epoch of the first light in the Universe.

ALMA will be composed of some sixty-four 12 m radio dishes spread over an area extending up to 10 km (see Figure 2). It is estimated to cost about 600 million euros. It will be located on the high-altitude (5000 m) Zona de Chajnantor, east of the village of San Pedro de Atacama in northern Chile, which is an exceptional site for (sub-)millimetre wave astronomy – possibly unique in the world. The present plan is to construct it between 2002 and 2010, with science operations starting in 2006. The costs will be divided 50–50 between Europe and the US, with joint overall direction. Japan expects to join at a later stage.

OWL

A second potential for advance in optical/infrared astronomy is in the quest for more photons. ESO is currently developing a ground-based, 100 m class optical/IR telescope. It is appropriately known as 'OWL' – originally this stood for Over-Whelmingly Large telescope, a worthy name for the successor to the Very Large Telescope, but one wonders how the name can be surpassed if even larger telescopes are built in times to come (OWL could also be 'Observatory at

World Level'). In 1997, it was recognised that significant progress in astronomy requires an order-of-magnitude increase in aperture size. Should we settle for the usual factor of two or three increases in telescope aperture that took astronomy in 50 years from the era of the 100 inch to the 200 inch telescopes in California? Or in 25 years from the 3.5 m ESO telescope to the 8.2 m aperture of one of the four VLTs? Is it unrealistic to accelerate the pace of change and reach for a factor of ten in a decade? The factor of ten increase of aperture of OWL over VLT would be about the same as the factor of increase of Galileo's telescope over the naked eye. We could anticipate as great scientific advances as were sprung on the world in 1610. Such an advance represents an enormous technological challenge. To make the project feasible, engineers have had to break the usual dependence of the total cost on the size of the telescope by coming up with a design that is based on the concept of assembling many identical components. This saves enough cost through serial production to make the enormous quantitative jump affordable. Clearly, such a great effort will be rewarded by a formidable science potential.

Initial efforts in the design of OWL have concentrated on finding suitable optical design and fabrication solutions. It is of crucial importance that proven mass-production solutions for the telescope optics are now readily available, because the OWL proposal is for a tessellated mirror made up of ~ 1600 2-metre mirrors (or, depending on the outcome of the optimization evaluation, possibly of an even larger number of smaller ones), each with identical hexagonal shape (see Figure 3). Most development effort is now necessary for the auxiliary equipment, in particular to find a technique that will correct for atmospheric turbulence much more effectively than is possible with the Adaptive Optics systems available at present. A preliminary analysis has confirmed the feasibility of OWL's major components within a cost of the order of 1000 million euros. A modular design allows progressive transition between integration and science operation, and the telescope would be able to deliver full resolution and unequalled collecting power 11 to 12 years after project funding.

What types of observations will become possible with an extremely large telescope such as OWL? The idea is not to include all kinds of studies, but merely to illustrate the large diversity. To a large extent, this overview is based on information from a recent study of the 'Science case for a 100-m telescope'.

Cosmology will profit greatly from future extremely large telescopes, allowing excursions into territory impossible to explore with present facilities. At the end of the Dark Ages, the formation of structure (galaxies, galaxy clusters and filaments) is beginning to emerge from the cosmic background. At the same time, the cosmological parameters seem to indicate that we are close to reaching a consistent view of the whole Universe. However, there are still considerable gaps in our understanding of the 'big picture', e.g. the conversion of primordial gas

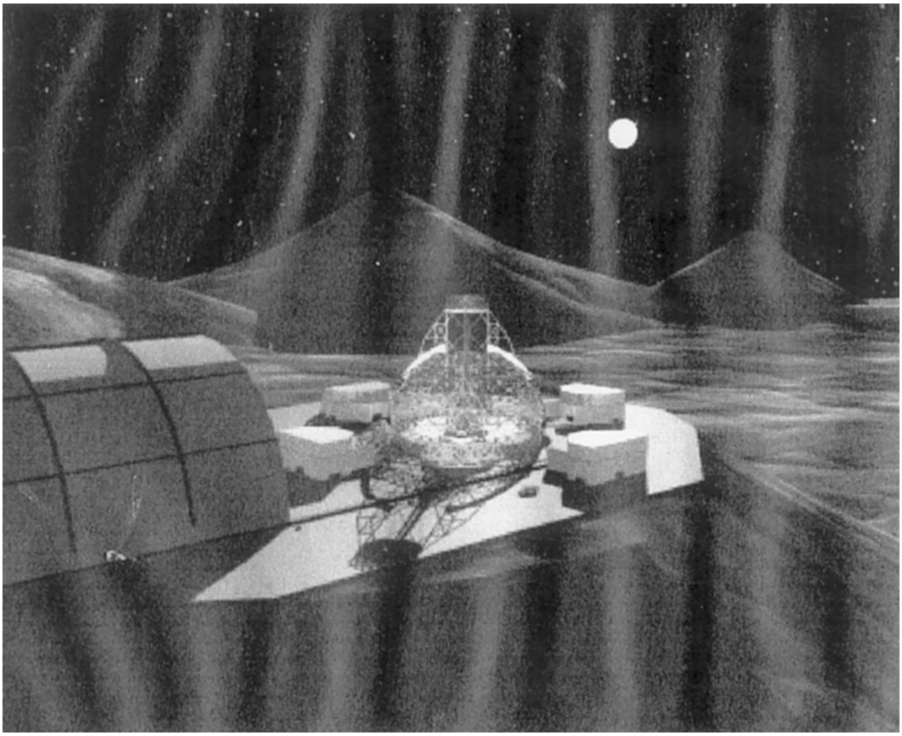

Figure 3. An artist's impression of the 100 m OWL telescope under the desert moon. Its 100 m diameter mirror in the girder-work structure dwarfs the truck parked on the concrete plinth in the right foreground. The arched protective shed is 150 m high and tracks aside on rails.

into stars and galaxies, the nature and distribution of 'dark matter', the nature of 'dark energy', the agglomeration of the largest structures, and the detection of the first luminous objects to appear in the Universe. In many theoretical models, present-day galaxies are assembled from smaller parts in successive 'mergers'; it will be a major observational goal to identify these smaller objects. Observational facilities such as OWL will help us to address these fundamental questions. However, we should also prepare ourselves for surprises. Dark energy is a notion that appeared only a few years ago and which added a completely new component to the Universe, indeed the biggest in terms of energy density. Other entities and forces may yet be discovered in the depths of space and time.

OWL will look at individual objects that are far away, and probe their structure, comparing and contrasting with what has been discovered by smaller telescopes about similar objects nearby. Small galaxies at great distances, quasars (these are extremely energetic nuclei of galaxies), supernovae and ionized gas clouds (HII regions) within galaxies all fall into this category. It will examine gamma ray bursters – energetic gamma ray explosions accompanied by a feeble optical pulse in their parent distant galaxy. Although there is one such burst detected per day, it has only recently become clear how far away these explosions are and their origin is unknown. The VLT has observed one such event at a record distance, and OWL will study many more.

Stars form in galaxies out of gas. The Big Bang made a nearly uniform inter-galactic medium of gas, and the process whereby this gas was compressed by gravitational instabilities and converted to stars is still exclusively the realm of theorists. In the future, OWL will allow detailed studies of this medium by taking high-resolution spectra of distant quasars. These act as back-illuminating sources of light allowing us to probe the inter-galactic medium along the line of sight to them. Already now, trailblazing high-resolution spectral observations of some of brightest, very distant quasars have been made with the UVES spectrograph at the VLT, resulting in chemical analysis of the intervening clouds, by means of absorption lines from different elements in the same cloud. However, OWL's capacity to do this with many more, fainter quasars will make it possible to map the distribution of this gas along a large number of lines of sight and relate this directly to the galaxy distribution. The detailed OWL data will provide the opportunity to study the early evolution of galaxies from the formation era to now, when galaxies have gained a mature state. It will be able to discern how star clusters evolve in early galaxies and how mergers between galaxies create new star clusters. It will be able to study the formation of black holes in galaxies, and show whether it is true, as we conjecture, that all massive galaxies have a central black hole and are quasars at some part of their early life. If they do have such black holes, what effects do the quasars have on the galaxies?

The superb image quality of OWL will provide direct views of the surface of various types of nearby stars, with 100-pixel images of at least 100 stars. Solar-type main sequence stars may be (marginally) resolved up to a distance of about 30 light-years. Do they all have spots like our own Sun? Varying in sunspot cycles? OWL will also be able to characterize extrasolar planets by spectroscopy, and elucidate their evolution. Only a large facility such as OWL will have the critically important ability to discover terrestrial planets by direct imaging and to study their atmosphere by spectroscopy, a topic of great scientific and philosophical importance. OWL is capable of a vast range of exo-planetary investigations, covering planets both outside and inside the star's 'Habitable Zone', the small range of orbital radii within which surface water will be liquid, and therefore favourable to the emergence or existence of life approximately as we know it. Are the planets in these zones covered with oceans like the Earth? Do they have oxygen atmospheres? Within our own solar system, OWL will be able to examine the surface detail on a few hundred asteroids. Most planetary

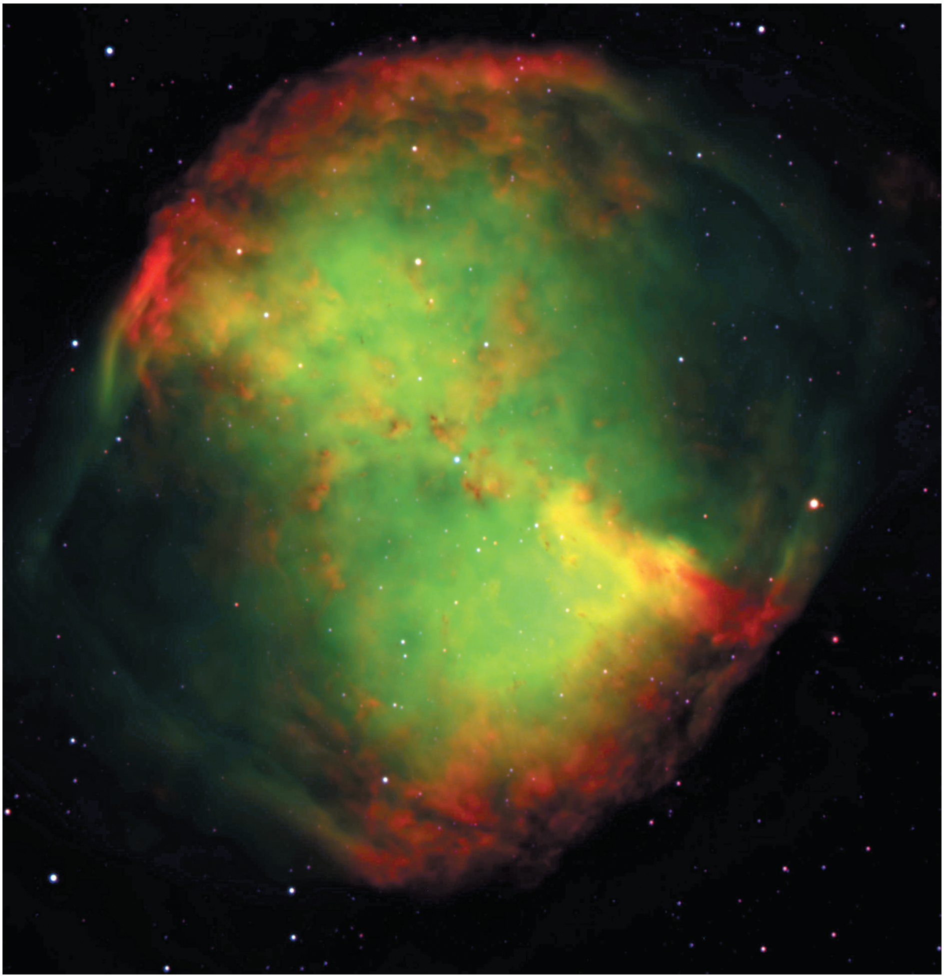

Figure 4. The Dumbbell Nebula is a 'planetary nebula' and is located in the constellation Vulpecula (The Fox) at a distance of around 1200 light-years. The Dumbbell Nebula is hot, very rarefied gas – the ejected atmosphere from a star nearing the end of its life. The core of the dying star that heats its nebula still shines at the centre of symmetry (it can readily be picked out on this picture). Nebulae like this are rare because the planetary nebula stage lasts only thousands of years in the lifetime of stars that live for hundreds or thousands of millions of years. The beauty of such nebulae makes them aesthetically valuable; they are scientifically important as the source of much of the material of which the solar system is made. Our own existence can be traced to nebulae like this, in generations of stars that lived before our Sun. The photo was made by the VLT telescope known as Antu ('The Sun').

moons are still unstudied, while for the majority of the others, a few images have been taken at rather large distances by passing space probes (see the accompanying article by Encrenaz). OWL will be able to take multi-wavelength pictures of the entire surface of each moon, with high resolution.

Outlook

It is obvious that, at the beginning of this century, astronomers can be looking forward to impressive new observational possibilities. This is a particular phase in the typical cycle in the development of science: whenever a new instrument has delivered new results from improved research capabilities, scientists are soon eager to get their hands on even more advanced equipment that will allow deeper and more detailed follow-up investigations. With the VLT and with other large telescopes now in the early stages of their active life, with several space- and ground-based facilities soon coming – such as the Herschel Observatory, ALMA and, presumably later, OWL – another exciting chapter in the never-ending progression will soon be opened. The current time horizon for large projects is of the order of 15–20 years. There is a continuous need to assess the observational possibilities and limits in order to prioritize available resources for future projects. With ALMA as the first 'global' astronomy project, it is safe to predict that the future top facilities will often emerge from joint efforts involving several countries, which together are able to match the high costs in terms of construction funds and operation manpower. The astronomers of the United States produce 'decadal reports' about the future of American astronomy and astrophysics, and various European countries (e.g. the UK, France, Germany) have established such prospective studies on similar timescales. In the future, perhaps the ten-year cycle to assess where astronomy stands and where it should go will involve the global astronomical community.

More astronomical programmes will involve massive data gathering. This needs exceptionally large resources. The chief results will be even more profound statistical investigations but also improved opportunities to discover unusual objects that may possibly become 'Rosetta Stones' in their respective fields. Nevertheless, it is also necessary to be prepared to do highly specialized observations at short notice whenever an unexpected opportunity arises, and thus a large amount of planning flexibility must be built into the systems. The current trend towards integration of theoretical and observational efforts will continue. As has been the case for particle physics for a long time, some research programmes will become increasingly complex and the collaborators more numerous. The overall task will fragment into smaller tasks involving more highly specialized individuals. The project management will become more demanding, requiring highly professional control. However, in astronomy, it will always remain possible for a small group, or even an individual, to make a big discovery in a few days, or rather, observing nights, at state-of-the-art installations – such is the richness and variety of the Universe we are exploring.

With its broad subject base, astrophysics will continue to attract specialists from many different research fields who will find it interesting and rewarding to participate in the joint work. The increasingly voluminous data sets will demand special efforts towards efficient, automated data handling, as there is only a limited number of staff positions available at most participating institutions. This is, in fact, a serious bottleneck for many current research programmes, and unlikely to change dramatically in the near future.

Astronomers will find it increasingly necessary to lobby for the preservation of a clean environment that will ensure continued good observing conditions for large ground-based facilities. This includes, in particular, a never-ending fight against light and radio pollution, as well as atmospheric pollution from industrially generated dust.

It is ultimately up to society to decide the resources to be made available to astronomy. Nevertheless, there is a growing perception of the communal importance of astronomy and astrophysics, as is currently demonstrated by the awakening interest in the various external forces that act on the Earth. The study of near-earth objects (asteroids that might hit the Earth) and the risk associated with impact is gaining political acceptance. The influence of the solar flux and long-term changes in the terrestrial orbit on meteorological and climatic fluctuations is being studied intensively and bio-astronomy appears to be moving into the public limelight. This gives good hope that society will continue to support astrophysical research and other associated fields on a basis of stable resources.

In the long run, the terrestrial atmosphere (useful spectral range, sky emission) will set a limit to the kind of astronomical observations that can be done from the ground. Hence, there will ultimately be a shift towards space observatories, some in terrestrial orbit, others in quasi-stable locations near the Earth (like Herschel) and, quite possibly, before the end of this century on the rear side of the Moon.

Looking back to what was known about the Universe 100 years ago, and extrapolating the present rate of progress, it would appear that no prediction about the state of knowledge 100 years from now can be too dramatic.

Further reading

Updated information about some of the projects mentioned in this article may be found at websites accessible from the following main sites:

ESO, VLT, ALMA, OWL, AVO	http://www.eso.org/
ESA, IRAS, ISO, Herschel, Planck	http://sci.esa.int/
HST	http://www.stecf.org/ and http://hst.stsci.edu
IAU	http://www.iau.org
History of astronomy	http://www.astro.uni-bonn.de/~pbrosche/astoria.html

About the authors

Catherine Cesarsky is Director General of the European Southern Observatory. She has spent the major part of her career in France at the Commissariat à l'Energie Atomique (CEA) where she was between 1984 and 1999 Director for all the basic research in physics and chemistry in the organization. She is Principal Investigator of the infrared camera ISOCAM, which flew between 1995 and 1998 on the European Space Agency satellite ISO, and with ISOCAM and now at the European Southern Observatory's VLT she participates in advances in the understanding of the formation of stars and the evolution of galaxies. She is a member of Academia Europaeae.

Richard West is a Senior Astronomer at the European Southern Observatory and Head of the ESO Education and Public Relations Department. He was at the Copenhagen University Astronomical Observatory before joining ESO in 1970. His current research interests focus on minor bodies in the solar system. From 1982 to 1985 he was General Secretary of the International Astronomical Union and he served on the ICSU Executive Board from 1982 to 1986. He is a member of Academia Europaeae.