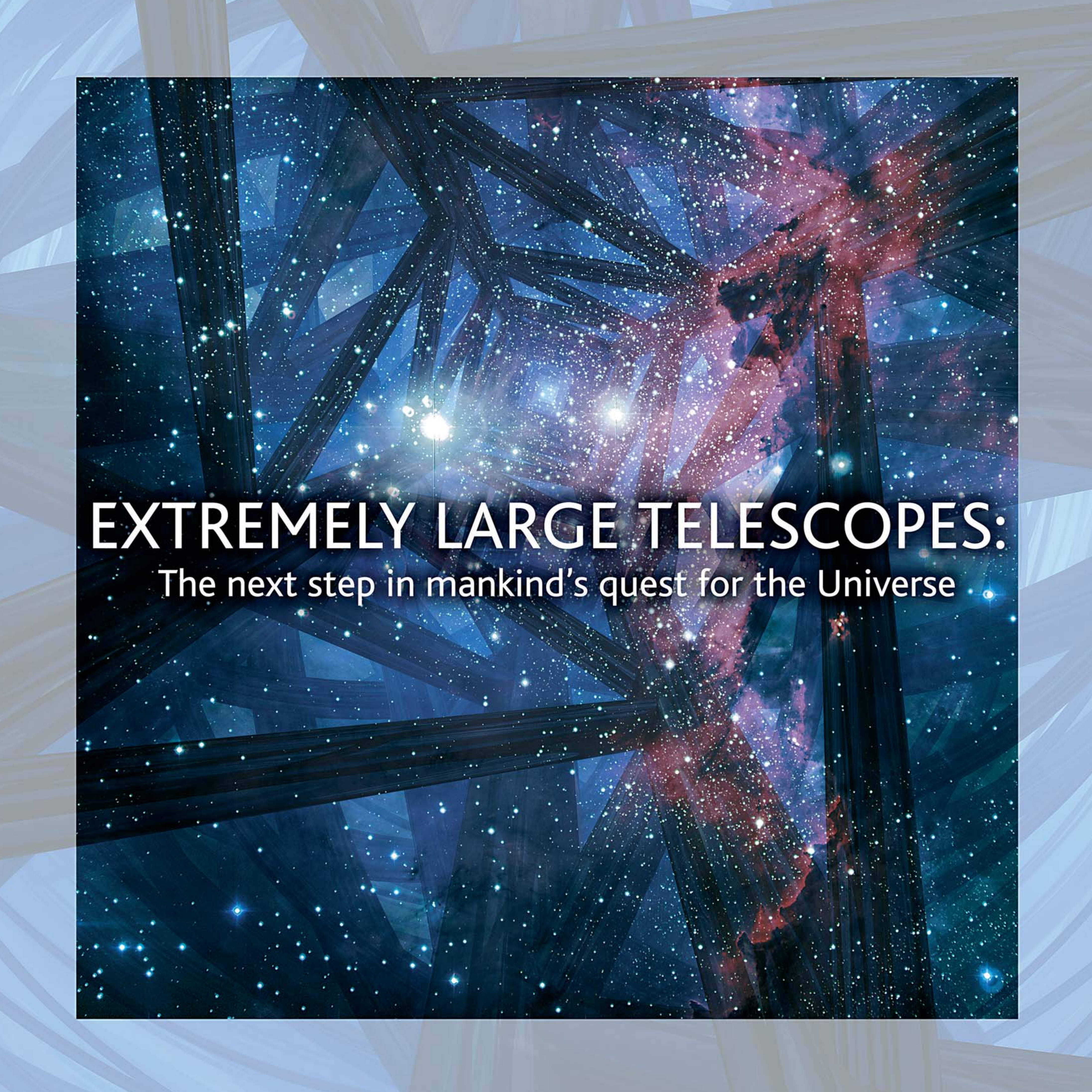


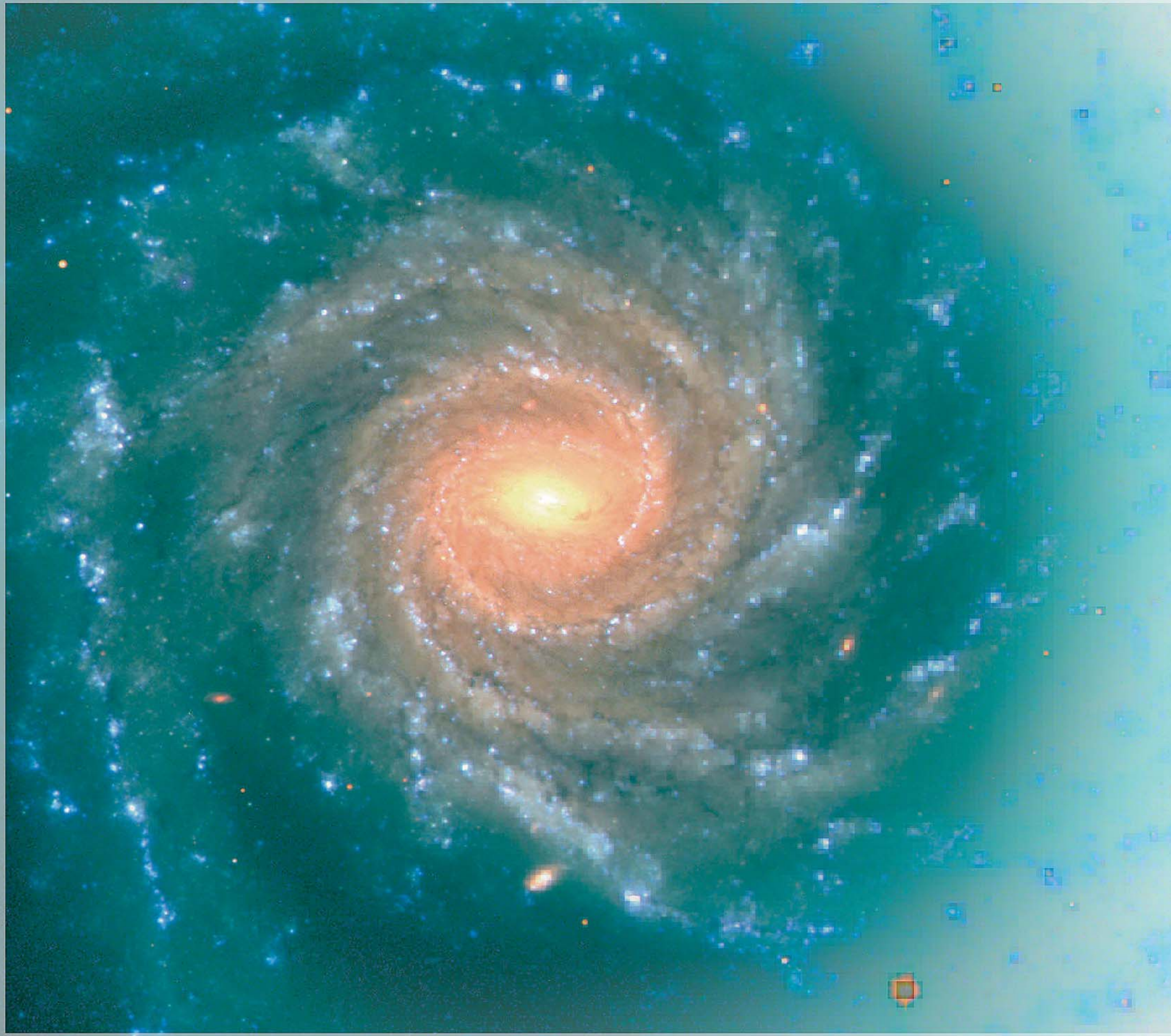
EXTREMELY LARGE TELESCOPES:

The next step in mankind's quest for the Universe

The Extremely Large Telescope

is the essential next step in mankind's direct observation of the nature of the universe.

It will provide the description of reality which will underlie our developing understanding of its nature.



ASTRONOMY IS IN ITS GOLDEN AGE.

Since the invention of the telescope, astronomers have expanded mankind's intellectual horizons, moving our perception of the Earth from an unmoving centre of the Universe to being one of several small planets around a typical small star in the outskirts of just one of billions of galaxies, all evolving in an expanding Universe in which planets are common.

The nuclear energy sources which provide starlight are identified, and we know that the chemical elements of which we are made are the ash of that process: stardust. Exotic states of matter are known: neutron stars, black holes, quasars, pulsars. We can show that the Universe started in an event, the Big Bang, and see the heat remnant of that origin in the cosmic microwave background. Tiny ripples in that background trace the first minute inhomogeneities from which the stars and galaxies around us grew. By comparing the weight of galaxies with the weight of all visible matter astronomers have proven that the matter of which we, the planets, the stars, and the galaxies are made is only a tiny part of all the matter which exists. Most matter is some exotic stuff which is not yet detected directly, but has weight which controls the movements of stars in our Galaxy. This 'dark matter' or 'unseen mass', whatever it is made of, is five times more abundant than are the types of matter of which we are made. Perhaps most exotic of all, some new force seems to be stretching space-time, accelerating the expansion of the Universe. The nature of this force, which controls the future of the Universe, remains quite unknown.

Astronomy is a technology-enabled science. Progress in astronomy demands new technologies and new facilities. Astronomical telescopes and associated instrumentation are the essential tools which allow access to the widest and most comprehensive laboratory of all, the Universe we live in. Telescopes allow discovery of the new, and subsequent exploration of the whole range of known phenomena, from Solar System objects such as planets, comets and asteroids, to the formation of stars and galaxies, extreme states of matter and space and the determination of the global matter-energy content of our universe.
In the past half-century a new generation of telescopes and instruments has allowed a golden age of 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.

In the last decade, satellite observatories and the new generation of 8- to 10-metre diameter ground based telescopes, have created a new view of our universe, a universe dominated by poorly understood dark matter and a mysterious vacuum energy density. 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. Some discoveries made using relatively modest technologies will require vast increases in technology to take the next step to direct study. Each new generation of facilities is designed to answer the questions raised by the previous one, and yet most advance science by discovering the new and unexpected. As the current generation of telescopes continues to probe the universe and challenge our understanding, the time has come to take the next step.

In the words of the Astronomer Royal for England Sir Martin Rees,
"Cosmologists can now proclaim with confidence (but with some surprise too) that in round numbers, our universe consists of 5 percent baryons, 25 percent dark matter, and 70 percent dark energy. It is indeed embarrassing that 95 percent of the universe is unaccounted for: even the dark matter is of quite uncertain nature, and the dark energy is a complete mystery".

A small step in telescope size will not progress these fundamental questions. Fortunately, preliminary studies indicate that the technology to achieve a quantum leap in telescope size is feasible. A telescope of 50-metre to 100-metre diameter can be built, and will provide astronomers with the ability to address the next generation of scientific questions.

Highlight science cases

for a 50metre -100metre Extremely Large Telescope.

Are there terrestrial planets orbiting other stars? Are we alone?

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 super-massive black holes exist?

Do all galaxies host monsters? Why are super-massive 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 is 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 200million years after the Big Bang, and made it transparent? These objects may be visible through their supernovae, or their ionization 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 will be remembered for discovering the unimagined new.

Astronomy With A 50metre – 100metre Telescope

The science case for 50m-100m diameter telescopes is spectacular. All aspects of astronomy, from studies of our own Solar System to the furthest observable objects at the edge of the visible Universe, 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. Several examples are outlined in the following sections. Furthermore, experience tells us that many of the new telescope's most exciting astronomical discoveries will be unexpected. Indeed the majority of the science highlights of the first ten years of the first 10m telescope, the Keck, such as its part in the discovery and study of very high-redshift young 'Lyman-break' galaxies, were entirely new, violated received wisdom, and being unknown, were not featured in the list of science objectives prior to the telescope's construction.

The vast improvement in sensitivity and precision allowed by the next step in technological capabilities, from today's 6-10m telescopes to the new generation of 50-100m telescopes with integrated adaptive optics capability, will be the largest such enhancement in the history of telescopic astronomy. It is likely that the major scientific impact of these new telescopes will be discoveries we cannot predict, so that their scientific legacy will also vastly exceed even that rich return which we can predict today.

Are we alone: how do planets, and planetary systems, form and evolve?

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 weight 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 8m-10m telescopes. It is only a matter of time until several reliable discoveries are available. Quantitative studies will become possible with advanced adaptive optics, using coronographic techniques to suppress the glare from the planet's parent star.

More detailed studies of the planets, especially via spectroscopy, will however remain impossible. This is for two main reasons – firstly planets are faint; and second they are many orders of magnitude fainter than their parent stars, which they lie very close to, so that reflected light or intrinsic emission from the planet is swamped by the glare from the star.

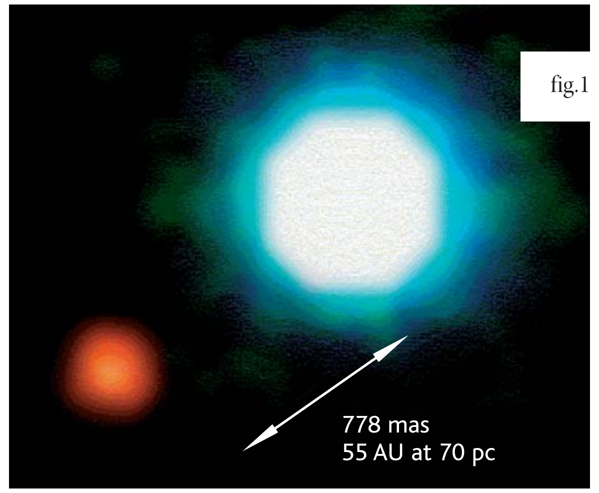


fig.1

Possibly the first ever image of an extra-solar planet around its parent star. This adaptive optics corrected picture was taken at near-infrared wavelengths with the VLT Yepun 8-m Telescope. Right (blue): the brown dwarf star 2M1 207.
Left (red): a very faint companion. If indeed physically associated with the star, this is a 5 Jupiter mass planet. The first confirmed images of planets will be of massive hot Jupiters, of which this may be one: an ELT is essential to image planets like our Earth.

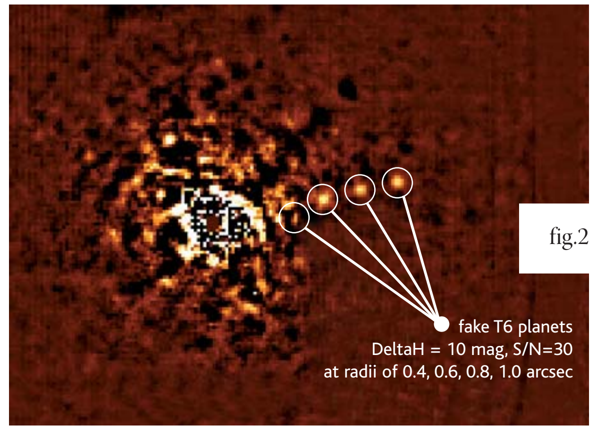


fig.2

This 40 minutes H-band observation with the ESO VLT around a bright star with AO correction and spectral differential imaging shows exquisite speckle subtraction. Simulated planets are added, showing they can be detected if present. With this technique, one can detect a companion 25,000 times fainter just 0.5 arcsec from its parent star in only 40 minutes on an 8-m class Telescope.

Earth-like planets and the search for extra-terrestrial life

Extremely Large Telescopes offer spectacular advances in studying planetary systems, since the spatial resolution of a telescope improves in proportion to its diameter. Thus, in addition to the improved collecting area, which is needed for observing such faint objects as the smaller extrasolar 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? Careful simulations of observations of extra-solar planets have been completed, showing that a 30m 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. 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. 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 pre-requisite for life as we know it. The search for earth-like planets within that narrow range of distances around a star requires both extreme light gathering power, to detect the faint planet, and extreme telescope size, to separate the planet from the bright star light. The challenge is to observe an object that is about 10 billion times fainter than its parent star. 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 proportional to the spatial resolution to the cube (i.e. to D^3, D telescope diameter). The time to achieve a specific reliability of detection under these background-dominated observing conditions is proportional to D^4. A 100m 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 50m telescope and 30 stars for a 30m telescope.

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

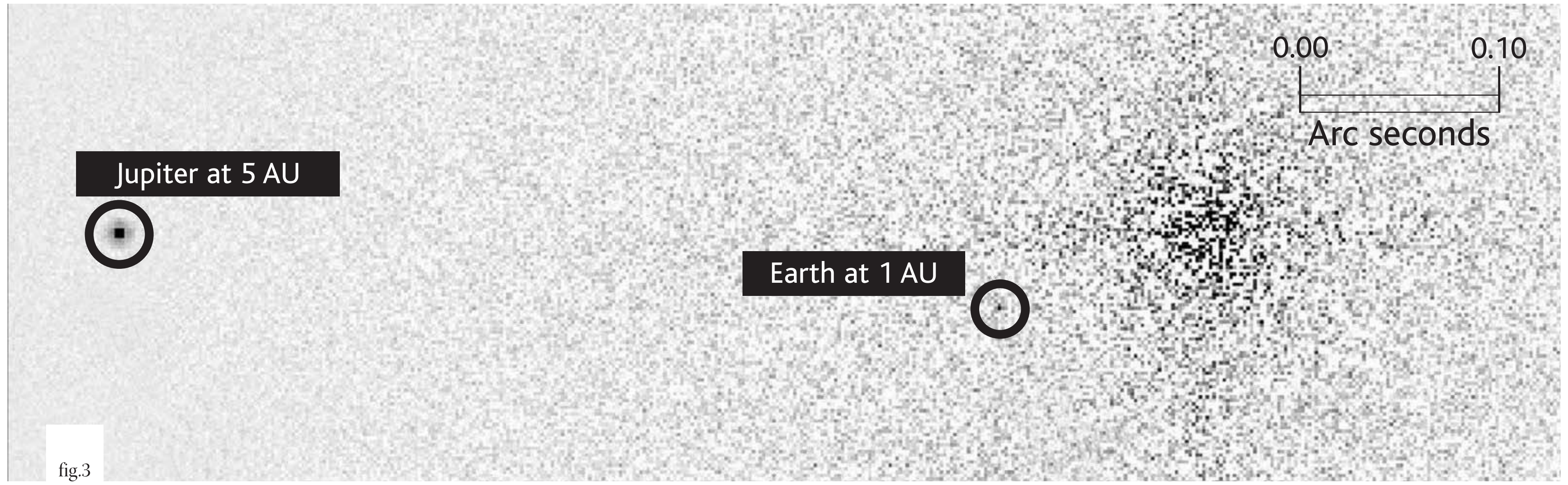


fig.3

Simulated image of a solar-type planetary system at 10 parsec (30 light-years), as seen by a 100-m telescope. This simulation subtracts the light of the parent star, and illustrates that planetary systems like our own can be discovered and studied with the next generation telescopes. The residual light of the masked parent star is also visible. A major challenge for the ELT is to deliver images of sufficient quality to allow this experiment.

Massive planets and comparative planetology

A limitation in studies of our own Solar System is that we have only one example. Is what we see typical, or is it unique or 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. This will tell us 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 whether there are planets around rare types of stars , such as white dwarfs or very old halo stars.

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 would reveal themselves (see Figure 4). On a range of timescales, brightness changes resulting from diurnal rotation, weather and even seasons offer a powerful technique for investigating surface and atmospheric conditions. For example, because of weather, seas, forests, deserts and ice-caps, Earth's brightness changes much more on all time-scales than does the brightness of Mars or of Venus.

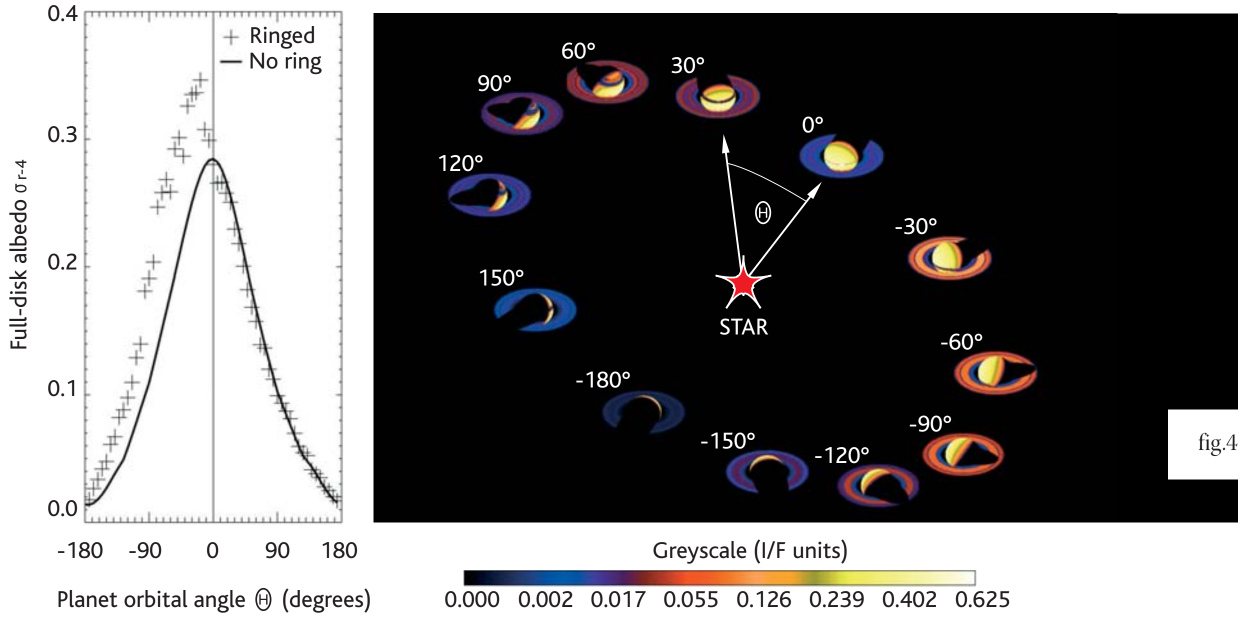


fig.4

An ELT capable of measuring contrasts of 1 part in 10^7 to 1 part in 10^{10} could determine whether 'Saturn-analogues' orbiting distant stars have rings or not by detecting the complicated brightness and shadow variations rings cause in the reflected starlight as a function of 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 5 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 disk locations where habitable planets should form. Repeated observation will detect directly the orbital changes in the disk as the planets grow. It is feasible to see a dark lane from a forming Earth-like planet against the glare of its parent star, provided adequate contrast control is achievable.

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

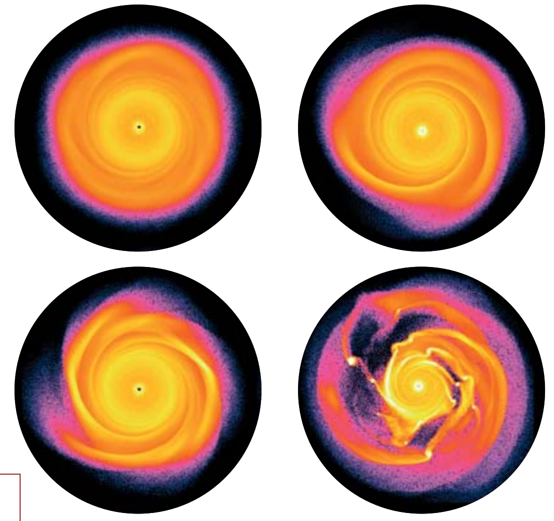


fig.5

Simulation showing the formation of gas giant planets via fragmenation of protoplanetary disks. As the planets form, detectable gaps are carved in the disk.

SOLAR SYSTEM ASTRONOMY

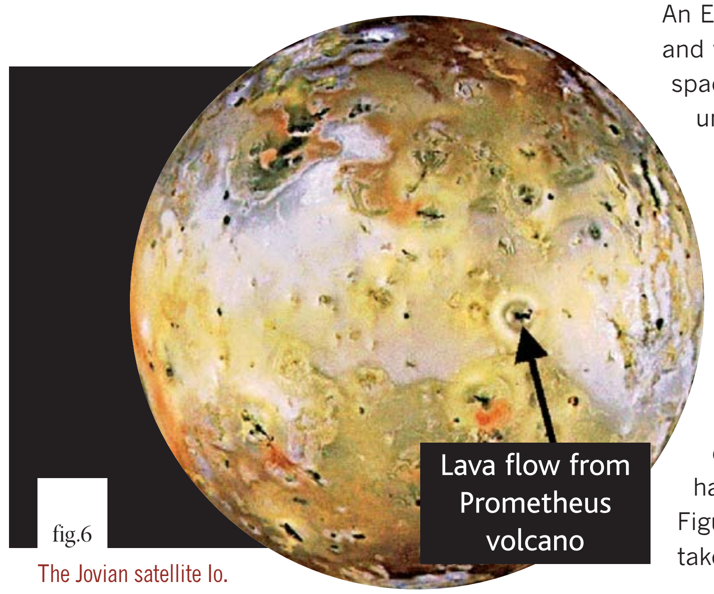


fig.6

The Jovian satellite Io.

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 6 shows an image of Jupiter's moon Io taken during a fly-by of the Jupiter-orbiter Galileo. A 50m telescope would offer resolution several times better than this reproduction, while a 100m would be able to resolve the indicated lava flow into more than 10 points at $\lambda = 4\mu m$, measuring the temperature gradient and following its changes as the lava cooled.

Such systematic series of imaging and spectroscopic observations would, for example, resolve current issues about wind velocities and flow patterns in Neptune's atmosphere, allow studies of changes in the contrasting terrains of Triton, and permit the monitoring of the evolution of the atmosphere of Pluto as it recedes from the sun.

WHEN AND WHERE DID THE STARS AND CHEMICAL ELEMENTS FORM?

Counting HII Regions in the Universe. The next big step in understanding the formation and histories of galaxies will follow direct resolution and analysis of the regions in distant galaxies where stars are forming, and chemical elements are being created and dispersed. Imaging and spectroscopy of the luminous gas clouds associated with the formation of massive stars is the proven technique, and requires the sensitivity and spatial resolution of an Extremely Large Telescope.

fig.7

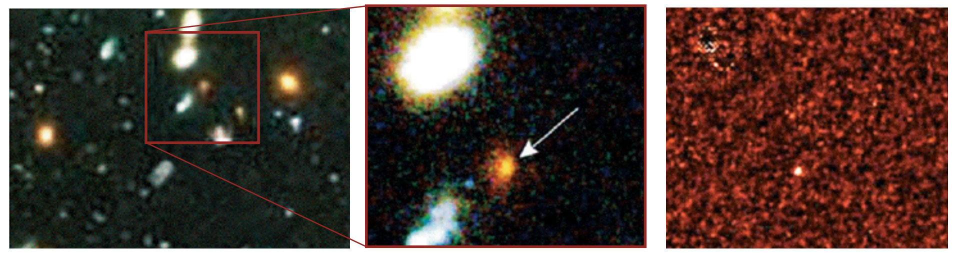


fig.8 Illustrating the 1997 discovery in the Hubble Deep Field of the most distant known supernova, at redshift z=1.7.

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 own and other galaxies, but at a very low rate. Most stars were formed long ago. But when were the legions of stars that make up the giant elliptical galaxies and the central 'bulges' of spirals like our own Milky Way formed? As a direct measure we can make use of the fact that massive stars die young. Some stars indeed, only a few million years after their birth die in spectacular supernovae: explosions whose flash can outshine whole galaxies. Figure 8 illustrates one such supernova found in the Hubble Deep Field (HDF) in 1997. At a redshift of 1.7 it is the most distant SN yet discovered. With an Extremely Large Telescope many such supernovae could be seen to vast distances, corresponding to redshifts up to ten in the case of a 100m telescope. Redshift ten corresponds to direct observation all the way back to 500 million years after the Big Bang, thus seeing 97 percent 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 is therefore a direct way to determine when stars formed and at what rate. Simulations suggest that a 100m telescope would require about 130 nights both to discover ~400 supernovae using 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 percent of its present age.

The more direct approach is to determine directly the ages of stars which make up galaxies today.

We can determine when stars formed by looking at the lower-mass ones that have not blown up as supernovae, and hence remain in their host galaxy to this day. Computer models of the lives of stars show that there is a close relation between basic observable characteristics such as luminosity and colour, and physical properties such as age and chemical composition.

Thus, we can use observations of stars to reconstruct the ages of these objects, and hence the times at which they formed. With a 100m telescope it will be possible to make the requisite observations of stars at much larger distances than is possible at present. This means that we will be able to determine the star formation histories of entirely new classes of object, such as elliptical galaxies. The closest examples of this important type of galaxy lie well beyond the distance that we can currently analyse, but are within the reach of an Extremely Large Telescope.

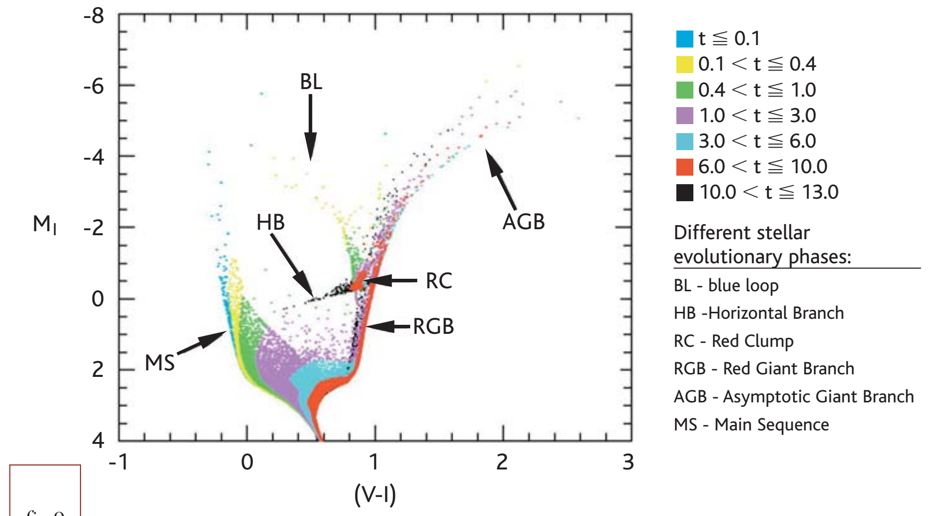


fig.9

A predicted distribution of stars as a function of brightness (vertical axis), colour (horizontal axis) and age, for a plausible galaxy model. Stars in different age intervals are plotted in different colours, and the colour code is given in the figure, with units of age in billions of years.

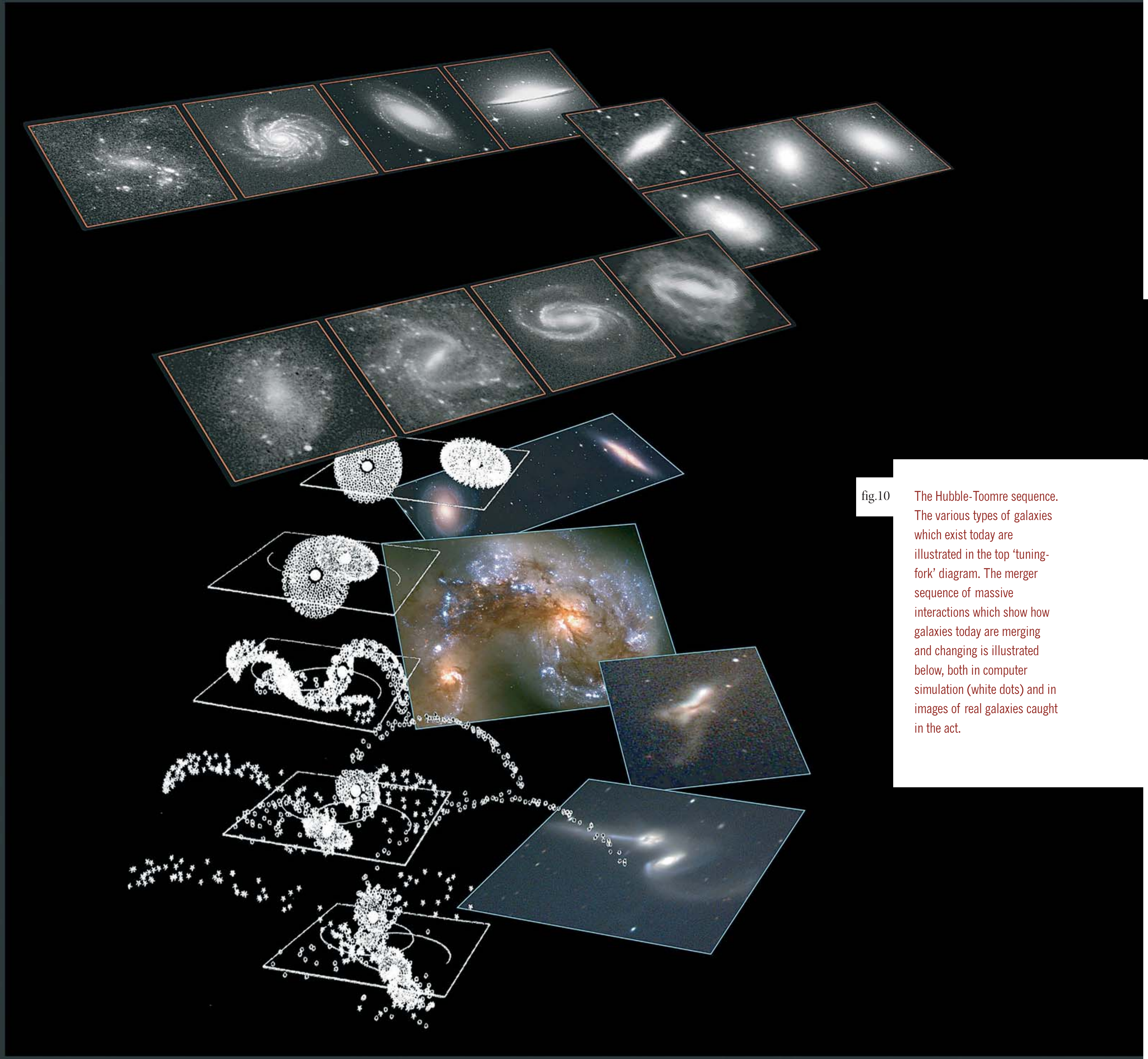


fig.10 The Hubble-Toomre sequence. The various types of galaxies which exist today are illustrated in the top 'tuning-fork' diagram. The merger sequence of massive interactions which show how galaxies today are merging and changing is illustrated below, both in computer simulation (white dots) and in images of real galaxies caught in the act.

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 most significant 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. The merging process itself must be dominated by gravity, and so depends sensitively on the dominant dark matter. In consequence of these mergers, we should see some fossil debris in particular stars now in the Milky Way which originated as members of a now-destroyed smaller galaxy. 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 these merger events gives clues as to the timing of the main mergers in the Milky Way's history and through this clues to the role of the mysterious dark matter.

Until now these studies have been limited to our own galaxy and its nearest neighbours. Much larger telescopes are required to study the star formation and chemical enrichment histories of a representative sample of galaxies.

? Do all galaxy types have similar merger histories?

How important is environment?

How many ways are there to produce an apparently single outcome?

To study a representative section of the Universe requires us to reach 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. Simulations show that a 100m class telescope should be able to observe individual stars in galaxies in the Virgo cluster, and determine their age and composition, even for the oldest, hence faintest, un-evolved stars. From these a detailed picture will be derived of the process by which, and the components from which, the target galaxies were assembled, and the role of dark matter in this process.

To understand the creation and evolution of galaxies in general we must address what is one of the major goals of future astrophysics: the mapping of the distribution and growth of both the baryonic (normal matter) and dark matter components of galaxies at moderate to high redshift (z=1.5-5). Although individual stars cannot be resolved at these cosmological distances, the ionised gas near massive hot stars (HII regions, see figure 7) is extremely luminous, and could be detected to extremely high redshifts with a suitable telescope. A 50m-100m Extremely Large Telescope will not only resolve the distant galaxies into their luminous components but will be able to characterise these individual components. It will win over smaller telescopes, even space-based ones, through its high angular resolution and large light collecting power. The HII regions can be analysed to determine the relative amounts of the elements which they contain, determining the history of the chemical elements. In addition, the velocities of these HII regions could be measured accurately, and their velocities inside their parent (proto-)galaxy determined, thus allowing one to map the dark matter content of individual galaxies throughout the observable universe. These individual gas clouds will then be used to trace the kinematics within the galaxies and in their extended dark-matter haloes. The measurement of the kinematics of their satellite objects, both internal and relative to their more massive partners, lets us estimate the amount of mass present in the system and infer its distribution. This is one of the few ways we have of detecting and examining the dark matter.

This will provide us with a detailed evolutionary history of the clumping of dark matter throughout the observable universe. We will be able to obtain about one million pixel images of very high redshift galaxies, seeing as many details in such infant galaxies as we see today in nearby ones. 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.

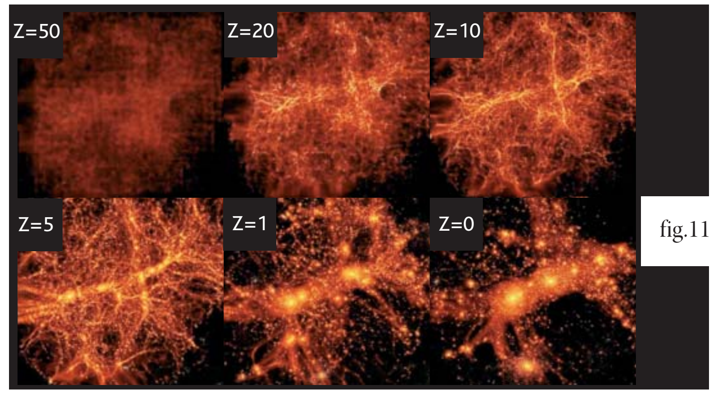


fig.11 Simulation showing stages in the formation of the galaxies in the Local Group in a cold dark matter scenario. Snapshots are shown at various times from the early Universe (z=50) to the present day (z=0).

Super-Massive Black Holes

The centres of most, perhaps all, galaxies harbour super-massive black holes. These exotic objects are usually discovered indirectly, as extreme radio or X-ray luminous sources, quasars and active galactic nuclei. Direct studies, which are 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. This methodology has been proven by observations at ESO over many years which demonstrate the existence of a massive black hole in the core of the Milky Way Galaxy, weighing some 3 million times the mass of the Sun. Direct measurements of the speed at which objects – stars, 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 the existence of the black hole and the determination of its weight.

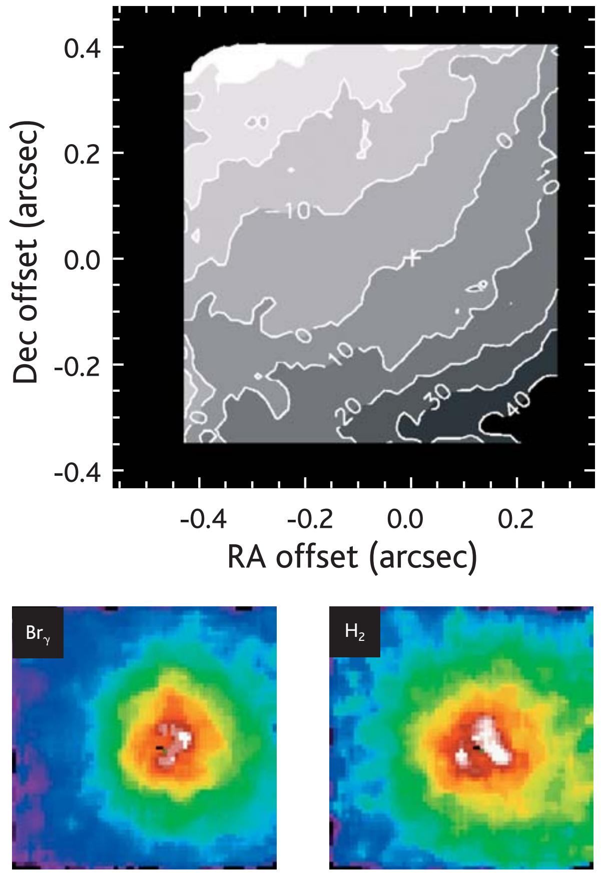


fig.12

Physical study of the environment of a billion solar mass class black hole from adaptive optics assisted spectrographic data of the central part (60 light years across) of the Circinus galaxy at the ESO VLT. Bottom left: ionised gas distribution (Br_γ). Bottom Right: shocked molecular hydrogen (H_2 band). Br_γ + H_2 iso-velocities (km/s) showing large angular rotation around the black hole.

For reasons which are not understood, the evolution and mass of super-massive 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? Why?

Progress on all of these questions requires detailed study of the masses and ubiquity of central black holes. In the vast majority of cases where there is no luminous X-ray or radio source for study, mapping stellar kinematics of the nuclei to detect and weigh any black hole is the only means available: it is in any case the most robust and reliable method. This requires the highest possible spatial resolution and faint object spectroscopy which is attainable only with an extremely large telescope.

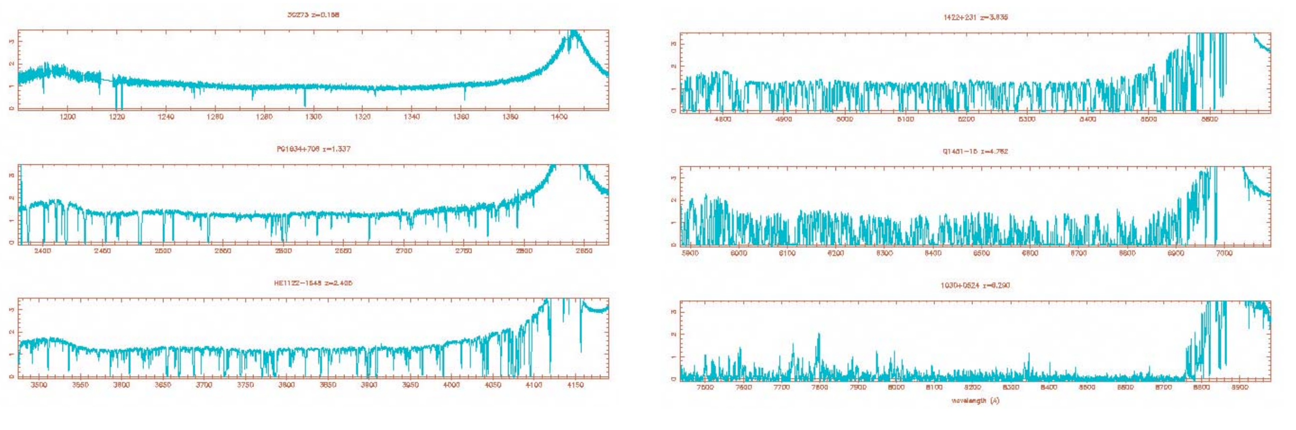


fig.13

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.

The first objects: where and when can we see them?

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 transparent again - 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 have been raised by recent results (Figures 13, 14). 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 180million years after the Big Bang (redshift ~ 17) while observations of the highest redshift quasars at about 700million 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 hydrogen. What is the solution to this apparent quandary? It may be that there were two re-ionisation epochs, an earlier one caused by the first generation of massive stars, followed by cooling, and then one later caused by the first quasars and galaxies? Alternatively, a slower, highly inhomogeneous re-ionisation process may have occurred over the period between the two epochs.

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 (Figure 13).

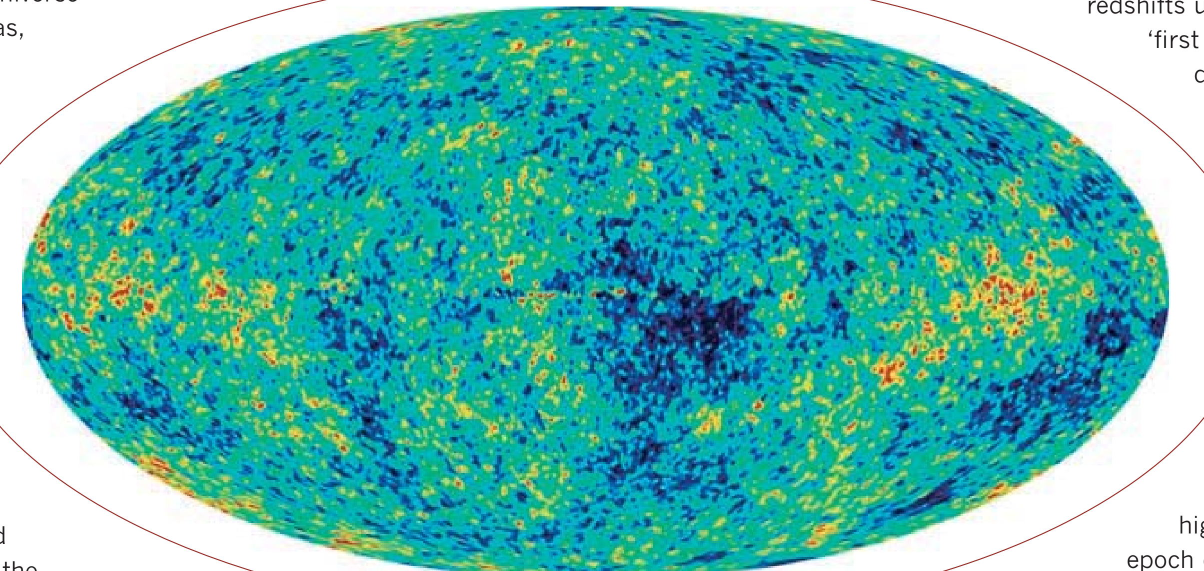


fig.14

Limits on the re-ionisation epoch of the universe. WMAP results, illustrating the residual temperature fluctuations superimposed on the cosmic microwave background radiation by the earliest growth of structures in the universe, imply that the epoch of re-ionisation could have begun as early as redshift ~20.

There are a few populations of sources that could clearly be observed at such very high redshift. The short-lived gamma-ray bursts, probably a rare type of supernova, are extremely bright for a short time, so much so that they should be detectable up to redshift~15-20. 'Normal' supernova explosions of the first stars to form would probably be fainter than this, but could still be used to probe the state of the gas at redshifts up to ten. 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. 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 presumed to be 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, which is the natural domain of ground-based Extremely Large Telescopes. Apart from the very rare extreme gamma-ray bursters or bursts caught very early, which could be observed with a 30m class telescope, spectroscopic observations of these faint background objects can only be carried out with telescopes of the 60-100m class.

Very High Redshift Galaxies

An ELT would allow study of the first galaxies, which were probably also the places of formation of the first stars, in order to resolve the question of whether they, or the first quasars were instrumental in 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 two reasons. Firstly, the analyses of the fluctuations in the cosmic microwave background indicate ionisation of the universe at redshifts >10, presumably by ultra-violet emission from the first objects. Secondly, the amount of time between redshift 10 and redshift 6.5 is so short (in cosmological terms - about 300 million years) that there is simply too little time to go from a universe containing no galaxies at redshift 10 to the universe we see at redshift 6. These 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 100m-class Extremely Large Telescope will be needed to provide the desired diagnostics of the astrophysics of both the gaseous inter-stellar medium and the early stellar populations in these galaxies.

Furthermore, a sub-millimetre capability on an Extremely Large Telescope would allow a large-scale survey 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.

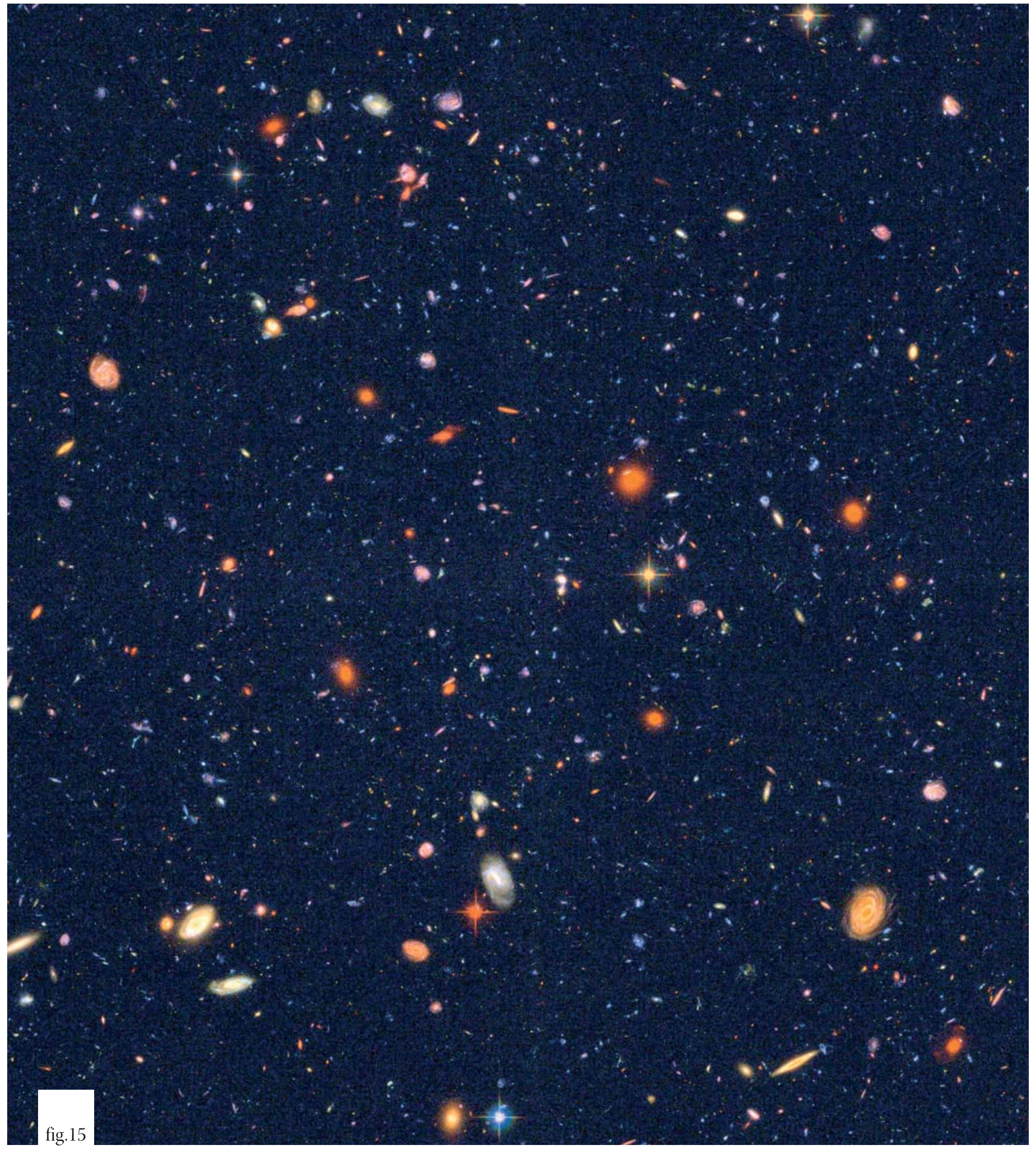


fig.15

A portion of the Hubble Ultra-Deep Field showing numerous, extremely distant, irregular (proto?) galaxies at this early cosmic epoch.

Dark Matter and Dark Energy in the Universe:

Testing Reality in a New Domain

Current observations indicate that dark matter dominates the dynamics of the Universe.
The dark matter distribution was initially very smooth, and became structured with time, influenced by its own gravity. This implies that only observations of distant, and hence faint, objects can tell us more about this growth process and how it really happened.

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 percent of the energy budget of the Universe 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.

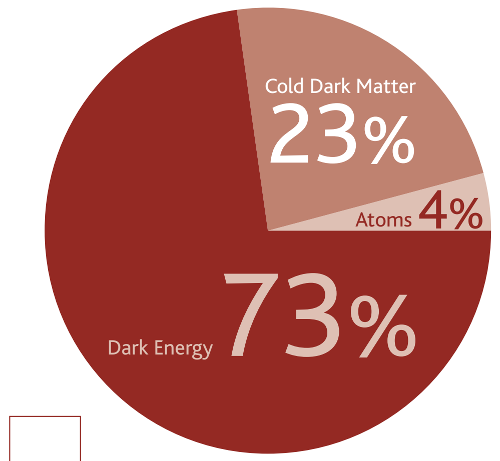


fig.16

The nature of reality: the mass-energy content of the Universe, based on the best current analyses. All 'normal' matter is a minor perturbation. Dark matter, of unknown nature, dominates mass. Dark energy, of unknown identities, dominates the universe. What is existence?

The direct measurement of the rate at which the expansion history of the universe has changed with time using supernovae has shown that 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, essentially in the time since the Sun was formed – though equivalent studies at high redshift, when feasible, may well have their own surprises in store.

Therefore, direct studies using well-understood astrophysical techniques of distance determination are the appropriate way forward. 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 distances where the effect of dark energy first became dominant in the universe, around the time the Earth formed. The exquisite sensitivity to point sources of an Extremely Large Telescope with appropriate adaptive optics capability, combined with its impressive light-gathering power, will allow it to detect supernovae possibly all the way to the time when the universe first became transparent to light. This will allow us to map the geometry of the universe on the largest scales.

By 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. The implications for all of physics and cosmology are vast.

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 characterisation of dark matter has so far relied entirely on astrophysical observations: such observations will always remain essential.

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 of understanding the next generation of physics theory. 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.

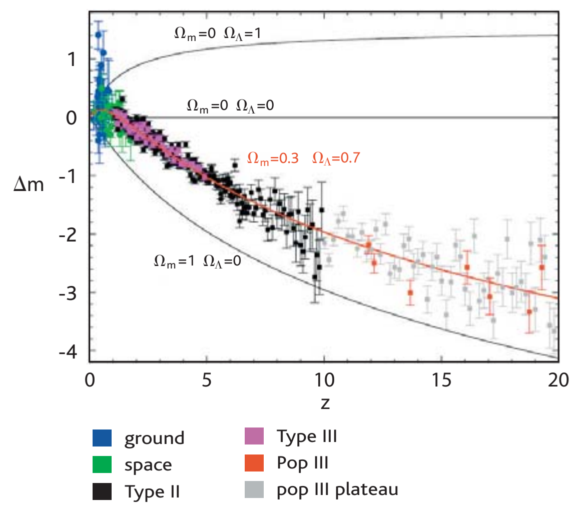
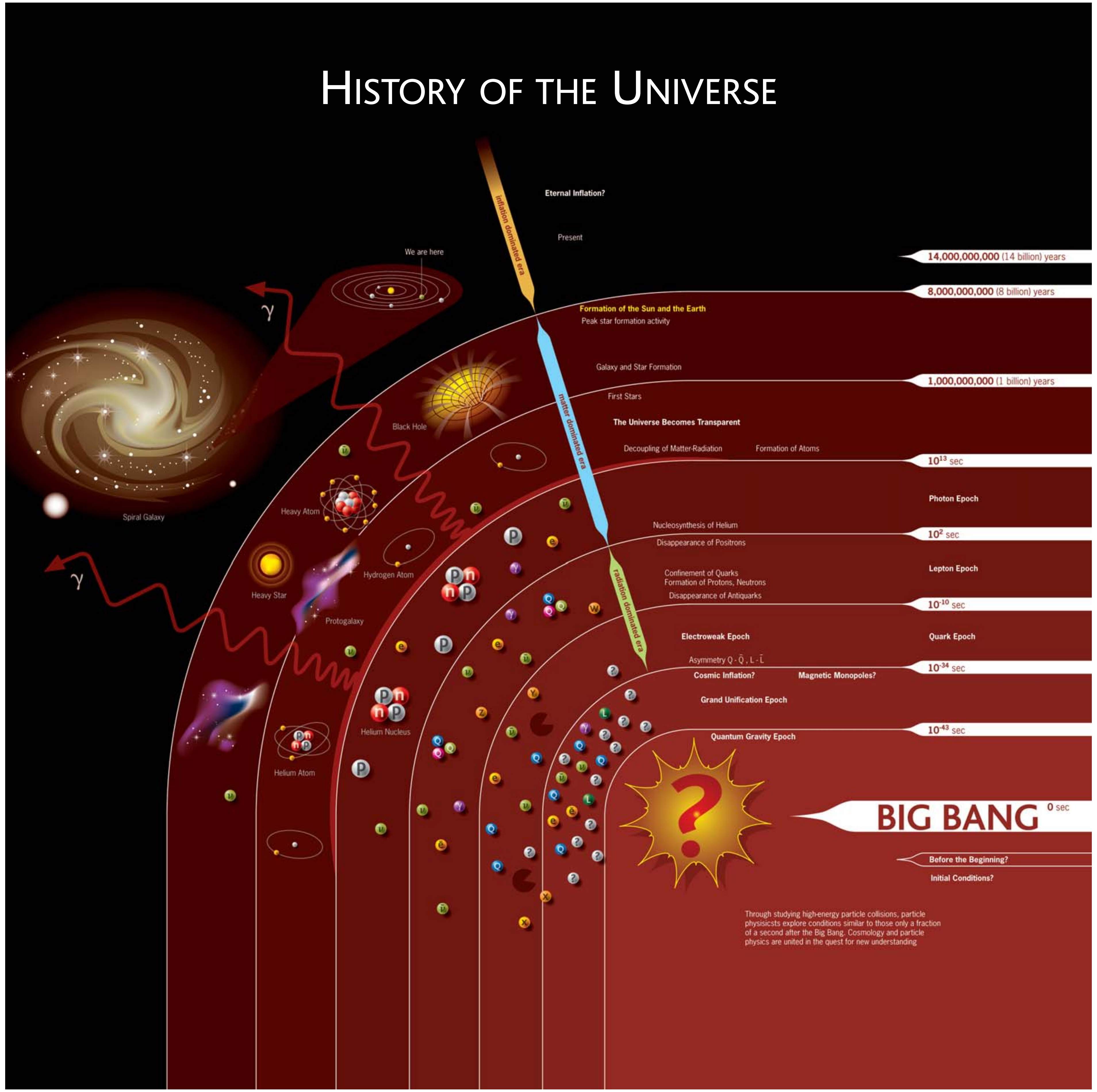


fig.17

Detailed simulations of the types of direct indicators of distance and past star formation which will be available to an Extremely Large Telescope. Observations which are currently feasible are illustrated in blue and green. The smooth curves indicate some types of cosmological predictions for the evolution of Space-Time. These and other models including those not yet considered will be tested directly.



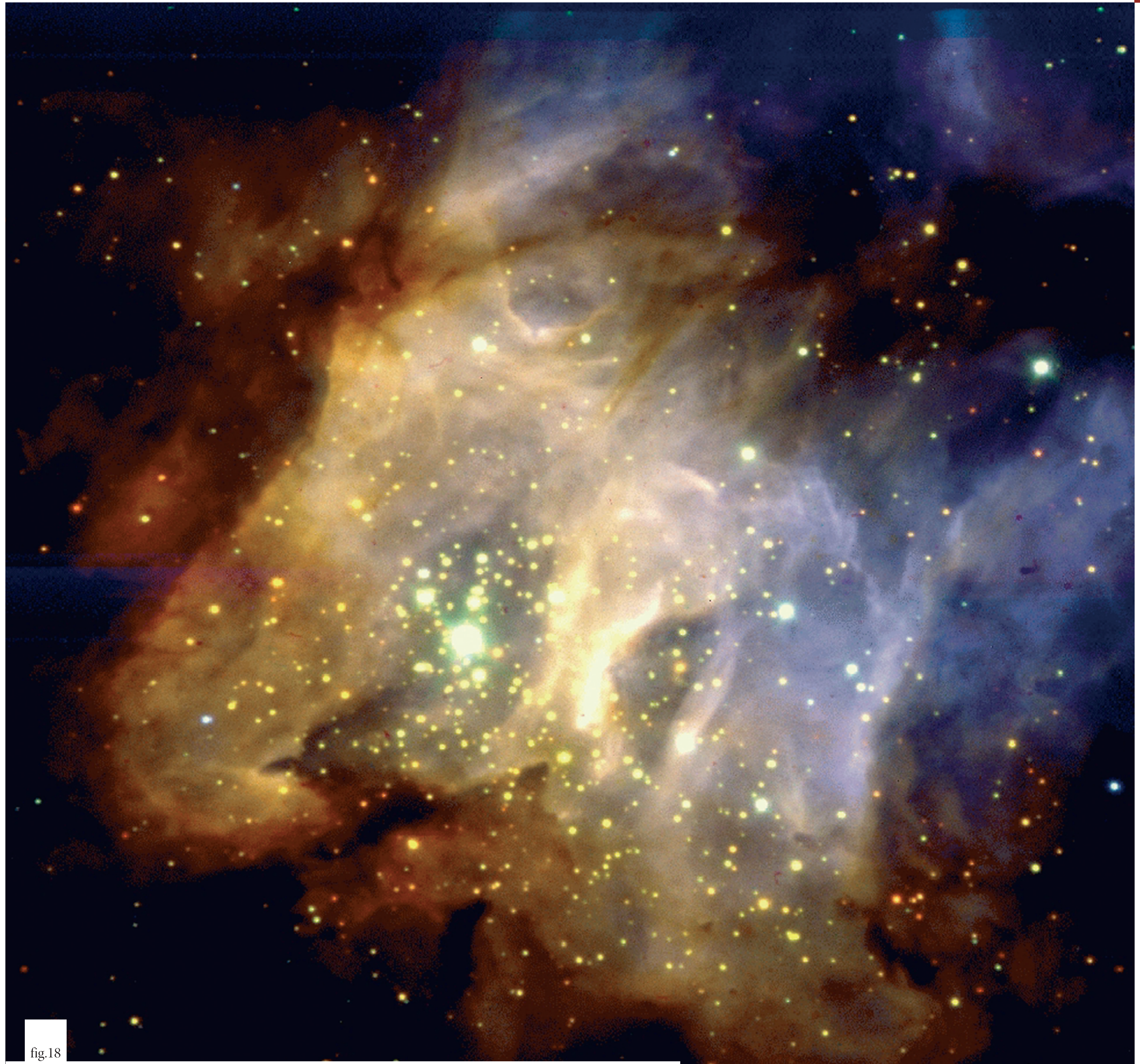


fig.18

The star forming region RCW38. Massive young stars are forming here, illuminating the surrounding gas to make regions like this visible across the Universe to an Extremely Large Telescope. The massive stars explode as supernovae, creating and dispersing the chemical elements, and providing probes of the history of star formation, and the geometry of space-time.

fig.19

The turbulent region around the ring-shaped nebula DEM L 299 in the Large Magellanic Cloud, a satellite galaxy of the Milky Way system. The Extremely Large Telescope will extend detailed studies of such regions out to high redshifts, and so quantify the creation and dispersal of the chemical elements across cosmic time.

fig.20

The famous 'Horsehead Nebula', which is situated in the Orion molecular cloud complex. Its official name is Barnard 33 and it is a dust protrusion in the southern region of the dense dust cloud Lynds 1630, on the edge of the HII region IC 434. The distance to the region is about 1400 light-years (430 pc).

fig.21

Centauris A, one of the nearest massive elliptical galaxies, still in formation as the dust lane indicates. A supermassive black hole lies at the centre of this galaxy, similar to those which power the quasars.

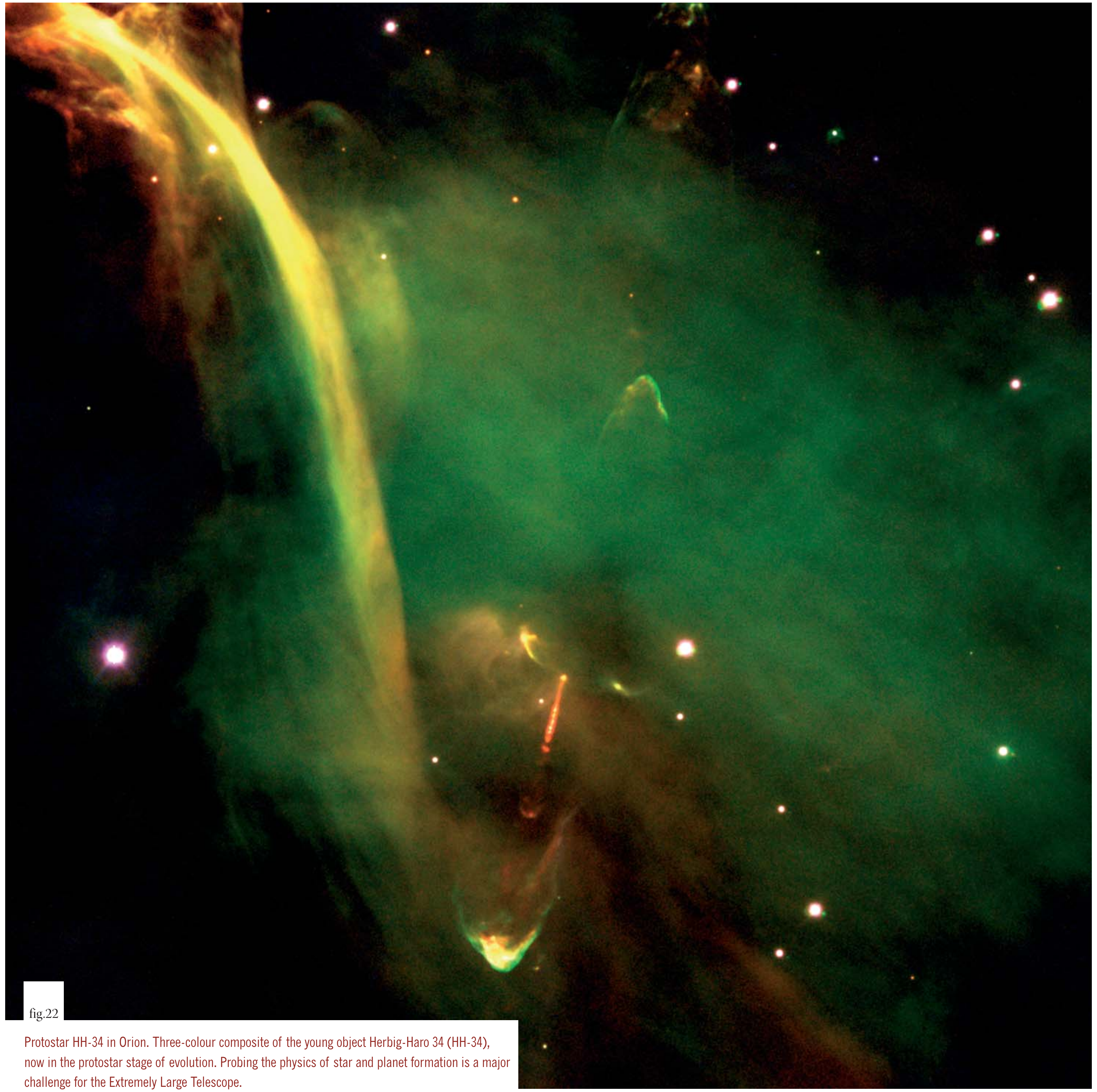


fig.22

Protostar HH-34 in Orion. Three-colour composite of the young object Herbig-Haro 34 (HH-34), now in the protostar stage of evolution. Probing the physics of star and planet formation is a major challenge for the Extremely Large Telescope.

How an ELT complements current developments in space and radio astronomy

Space Astronomical Facilities

For many observations a telescope's ability to detect faint sources scales as D^2 and the time to carry out a given observation as D^4, where D is the primary mirror diameter. The relatively large apertures which are affordable and technically feasible for ground-based telescopes means that these facilities are the natural means to provide maximal light-gathering power. This sensitivity is offset by the brightness of the background sky, and the attainable image quality. In general, both of these are easier to provide in orbit, away from the earth's atmosphere. The net effect is that it is natural to provide complementarity between very large, relatively low-cost ground-based facilities, and special-purpose orbiting observatories. For example, for high-resolution spectroscopic applications the new ground-based Extremely Large Telescopes will have a natural balance in performance with the next generation James Webb Space Telescope, the successor to the Hubble Space Telescope.

The primary motivation for the considerable expense of space facilities is to allow observations at wavelengths which are made inaccessible from the ground because of absorption by the Earth's atmosphere, especially in the far-Infrared, ultraviolet, X-ray and γ-ray regimes. The space observatories, 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 infra-red, to be detected or investigated by existing telescopes.

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 2011, will increase this imbalance. This space telescope will reveal objects an order of magnitude fainter than can be studied in detail with existing telescopes on the ground. Until the astronomical community acquires complementary ground-based 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 ground-based Extremely Large Telescopes.

Planned next-generation X-ray missions, such as XEUS and Constellation-X, 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. The Table summarises some future astronomical space missions and the complementarity they provide for ground-based Extremely Large Telescopes.

A subset of future Space Missions and their ground-based needs

Mission	Wavelength range, type	Launch Date	ELT follow-up and support required *(critical areas emphasised)*
Planck	CMB map, submm sky survey	2007	Optical/Near-IR imaging & spectra of clusters of galaxies revealed by Sunyaev-Zeldovich effect
GAIA	1.7m optical tel. for stellar kinematics	2011	*ELT exploits catalogue of solar-systems for exo-earth search*
James Webb Space Telescope	6.5m NIR/MIR telescope; imaging & multi-object spectra	2011	*Spectroscopy and high-resolution imaging of extremely faint sources*
TPF and DARWIN	Coronograph and 6(4)x1.5m mid-IR interferometer; exo-Earths imaging and spectra	2014-2020	Complementary approach to terrestrial planet finding and spectroscopy

Forthcoming radio astronomy Facilities

New radio-astronomy ground-based facilities are being built that will naturally complement an Extremely Large Telescope's optical and infra-red capabilities, and discover sources which will demand further study at other wavelengths.

The Atacama Large Millimetre Array (ALMA) will be an interferometric array of up to 64 antennae, each 12m in diameter, located at Llano de Chajnantor in the high Atacama of Chile. This high, dry site will offer exceptional atmospheric transmission, permitting work at all sub-millimetre bands including the 200μm window which has not yet been exploited at any telescope. ALMA will provide very high sensitivity and spatial resolution beyond the limits of current ground-based telescopes. It is expected to become operational early next decade and will cover a very wide range of science, detecting both thermal continuum emission from dust and line emission, especially from CO, in objects ranging from the nearest star-formation regions, where it will reveal structures down to ~3 AU in size, to luminous galaxies at redshift 20. Ground-based 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. ALMA is under construction, and will be fully operational by 2012.

The Low-Frequency Array (LOFAR) will comprise around 10,000 small antennae, probably located across northern Netherlands and Western Germany. It will operate in the frequency bands between 10-90 MHz and 110-300 MHz. LOFAR is due for completion in 2008, and is a precursor to a more ambitious project, the Square Kilometer Array. LOFAR will have a very wide range of scientific applications, from ionospheric physics to studies of the epoch of re-ionisation. At LOFAR's wavelengths most sources are synchrotron emitters, but it will be sensitive to neutral hydrogen emissions and absorptions, at redshifts $3.5<z<11$ and will provide a cross-section of the history and evolution of the intergalactic medium at these epochs. Extremely Large Telescope spectroscopy of faint LOFAR sources will provide a direct picture of the nature of these early star-forming objects.

Credits:

This summary science case is based on a larger science case developed at a series of meetings over four years involving over 100 astronomers, 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 program, by ESO, and by many European national agencies and organisations. European astronomers' involvement is sponsored by the European Commission through the OPTICON program.
The OPTICON ELT science case program, and this summary document, are coordinated by Isobel Hook and Gerry Gilmore, based on contributions by many astronomers. Figure credits: figure 1 Chauvin, Lagrange, etal; figure 2 ESO; figure 3 O Hainault and R Gilmozzi, ESO; figure 4 Dyudina, Sackett, Bayliss etal, Australian National University; figure 5 Lucio Mayer, Quinn, Wadsley and Stadel (Zurich, Washington, McMaster); figure 6 NASA; figure 7 R Gilmozzi; figure 8 NASA/HST Riess etal HDF SN; figure 9 A. Aparicio & C. Gallart; figure 10, R Sword, Cambridge; figure 11, B Moore (Zurich); figure 12 ESO; figure 13 WMAP courtesy of NASA; figure 14: 3C273 HST/STIS, Sally Heap; PG1634+706, HST/STIS Buell Jannuzi; HE1122-1648, ESO/VLT, Tae-Sun Kim; 1422+231, Keck/HIRES, Wal Sargent, Michael Rauch; Q1451-15, ESO/VLT Tae-Sun Kim; 1030+0524 Keck.ESI, Max Pettini; compilation courtesy of Bob Carswell, Cambridge; figure 15 HUDF courtesy NASA/ESA; figure 16 Massimo DellaValle; figure 18 ESO/La Silla; figure17 courtesy WMAP; figures 18,19,20,21,22 courtesy ESO

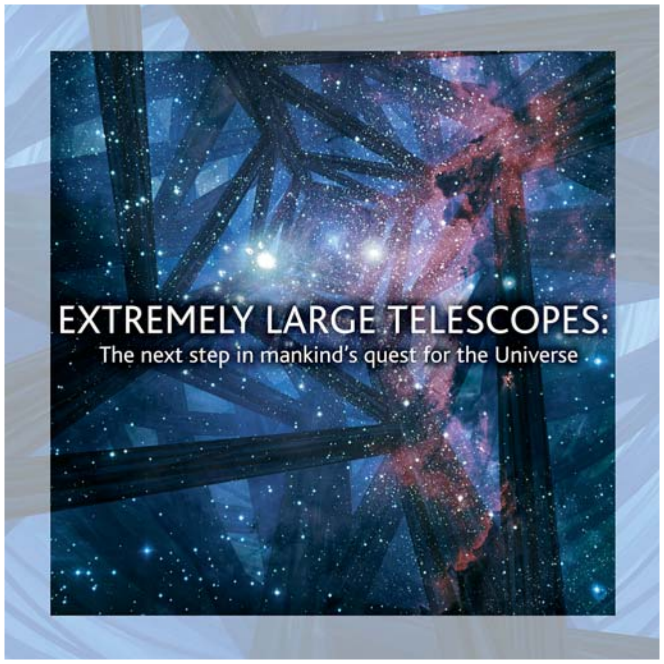
We shall not cease from exploration

and the end of all our exploring

will be to arrive where we started

and know the place for the first time

T S Eliot



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WWW sites for further information:

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

http://www.eso.org/projects/owl/

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