Science with Extremely Large Telescopes

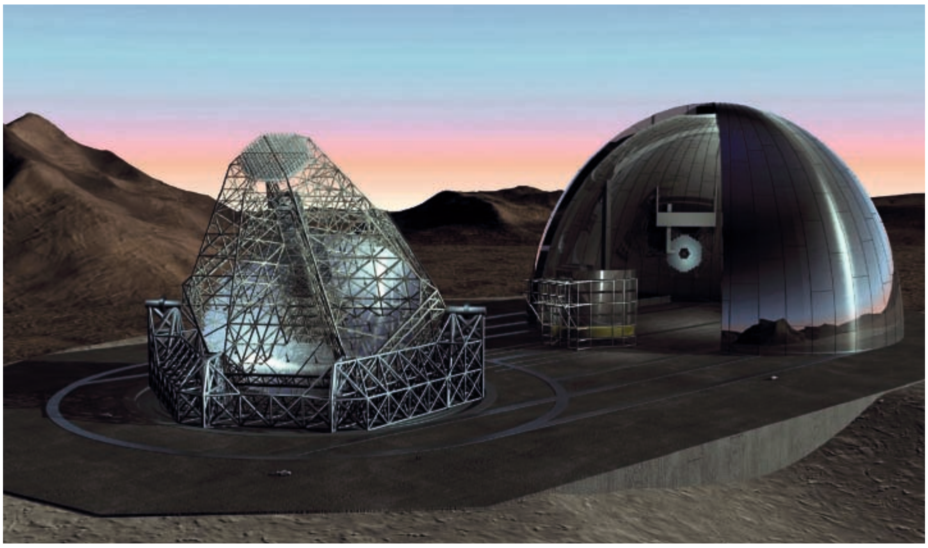
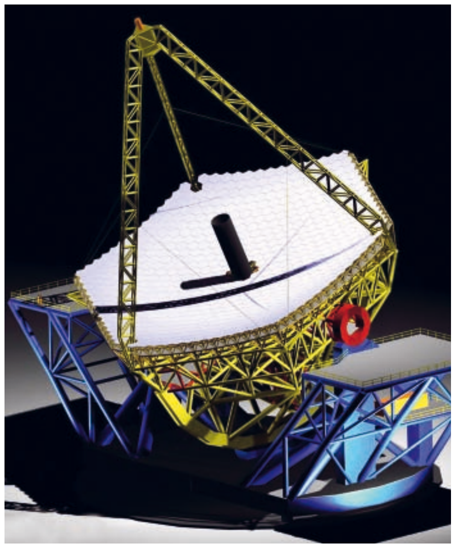

Figure 1: Concepts for 50–100-m ELTs. Left: the OWL (Over Whelmingly Large) Telescope, a design for a 100-m-class telescope being developed by ESO (Gilmozzi 2004, Dierickx et al. 2004). Right: The Euro-50 concept (Andersen et al., 2003, 2004).

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http://www.astro-opticon.org/networking/elt.html

Astronomers around Europe are gearing up for the next generation of ground-based telescopes to follow on from the success of the VLT and other 6–10-m telescopes. All aspects of astronomy will be dramatically advanced by the enormous improvements attainable in collecting area and angular resolution: major new classes of astronomical objects will become accessible to observation for the first time. In July of this year a book[1] was produced by a group of European astronomers, which describes the science achievable with a telescope of diameter 50–100 m. Here we present some highlights from this science case, ranging from direct observations of Earth-like planets outside our own Solar System to the most distant objects in the Universe.

[1] Hook, I. M. (Ed.), 2005, "The Science Case for the European Extremely Large Telescope: The next step in mankind's quest for the Universe". Printed copies and CDs are available on request from Suzanne Howard (*showard@ast.cam.ac.uk*). PDF files can be downloaded from *http://www.astro-opticon.org/networking/elt.html*

In the past half-century a new generation of telescopes and instruments allowed remarkable new discoveries: quasars, masers, black holes, gravitational arcs, extra-solar planets, gamma ray-bursts, the cosmic microwave background, dark matter and dark energy have all been discovered through the development of a succession of ever larger and more sophisticated telescopes. This progress poses new, and more fundamental, questions, the answers to some of which will perhaps unite astrophysics with elementary particle physics in a new approach to the nature of matter, while others may give us insights as to the existence (or otherwise) of other life-supporting planets in our Galaxy. As the current generation of telescopes continues to probe the universe and challenge our understanding, the time has come to take the next step.

Several projects are under way around the world to design and construct the next generation of ground-based, Extremely Large Telescopes (ELTs), which will provide astronomers with the ability to address the next generation of scientific questions. Initial studies in the United States and Canada are concentrating on potential designs in the 20–30-m range, such as the proposed Giant Magellan Telescope (GMT) and Thirty Meter Telescope (TMT). In Europe the focus is on even larger telescopes – preliminary studies indicate that the technology to achieve a quantum leap in telescope size is feasible, and a detailed design study is now under way in Europe (led by ESO) to develop the technology needed to build a 50–100-m telescope (see Figure 1).

A larger telescope is beneficial for two main reasons – firstly, a larger collecting area (proportional to the square of the diameter) allows fainter and more distant objects to be observed. Secondly, the resolution achievable improves in proportion to diameter of the telescope, provided that the telescope is equipped with an adaptive optics system that corrects for the blurring effects of the Earth's atmosphere. Thus a 50-m telescope working at its diffraction limit could in theory produce images over five times sharper than the best images from today's 6–10-m telescopes. These two effects together have a profound effect on the scientific observations that can be made – from the ability to resolve faint planets around other stars, to studying the most distant object in the Universe.

Some examples are given below of the potential scientific breakthroughs achievable with the vast improvement in sensitivity and precision allowed by the next step in technological capabilities, focusing on the science case for a 50–100-m telescope, which is being developed in Europe. Additionally, as we have seen in the past, each new generation of facilities has advanced science by discovering the new and unexpected. Therefore it is likely that the major scientific impact of these new telescopes will be discoveries beyond those we can predict today.

Are we alone?
Planets beyond our Solar System

In 1995 the first planet around a normal star other than the Sun was detected, by the Swiss astronomers Mayor and Queloz, using a small French telescope with sophisticated instrumentation. The rate of announcement of new discoveries of extra-solar planets currently exceeds several tens per year, with discoveries dominated by indirect methods: either the motion of the parent star induced by the gravitational pull of the planet, or the light-loss resulting as the planet transits in front of its star, as seen by us. First claims of direct imaging of planets have already been made using 8–10-m telescopes (see Figure 2): it is only a matter of time until several reliable detections are available. Quantitative studies will become possible with advanced adaptive optics, using coronographic techniques to suppress the glare from the planet's parent star. Studies of Earth-like planets, especially via spectroscopy, will however remain impossible.

Extremely Large Telescopes offer spectacular advances in studying planetary systems. In addition to the improved collecting area, needed for observing such faint objects as the smaller extra-solar planets, the improved resolution allows cleaner separation of a planet from the image of its star. As a result, one of the most exciting new opportunities for Extremely Large Telescopes is the ability directly to detect *and to study* large samples of planets in other solar systems.

Planets of course come in a wide range of types, sizes and distances from their parent stars. What sort of planets can be studied with different types of telescope, and how many different planetary systems might one be able to detect? Simula-

Table 1: Highlight science cases for a 50–100-m Extremely Large Telescope.

Are there Terrestrial planets orbiting other stars?	Are we alone? Direct detection of earth-like planets in extra-solar systems and a first search for bio-markers (e.g water and oxygen) becomes feasible.
How typical is our Solar System? What are the planetary environments around other stars?	Direct study of planetary systems during their formation from proto-planetary disks will become possible for many nearby very young stars. In mature planetary systems, detailed spectroscopic analysis of Jupiter-like planets, determining their composition and atmospheres, will be feasible. Imaging of the outer planets and asteroids in our Solar System will complement space missions.
When did galaxies form their stars?	When and where did the stars now in galaxies form? Precision studies of individual stars determine ages and the distribution of the chemical elements, keys to understanding galaxy assembly and evolution. Extension of such analyses to a representative section of the Universe is the next great challenge in understanding galaxies.
How many supermassive black holes exist?	Do all galaxies host monsters? Why are supermassive black holes in the nuclei of galaxies apparently related to the whole galaxy? When and how do they form and evolve? Extreme resolution and sensitivity are needed to extend studies to normal and low-mass galaxies to address these key puzzles.
When and where did the stars and the chemical elements form?	Can we meet the grand challenge, to trace star formation back to the very first star ever formed? By discovering and analysing distant galaxies, gas clouds, and supernovae, the history of star formation, and the creation history of the chemical elements can be quantified.
What were the first objects?	Were stars the first objects to form? Were the first stars the source of the ultraviolet photons which re-ionised the Universe some 200 million years after the Big Bang, and made it transparent? These objects may be visible through their supernovae, or their ionisation zones.
How many types of matter exist? What is dark matter? Where is it?	Most matter is transparent, and is detectable only through its gravitational effect on moving things. By mapping the detailed growth and kinematics of galaxies out to high redshifts, we can observe dark-matter structures in the process of formation.
What is dark energy? Does it evolve? How many types are there?	Direct mapping of space-time, using the most distant possible tracers, is the key to defining the dominant form of energy in the Universe. This is arguably the biggest single question facing physical science.
Extending the age of discovery	In the last decades astronomy has revolutionised our knowledge of the Universe, of its contents, and the nature of existence. The next big step is likely to be remembered for discovering the unimagined new.

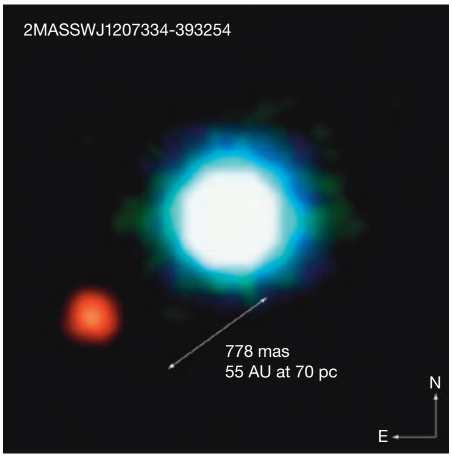


Figure 2: Infrared image obtained with the NACO adaptive optics facility on the VLT of the young (~ 10 Myr) brown dwarf 2M1207 (centre) in the nearby TW Hydrae association (Chauvin et al. 2004). The fainter object seen near it at an angular distance of 778 milliarcsec has recently been confirmed to be gravitationally associated with the brown dwarf. Models suggest that it is a giant exoplanet with a mass about five times that of Jupiter. The source is very young, is still liberating considerable energy as it contracts and cools, and probably formed in a way unlike that of planets in our Solar System. An ELT is essential to image fainter planets like our Earth, particularly as they are likely to be closer to their parent stars.

tions of observations of extra-solar planets show that a 30-m telescope at a "standard" site, equipped with suitably sophisticated adaptive optics instrumentation, should be capable of studying Jupiter-like gas giant planets out to several tens of light years, while only a much larger, 100-m-class, telescope would be capable of detecting and studying a sample of *Earth-like* planets – the key here is the extremely high spatial resolution needed to observe an object that is about 10 billion times fainter than, and very close to its parent star. Earth, for example, would appear only 0.1″ from the sun if the Solar System were observed from a distance of 10 parsecs (~ 30 light years): see the simulation in Figure 3.

The *habitable zone* is the narrow region in a planetary system where water exists in liquid form: this is a prerequisite for life as we know it. Not all stars have planets, and perhaps only a very few will have planets in the habitable zone, so the largest possible sample has to be surveyed if we are to be confident of identifying a true Earth-twin. The number of stars that can be studied is approximately proportional to the spatial resolution to the cube (i.e. to D^3, where D is the telescope diameter). A 100-m telescope can in principle detect an Earth-like planet around a solar-type star out to a distance of 100 light years. This distance limit means that there are about 1000 candidate Sun-like stars to be observed. The corresponding numbers are about 200 stars for a 50-m telescope and 30 stars for a 30-m telescope.

The large telescope collecting area, which is the key to achieving the challenging goal of detection of an Earth-like planet in a habitable zone, will automatically allow substantial extra analysis, beyond 'just' detection: it will characterise planetary surfaces and atmospheres.
The search for biomarkers in the planet atmosphere has the potential to discover life beyond our Solar System.

Massive planets

A limitation in studies of our own Solar System is that we have only one example: is what we see typical? unique? transient? It is clear that a telescope and instrumentation which could detect Earth-like planets would with ease detect larger planets, and planets with larger separation from their star. Imaging of entire planetary systems will become possible. Such data will define the outcome of the formation of planetary systems, by discovering and defining the types of systems which form and survive. Basic questions which remain unanswered to date include which stars have which types of planets, what conditions are required to form the various types of planet, what are the special properties, if any, of the parent stars and are there planets around rare types of stars (e.g. white dwarfs, very old halo stars: planets near neutron stars are already known).

By repeated imaging, planets will be followed around their orbits. Variations in their apparent brightness during this process then can be used to determine many properties. For example, their reflectivities (albedo) determine their surface temperatures. For larger planets, rings like those around Saturn, and the presence of moons may be inferred indirectly from the small deviations they produce in brightness, position of the planet and its velocity over time.

Worlds in formation

At least as important as determining the diversity of mature planetary systems is understanding the formation and early evolution processes. Is planet formation ubiquitous but survival unlikely? Or vice-versa? How long does planet formation take? How is it terminated? What happens to a planet after it forms? All these, and many related, questions require detection of the observable effects generated by on going planet formation around young stars. Current models, as yet untested by direct observations, suggest that planets form from condensations in a dusty disc encircling a young star, and subsequently create circular gaps at discrete positions in the disc; Figure 4 shows a simulation of this process. A telescope with sufficient resolving power and a coronagraph to suppress light from the central young star will be able to detect these planetary birthplaces, even at the inner disc locations where habitable planets should form.

A sub-millimetre detection capability on a suitably large telescope would even permit the mapping of the colder, outer regions of protoplanetary systems out to their Kuiper Belts, where the debris of planetary formation is believed to accumulate and survive.

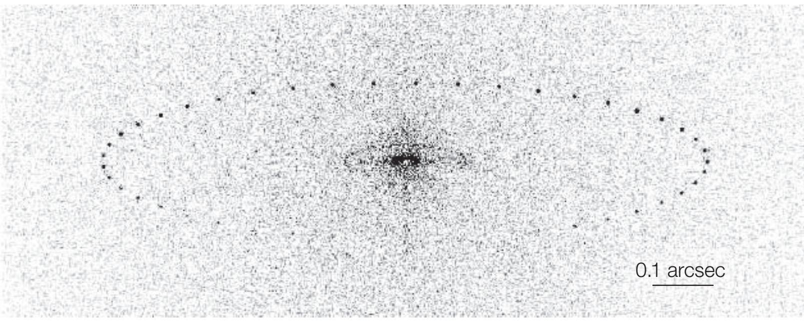


Figure 3: A simulated time-series image of a solar-system analogue, containing a Jupiter-like and an Earth-like planet at a distance of 10 pc. The system has been "observed" at number of epochs as the planets go around in the 15-degree obliquity orbits to illustrate the phase effect. Each epoch is represented by a 100-ksec exposure in the V-band with the OWL 100-m telescope, based on adaptive-optics simulations. The PSF of the central star has been subtracted from the image. (From Hainaut, Rahoui, & Gilmozzi 2005.)

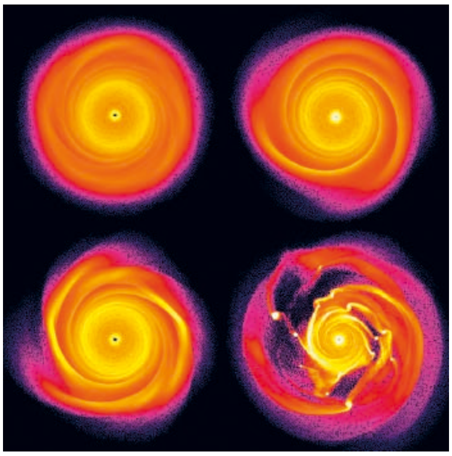


Figure 4: Simulation showing four stages in the formation of gas giant planets via fragmentation of protoplanetary discs (from Mayer et al. 2004). As the planets form, gaps are carved in the disc. An ELT has the potential to detect such gaps.

Solar System astronomy

An Extremely Large Telescope provides a natural and valuable complement to dedicated spacecraft. It would be capable of assembling a unique atlas of the surfaces of hundreds of solar system objects. Of unique value will be an Extremely Large Telescope's ability to make repeated highly-resolved imaging and spectroscopic observations of planets and moons with evolving surfaces and atmospheres. Detailed and continuing observations of this kind cannot otherwise be obtained except by dedicated (single-target) orbiters, none of which have yet been sent to the outer Solar System. Figure 5 shows an image of Jupiter's moon Io taken during a fly-by of the Jupiter orbiter Galileo: a 100-m telescope for example would have a diffraction-limited resolution of about 8 km (at a wavelength of 1 μm) at the distance of Io, allowing detailed surface maps to be made and changes to be monitored (such as the volcanic activity shown in Figure 5). Thermal-infrared images at these resolutions have never been secured.

Such a systematic series of imaging and spectroscopic observations would also allow us to follow the seasonal and long-term variability of Titan's dense haze layers, allow studies of the structures generated by the gas geysers on Triton and permit the monitoring of the evolution of the atmosphere of Pluto as it recedes from the sun.

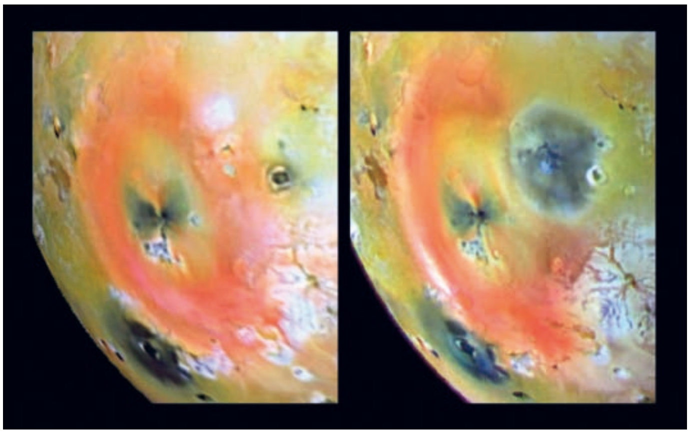
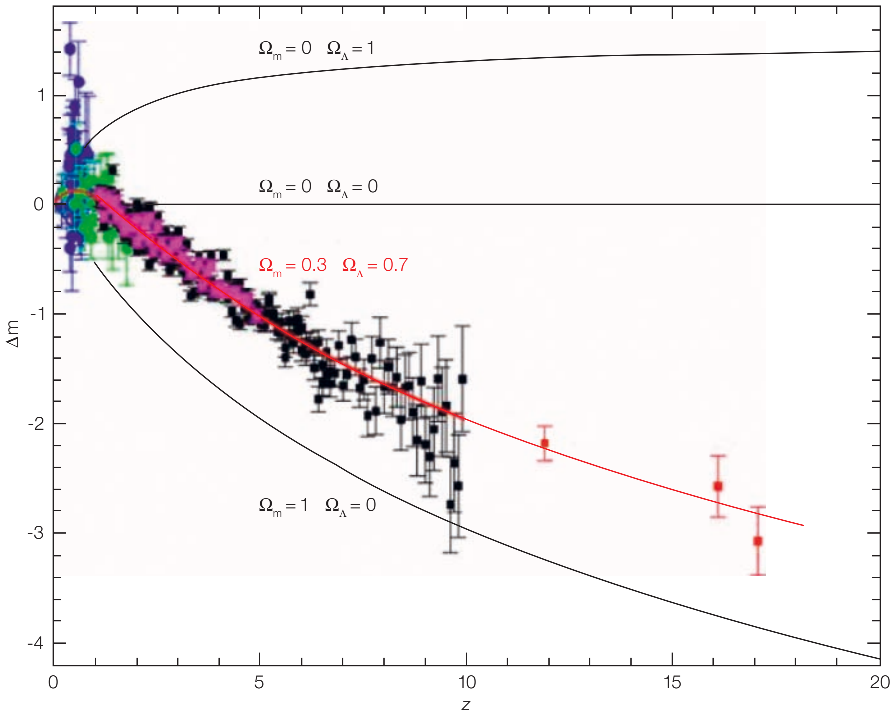


Figure 5: Changes in the surface of Io observed by the Galileo spacecraft. The images were taken on April 4 and September 17 1997. (Credit NASA/JPL). Ground-based ELTs will allow repeated imaging and monitoring of such events.

When and where did the stars form?

When did the stars form? This basic question is a key puzzle in astronomy and is only partly answered: young stars are being born today in our and other galaxies, but at a very low rate. Most stars were formed long ago. But when were the stars that make up the giant elliptical galaxies and the central bulges of spirals like our own Milky Way formed? To answer this we can make use of the fact that massive stars die young. Indeed many explode only a few million years after their birth, in spectacular supernovae explosions, whose flash can outshine whole galaxies. With an Extremely Large Telescope, such supernovae could be seen to vast distances, corresponding to redshifts up to ten in the case of a 100-m telescope (see Figure 6) and possibly to redshift 20 for supernovae from the very first (population III) stars. Redshift ten corresponds to direct observation back to 500 million years after the Big Bang, barely 3 per cent of the present age of the Universe. The frequency of supernovae at different times in the history of the Universe is directly related to the number of stars that formed at that particular cosmic epoch. Measuring the rate of supernova explosions across the Universe can therefore tell us when stars formed and at what rate. Simulations suggest that a 100-m telescope would require about 130 nights both to discover ~ 400 supernovae (using

Figure 6 (below): Hubble diagram, normalised to a cosmological model for an empty Universe, for supernovae out to redshift 20 (from Della Valle et al. 2005). Pink dots are simulated Type Ia SNe, black dots Type II (+Ib/c), blue and green dots are Ia SNe actually discovered by groundbased telescopes (Perlmutter et al. 1998, 1999; Riess et al. 1998; Knop et al. 2003, Tonry et al. 2003) and from HST (Riess et al. 2004). The SNe have been distributed around the track $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ after taking into account the intrinsic dispersion of the peak of the luminosity of Type Ia and II SN populations, while the photometric errors have been derived from the S/N ratio that has been computed for each simulated observation, assuming a 100-m telescope. Red dots represent SNe from Pop III star population. A 100-m ELT could generate such a sample of supernovae in about 130 nights of observing, including crucial measurements of spectroscopic redshifts and determination of the supernova types.



near-infrared imaging in the *J*-, *H*- and *K*-bands) and to carry out spectroscopy to confirm their nature, redshift and properties. Such a sample will provide a reliable measure of the star-forming history of the Universe back to a time when the Universe was a few per cent of its present age.

When did the stars assemble into today's galaxies?

How did the galaxies that we observe around us come to be formed? This remains one of the outstanding questions in modern astronomy. The current best model suggests that a hierarchical sequence of mergers of smaller component galaxies built up most of the galaxies we see today. Indeed, recent studies of our own Milky Way galaxy have revealed a few small galaxies currently merging into the Milky Way, while similar behaviour is apparent in our neighbour the Andromeda galaxy M31. Detailed analysis of merger events gives clues as to the timing of the main mergers in a galaxy's history and through this, the role of the mysterious dark matter, which must play an important part in galaxy formation through its dominant gravitational effect.

Up until now these studies have been limited to our own Galaxy and its nearest neighbours. But do all galaxy types have similar merger histories? How important is environment? To study a representative section of the Universe requires reaching at least the nearest large galaxy clusters which contain large elliptical galaxies. This means observing galaxies in the Virgo or Fornax clusters at distances of 16 or 20 mega-parsecs respectively. Initial feasibility studies look very promising – simulations show that a 100-m-class telescope should be able to resolve individual stars in galaxies in the Virgo cluster, and obtain sufficiently accurate photometry to determine their ages and composition, even for the oldest, hence faintest, unevolved stars. Spectroscopic observations of the brighter stars will also be possible, allowing measurements of the kinematic motion of the stars and accurate determination of their chemical composition. From these a detailed picture will be derived of the process by which (and,

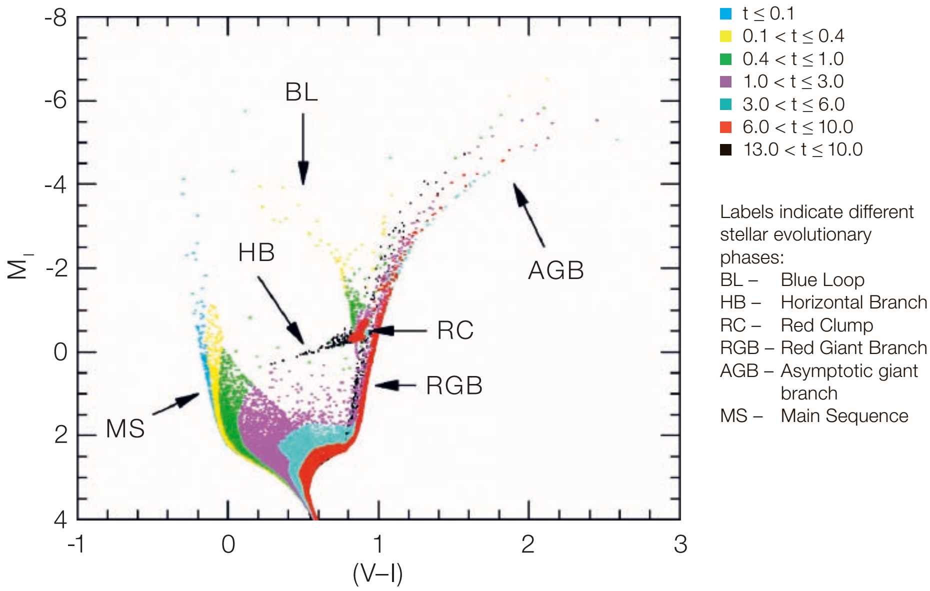


Figure 7: A predicted distribution of stars as a function of magnitude (vertical axis), colour (horizontal axis) and age, for a plausible galaxy model (from Aparicio & Gallart 2004). The colour coding represents stars in different age intervals, with units in billions of years. A 100-m-class ELT would have the resolving power and collecting area needed to place individual stars on such a diagram, and hence measure the age of the stellar populations, in galaxies as distant as the Virgo cluster.

indeed, of the components from which) the target galaxies were assembled, and the role of dark matter in this process.

The physics of galaxy formation

To understand the creation and evolution of galaxies in general we must address what is one of the major goals of future astrophysics: to map the distribution and growth of both the baryonic (normal matter) and dark matter components of galaxies at moderate to high redshift (z = 1–5), a key epoch for galaxy formation. Although individual stars cannot be resolved at these cosmological distances, a 50-m to 100-m Extremely Large Telescope will not only resolve the distant galaxies into their luminous components, but will be able to characterise these individual components.

Using techniques such as integral-field spectroscopy, in which spectra are obtained at thousands of locations across a (proto-) galaxy simultaneously, it will be possible to determine the relative star formation rate, the mass of stars and the chemical composition at these different locations within each galaxy. This will shed light on the "feedback" mechanisms believed to affect the formation of galaxies, such as the effects of a newly-formed active galaxy nucleus, or supernova explosions, on surrounding star formation.

In addition, the bulk motions of gas and stars inside galaxy could be determined, thus allowing one to map the dark matter content of individual galaxies at a range of redshifts, corresponding to epochs when the galaxies were in the process of assembly. Then, measuring the kinematics of their satellite objects, both internal and relative to their more massive partners, we can estimate the amount of and infer the distribution of the mass present in the galaxy's halo, which is one of the few ways we have of detecting and examining the dark matter and its distribution.

This will provide astronomers with a detailed evolutionary history of the clumping of dark matter (Figure 8). We will "see" galaxy formation in all its glory from formation to maturity, and so directly test our understanding of the basic evolutionary processes in the Universe.

Supermassive black holes

The centres of most, perhaps all, galaxies harbour supermassive black holes. These exotic objects are usually discovered indirectly, as extreme radio- or X-ray-luminous sources, quasars and Active Galactic Nuclei. Direct studies, critical for reliable mass determination, and essential when the hole is not active, are possible only when precision studies of the very local region of the galactic nucleus are feasible: only (relatively) close to a black hole is the gravity of the whole galaxy dominated by the mass of the black hole, so that the black hole's presence can be deduced. The methodology has been proven by observations at ESO over many years proving the existence of a massive (~ 3×10^6 $M_\odot$) black hole in the core of the Milky Way galaxy. Direct measurements of the speed at which stars and gas clouds are orbiting the centre of a galaxy are required. The closer to the centre these can be measured, the more reliable is the evidence for, and the determination of the mass of, the black hole.

For reasons which are not understood, the evolution and mass of the supermassive black holes is apparently very closely related to the properties of the very much larger host galaxy. Understanding this, and determining if it is indeed ubiquitous, would be the first clue relating the nuclei of galaxies to their major parts, and the first link between the exotic and the typical in galaxies. How do the black holes first form? How do they grow, and at what rate? Are growing black holes always active? How does a central black hole "know" the properties of the larger galaxy in which it resides? Does every galaxy have a massive black hole?

All these questions require for progress detailed study of the masses and ubiquity of central black holes. This requires the highest possible spatial resolution and faint-object spectroscopy, attainable only with an extremely large telescope. For example, Figure 9 shows that a 100 m telescope working at its diffraction limit can in principle resolve the sphere of influence of a supermassive (10^9 $M_\odot$) black hole at all redshifts across the Universe (provided they exist of course!) and even detect the influence of a modest 100 $M_\odot$ black hole in the local Universe, out to about 1 Mpc from us. It will then be possible to carry out a systematic census of black holes as a function of cosmic epoch and begin to understand their formation in relation to the galaxies around them.

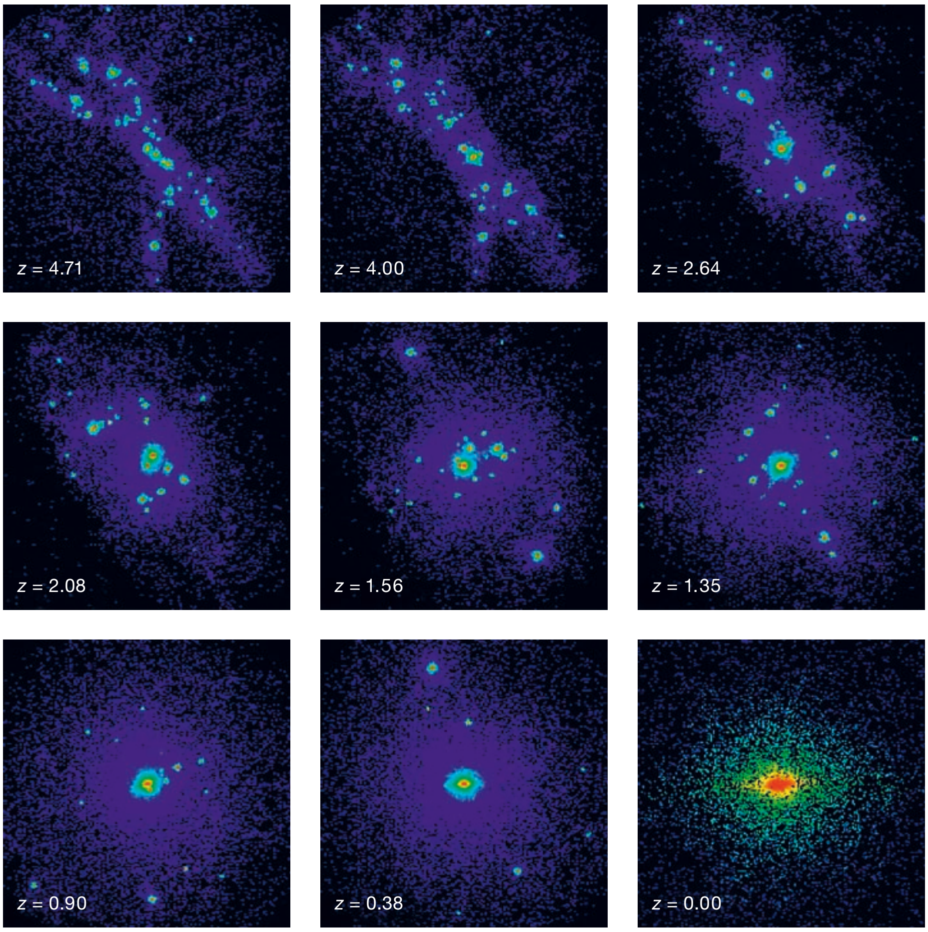


Figure 8: Simulations showing Dark Matter particles within a cube of 320 physical kpc on a side, shown at various redshifts and projected so that the luminous galaxy at $z = 0$ is seen edge-on (from Abadi et al. 2003). The bottom right panel zooms into the innermost 40 kpc of the system. Each particle is coloured according to the logarithm of the local dark matter density using a palette that runs from red to blue: red and blue correspond to ρ_{dm} greater than and less than about 10^{10} $M_\odot$ kpc^{-3} respectively. An ELT has the potential to observe such galaxy haloes in the process of formation: observations of the motion of the central galaxy and its satellites will provide a measurement of the distribution of dark matter in the extended galaxy halo.

The ionisation of the Universe

The early Universe was hot (ionised) and transparent. With time, the gas cooled. The aftermath of the Big Bang left the early Universe an opaque gas of hydrogen and helium. Some time later, the first objects heated the hydrogen and helium, making it (again) transparent – the "era of (re-)ionisation". A key goal of astrophysics is to understand how and when the first luminous objects in the universe formed from the primordial gas, what they were, and how they contributed to ionising and enriching the gas with heavy elements.

Tantalising questions about the re-ionisation history of the universe are raised by recent results. Those from the Wilkinson-MAP Cosmic Microwave Background satellite probe, when combined with ground-based surveys of the large-scale structure of the Universe today, suggest that the gas was re-ionised by about 180 million years after the Big Bang (redshift ~ 17) while observations of the highest redshift quasars at about 700 million years (redshift ~ 6) demonstrate that enough of the intergalactic medium remained un-ionised at that time to absorb almost completely all radiation bluer than the Lyman α recombination line of HI (Figure 10). What is the solution to this apparent quandary? It may be that there were two re-ionisation epochs, an earlier caused by the first generation of massive stars, followed by cooling, and then one later by the first quasars and galaxies. Alternatively, a slower, highly inhomogeneous re-ionisation process may have occurred over the period between the two epochs.

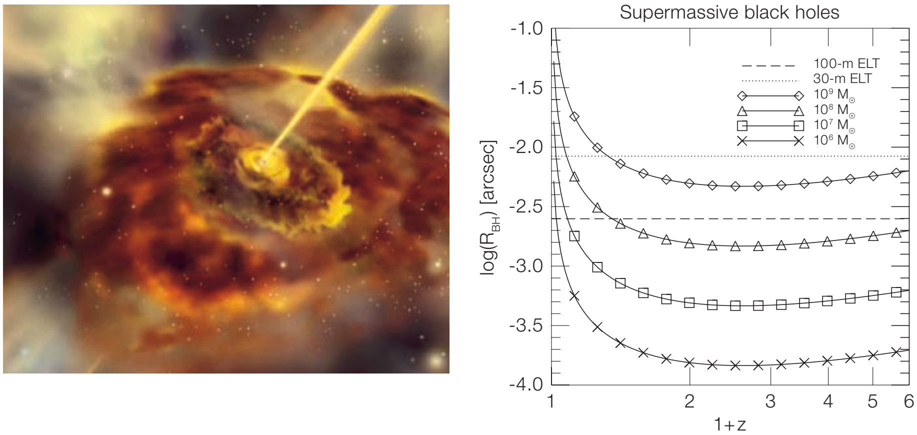


Figure 9: **Left:** Artist's conception of an AGN with the black hole surrounded by accreting material and ejecting jet at relativistic velocities. **Right:** The impact of a 100-m-class telescope on studies of intermediate and massive black holes would be considerable. Shown here are the distances to which the sphere of influence can be resolved (for comparison, the resolution of a 30-m telescope is also shown). With a 100-m ELT we be able to detect 10^9 $M_\odot$ black holes at all redshifts (where they exist). Here we assume a cosmology of $H_0 = 70$ km $s^{-1}Mpc^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$. The point spread function is given by 1.22 λ/D, where D is 30 m or 100 m and λ = 1 µm. (Figure credits: Left: GLAST/NASA, Courtesy Aurore Simonnet, Sonoma State University, Right: M. Hughes.)

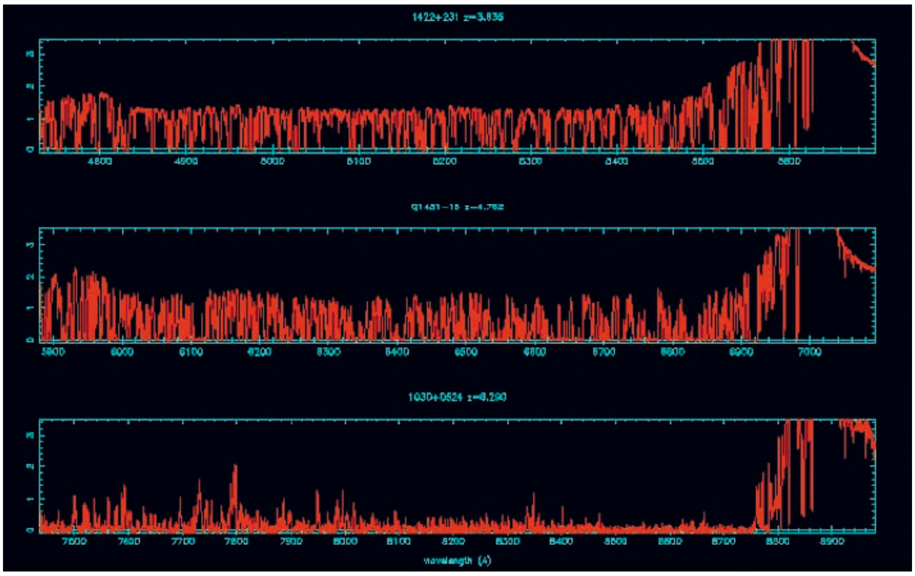


Figure 10: Spectra of quasars of increasing redshift illustrating the increase in absorption due to intervening neutral gas with increasing redshift. At the highest redshifts these show a "Gunn-Peterson" absorption trough – the complete absorption of light at wavelengths shortward of the Lyman α line of atomic hydrogen – implying that the re-ionisation epoch which began at redshift ~ 20 must have continued until redshift ~ 6. An ELT's supreme sensitivity to point sources (such as quasars, gamma ray bursts and supernovae) will allow observations of the ionisation state of the Universe to very high redshift, possibly all the way back to when the re-ionisation process began. (Figure shows observations by W. Sargent & M. Rauch; Tae-Sun Kim; M. Pettini. Compilation by R. Carswell.)

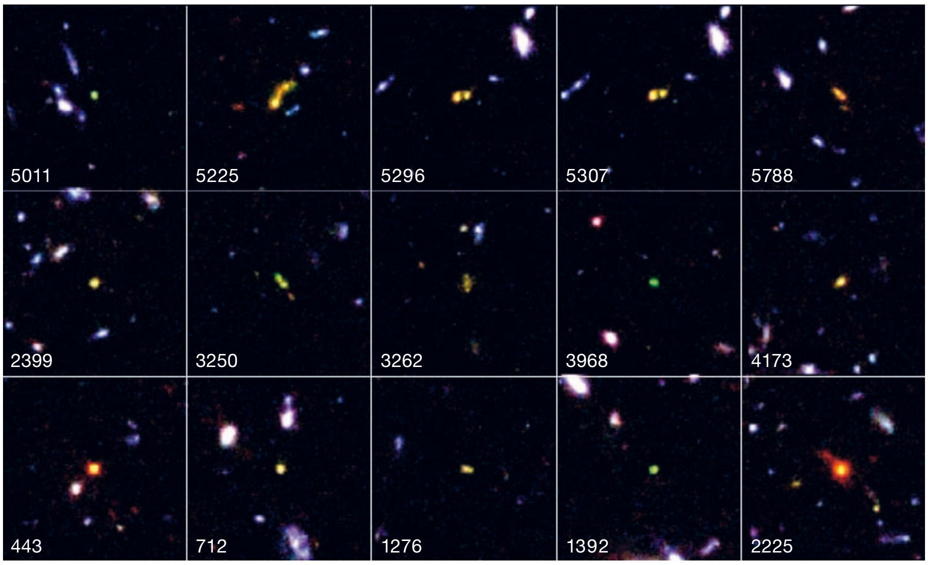
These models, together with other more complex possibilities, could be tested if we can observe the ionisation state of the high-redshift Universe directly: this is feasible, through analysis of the absorption features produced in the spectra of suitably-luminous very distant "background" objects. There are a few populations of sources that could be observed at such very high redshift with an ELT. The short-lived gamma-ray bursts are extremely bright for a short time, so much so that they should be detectable up to redshift ~ 15–20. Supernova explosions of the first stars to form, though not yet detected, would probably be fainter than this, but could still be used to probe the state of the gas at redshifts up to 10. This population of "first supernovae" may well disappear once the local heavy-element enrichment becomes higher than 1/10000 of the solar value. Testing this prediction will itself be a major challenge, and discovery.

Quasars are currently used as powerful background sources, and will continue to be useful in future, if they exist at higher redshift. Although the epoch of first quasar formation remains an open question, the quasars being found at redshifts around 6 are (presumably!) powered by supermassive black holes, so we infer that intermediate-mass black holes (corresponding to quasars of intermediate luminosity) must have existed at earlier epochs, up to at least redshifts of about 10. Probing the physics of the gas in the early Universe requires intermediate/high-resolution spectroscopy of these "background" sources in the near infrared, the natural domain of ground-based Extremely Large Telescopes. Apart from the very rare extreme gamma-ray bursters (and/or bursts caught very early), which could be observed with a 30-m-class telescope, spectroscopic observations of these faint background objects can only be carried out with telescopes of the 60–100-m class.

The first galaxies

The first galaxies, being the places of formation of the first stars (a prediction well worth verifying!) compete with the first quasars for the re-ionisation of the gas in the early Universe. Candidate star-forming galaxies out to redshift about 6 have already been discovered and a few have been confirmed spectroscopically. Equivalent objects are expected to exist out to redshifts greater than 10 for several reasons. Firstly, the analyses of the fluctuations in the Cosmic Microwave Background indicate ionisation of the universe at redshifts > 10, presumably by ultraviolet emission from the first objects. Secondly, SPITZER satellite observations of the higest redshift galaxies known to date show evidence for old stellar populations – indicating that these galaxies formed

Figure 11: HST/ACS images of high-redshift (z ~ 5–6) galaxies from Bremer & Lehnert (2005) showing the small but resolved nature of the galaxies, with typical half-light radii of 0.1–0.2 arcsec (1–2 kpc). A 50 to 100-m ELT will not only measure detailed physical properties of such galaxies but will also be capable of finding and confirming (with spectroscopy) galaxies at significantly higher redshifts (10 and beyond), possibly including the first galaxies to form in the Universe.



much earlier. Very high-redshift star-forming galaxies will probably be detectable in considerable numbers with future spacecraft (James Webb Space Telescope) and ground-based (ALMA) facilities. However a 100-m-class Extremely Large Telescope will be needed to provide the desired diagnostics of the astrophysics of both the gaseous interstellar medium and the early stellar populations in these galaxies.

Furthermore, a sub-millimetre capability on an Extremely Large Telescope, if it were at a suitable site, would allow a large-scale survey (with mapping speed thousands of times faster than ALMA at 850 μm) that would detect the millions of dusty high-redshift galaxies which (probably) contribute the cosmic far-infrared and sub-mm background, resolved down to quite faint levels throughout the Universe. With redshift estimates from sub-mm flux ratios, such a survey would yield a treasure-trove of information on large-scale structure from very early epochs to the recent past.

Dark energy and fundamental physics

The recent discovery of the accelerating expansion of the Universe has led to an urgent need to understand the nature of the mysterious "dark energy" which is driving this expansion. The dark energy is believed to account for about 70 per cent of the energy budget of the Universe (Figure 12, see next page) and yet its nature is completely unknown. One potential candidate is the vacuum energy implied by the "cosmological constant" term in Einstein's field equations (whose solutions represent global pictures of the Universe). However measurements of the effects of dark energy on cosmological scales constrain its contribution to be many orders of magnitude smaller than the vacuum energy scale predicted by particle physics theories.

The direct measurement of the dynamical expansion history of the Universe via Type Ia supernovae has shown that the dark energy exerts a negative pressure and hence accelerates the universal expansion. Direct analysis of the expansion rates of the Universe across space-time is needed to investigate this remarkable form of energy. Intriguingly, most of the effects of dark energy are apparent at relatively low redshifts (less than about z = 1), although equivalent studies at high redshift, when feasible, may well have their own surprises in store.

An Extremely Large Telescope can determine the expansion history of the Universe using several different and complementary astrophysical objects, thus decreasing any dependency on possibly unknown systematic effects. The well-understood primary distance calibrators, pulsating Cepheid stars, globular clusters, planetary nebulae and novae, could all in principle be observed to cosmological distances where the effect of dark energy is dominant in the Universe. The exquisite sensitivity to point sources of an Extremely Large Telescope with appropriate adaptive optics capability, combined with its impressive collecting area, will allow it to detect Type Ia supernovae to redshift of about 4, and Type II supernovae (which can also be used as distance indicators via the expanding photosphere method) possibly all the way to redshifts of about ten (see Figure 6).

By mapping the geometry of the Universe on the largest scales and accurately determining any variations of the strength of dark energy with time, astronomers can answer the fundamental question of whether dark energy corresponds to Einstein's cosmological constant or to some "quintessence field" as suggested by modern versions of quantum field theories. The need for these observations is critical and the implications for all of physics and cosmology are vast.

Furthermore, ELTs offer the intriguing possibility of observing the expansion of the Universe directly – by observing the minute increase in redshift of absorption lines in quasar spectra over a period of about 10 years it will be possible to watch the Universe expanding in "real time"! Such detailed and direct measurements will provide an important test of cosmological models and also allow tests for the constancy of fundamental parameters such as the fine structure constant.

Cosmological observations have now become the only way to characterise several of the most promising unexplored sectors beyond the Standard Model of particle physics. The discovery and description of dark energy is possible only with cosmological-scale observations: no small-scale effects are yet known. However, dark energy and dark matter must be part of the process towards understanding the next generation of theory in Physics: they are related to super-symmetric particles, string theory, theories of gravity and quantum gravity, theories of higher dimensions, and the constancies of the fundamental constants. An Extremely Large Telescope is the next big step in direct observation of the nature of the Universe.

Why an ELT now?

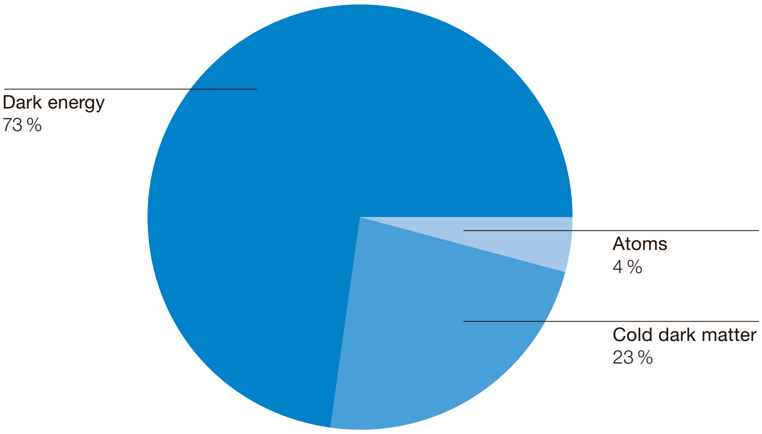
The relatively large apertures which are affordable and technically feasible for groundbased telescopes means that these facilities are the natural means to provide maximal light-gathering power. Natural complementarity exists between these and orbiting observatories which, although considerably more expensive for the same size of telescope, benefit from being clear of the thermal background and the seeing effects of the Earth's atmosphere.

For example, routine images from the Hubble Space Telescope's Advanced Camera for Surveys reveal objects which are so faint the largest existing telescopes are unable to acquire their spectra. Without spectroscopic information we can learn only a limited amount about the basic nature and properties of an astrophysical object. The advent of the James Webb Space Telescope, currently scheduled for launch in 2012, will increase this imbalance. Until the astronomical community acquires complementary groundbased facilities which are much larger than those available at present, the majority of future discoveries will be beyond our spectroscopic reach and detailed understanding. This is a major reason why astronomers are urgently seeking to begin construction of the first groundbased Extremely Large Telescopes.

Space observatories which are designed for observations at wavelengths inaccessible from the ground (because of absorption by the Earth's atmosphere), such as the flagship X-ray facilities XMM-Newton and Chandra, regularly discover sources which are too faint in the wavelength range readily accessible to the ground, the optical and near infrared, to be detected or investigated by existing telescopes. Planned next-generation missions will further increase the need for a major enhancement in the performance of our large optical/near infrared telescopes if the new phenomena which they reveal are to be understood.

New radio and sub-millimetre astronomy groundbased facilities are being built that will also naturally complement an Extremely Large Telescope's optical and infrared capabilities, and will discover sources which will demand further study at other wavelengths. For example the Low-Frequency Array (LOFAR), due for completion in 2008, will operate at long radio wavelengths, and a more ambitious project, the Square Kilometer Array is being proposed to follow as the next-generation radio facility. In the sub-mm bands the Atacama Large Millimeter Array (ALMA), an interferometer currently in the initial stages of construction and a key element of ESO's scientific strategy, will provide very high sensitivity and spatial resolution beyond the limits of current ground-based telescopes. ALMA is due to be fully operational by 2012 and will cover a very wide range of science, detecting both thermal continuum emission from dust and line emission in objects from the nearest star-forming regions to luminous galaxies at very high redshift. Groundbased Extremely Large Telescopes will be ideally matched to provide imaging and spectroscopic follow-up of these sources at optical to mid-infrared wavelengths, with matched angular resolution.

Figure 12: Our current understanding of the mass-energy content of the Universe. All "normal" matter is a minor contribution of only about 4 %. Dark matter, of unknown nature dominates mass. Dark energy, of unknown identities, dominates the Universe. What is it? ELTs can tackle this question by measuring the expansion history of the Universe using a range of independent techniques.



Science Case Development

This summary is based on a full science case document developed at a series of meetings over four years involving over 100 astronomers. The work is sponsored by the EC network OPTICON, and maintained as part of the European Extremely Large Telescope Design Study, funded in part by the EC FP6 programme, by ESO, and by many European national agencies and organisations.

WWW sites for further information:
OPTICON European ELT science case work: *http://www.astro-opticon.org/networking/elt.html*
Euro-50 telescope web site: *http://www.astro.lu.se/~torben/euro50/*
OWL telescope web site: *http://www.eso.org/projects/owl/*

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