

# NEW EYES, NEW SKIES

The next 40 years will see telescopes that far outstrip any ever seen before. **Jeff Kanipe** profiles four of them; illustrations by **Lynette Cook**.

The armillary and astrolabe are now seldom seen outside museums and antique shops; but the telescope, which joined them in the observatories of early modern Europe 400 years ago, is still at the centre of the astronomical world. In optical precision, in the wavelengths that are used and in their sheer size, they have changed almost beyond recognition (see page 28). After two centuries in which they left no records other than the users' sketches, and a century in which their visions were recorded on photographic plates, they have in the past decades become entirely electronic. And they are now stationed everywhere — oceans, deserts, mountain tops and all kinds of orbit. But the job is still the same: collecting and focusing whatever information the Universe sends our way.

Yet for all its glorious 400-year history, the astronomical telescope's best days may still be to come. Telescopes currently in development show an unprecedented degree of technical ambition as they seek to provide near-definitive answers to questions that, a generation or two ago, it was hard to even imagine investigating.

To answer these questions, the telescopes profiled here will often work in complementary ways. The infrared capabilities of the James Webb Space Telescope and the radio acuity of the Square Kilometre Array will



both be used to probe the Universe at the time of its own 'first light' — the birth of the first stars and galaxies. The radio array will map the large-scale structure of the Universe, elucidating the role in that structure of 'dark matter' and 'dark energy', as will studies of the faintest galaxies by the Large Synoptic Survey Telescope and European Extremely Large Telescope. That behemoth and the orbiting Webb will, in turn, complement each other in their attempts to characterize planets around other stars with unprecedented detail.

This quartet, for all its ambition and expense, does not exhaust the possibilities being explored and wished for. The Atacama Large Millimeter/Submillimeter Array will soon revolutionize astronomy at its chosen wavelengths. Other projects are planned throughout the electromagnetic spectrum and beyond into the new realms of gravitational waves and neutrinos. These instruments are all being designed with specific scientific challenges in mind. But at the same time, all concerned hope devoutly to discover something as strange and unlooked for as Galileo's mountains on the Moon — or spots on the face of the Sun.

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See Editorial, page 7, and online at [www.nature.com/astro09](http://www.nature.com/astro09).

## The James Webb Space Telescope

Like the Hubble Space Telescope, to which it is in some ways the successor, the James Webb Space Telescope (JWST) will be the orbital flagship of its generation. But whereas the Hubble sees mainly in the visible and ultraviolet, JWST is optimized for the infrared. That means it can see things hidden from the Hubble and its like by dust, and peer into the high-red-shift epoch just after the Big Bang at objects indiscernible at visible wavelengths — such as the first stars.

Astronomers at the Space Telescope Science Institute in Baltimore, Maryland, started their first plans for a follow-on instrument in 1989 — a year before the Hubble itself was launched. It should finally make it to the launch pad 24 years later. Although its design and cost have changed a few times over the past two decades (see *Nature* 440, 140–143; 2006), its main mission remains simple and visionary — to study unseen aspects of every phase of the history of the Universe. To do so, the telescope will make use of several innovative technologies, such as ultra-light-

weight optical systems made from beryllium, extremely sensitive infrared detectors and a cryocooler that can maintain the mid-infrared detectors at a frosty 7 kelvin indefinitely.

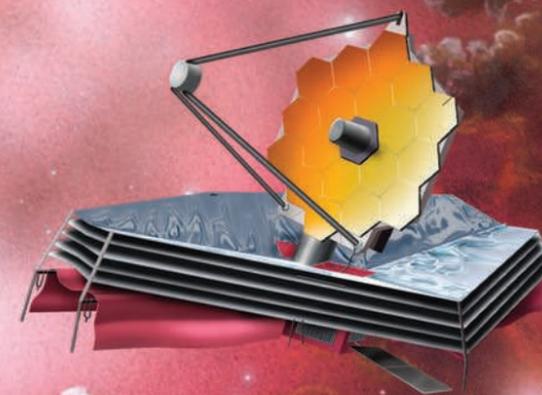
The most striking of the new technologies, though, affects the very heart of the telescope. JWST's designers wanted a mirror that would have been too large to fit into the payload fairing of any rocket available. So they designed one in segments, a mirror that could be launched folded up and then deployed to its full 6.5-metre diameter once the telescope settles into its final orbit, 1.5 million kilometres from Earth. That distance gives the telescope much more sky to look at than the Hubble gets, and keeps it cooler, too. But it has its downside: as yet there is no way to get there to fix any problems so, unlike the Hubble, JWST has to work perfectly from the start.

At the moment, says John Mather, Nobel laureate and senior project scientist for JWST, the telescope is designed to last for at least five years, but longer may be possible. It will carry the ten years' worth of fuel, and the presence of the cryocooler means that, unlike earlier

infrared missions, its lifetime is not limited by a fixed supply of coolant. "If we are lucky and clever we hope to conserve fuel and perhaps run much longer," says Mather. "But we can't promise that." What Mather thinks he can promise is discovery. "We do not know which came first, black holes or galaxies, and we do not know how it happens that there is a massive black hole at the centre of almost every massive galaxy. If there are any surprises about the early Universe, I am guessing that they will be in these areas."

JWST is not just about deep space and distant epochs, though; it will also scrutinize the shrouded origins of objects closer to home — such as nascent solar systems, coalescing stars and star clusters amassing within dusty nebulae, says Matt Mountain, director of the Space Telescope Science Institute.

But where the telescope will really stand out will be its ability to probe the very early Universe. "JWST is so sensitive," says Mountain, "that we can take actual spectra of the very earliest objects you can just barely detect with Hubble."



### JWST

**Collection area:** 33 square metres

**First light:** 2013

**Cost:** US\$4.5 billion all in

**Unique selling point:** The best infrared possible

# A DEEP, MOVING IMAGE

## The Large Synoptic Survey Telescope

Sometimes telescopes see double not because of any aberration, but because that is the way the Universe works. The bending of light by intervening masses — called gravitational lensing — means that some galaxies are seen by Earthly observers in more than one place. By adding together survey image after survey image, and so measuring things that no individual image would show, the designers of the Large Synoptic Survey Telescope (LSST) hope to find a significant fraction of the 10,000 or so such images in every square degree of sky. They also hope to open up a neglected dimension in astronomy: time. As well as adding together images of the same part of space taken again and again to reveal new depth, they will compare those images to spot any differences, turning up a wealth of supernovae, asteroids and Kuiper belt objects on the fringe of the Solar System that would otherwise be missed. The telescope's proponents call it celestial cinematography.

The telescope will suck in celestial data by the terabyte every night, surveying almost all of the sky visible from Cerro Pachón, Chile, every week. Such coverage is made possible by an 8.4-metre primary mirror,

which will be ground so as to provide a field of view of 10 square degrees. That's 49 times the size of the full Moon, and more than 300 times the field of view of the Gemini telescopes, which have mirrors of similar size optimized for staring in a single spot. Over ten years, says Željko Ivezić, of the University of Washington in Seattle, the LSST system will look at everything in its field of view about 1,000 times. A massive amount of computing power will be used to correlate, compare and catalogue the torrent of data — and to make them all available

on the Internet. Anyone with a computer — students, and amateur and professional astronomers — will be able to participate in the process of scientific discovery.

Studies of objects that have been gravitationally lensed should reveal huge amounts about the structure of the Universe in general, and the distribution of dark matter and the effects of dark energy in particular. At the same time, though, LSST will mount a virtual space patrol, looking for potentially hazardous near-Earth asteroids. Astronomers already know where most of the big,

killing-off-species-wholesale asteroids are. LSST will be one of the tools that catalogues the vast majority of lesser asteroids still capable of smashing a city. But with a sensitivity to faint, transient events 1,000 times greater than ever previously achieved, the telescope will not restrict itself to the 'vermin of the skies' in Earth's backyard. It will observe vast distant cataclysms, such as collisions between neutron stars, and is all but sure of discovering whole new categories of transient events.

The project is overseen by the LSST Corporation, comprising more than 100 scientists and two dozen laboratories, universities and institutes based mainly in the United States. Although the project's design is still being worked out, the main mirror has already been cast. Astronomers with the corporation are hopeful that construction will begin as planned in 2011 and that first light will occur in 2015. In the subsequent ten-year survey, LSST will take stock of every object in the Universe, known, unknown and newly discovered. "For the first time in history," says Ivezić, "we will catalogue and study more celestial objects than there are people on Earth."

### Follow up around the world

LSST will be able to send out alerts on the Internet within a minute of seeing something untoward in the sky. The Las Cumbres Observatory Global Telescope will be eager to hear them. When completed, this will be a network of robotic telescopes distributed in two rings, one circling each hemisphere. Currently the network — a privately funded, non-profit organization — has just two telescopes up and running, one on Haleakala, Hawaii, and another in the Siding Spring Observatory in New South Wales, Australia. More are planned for sites in Mexico, the Canary Islands, Chile, South Africa and Australia. The final goal is to have two dozen or so 0.4-metre telescopes and a similar number of 1-metre telescopes. The smaller ones will be skewed towards educational use, the larger ones towards science, but there will be a lot of overlap. Once fully operational, the network will be able to keep a constant eye on new-found objects, such as supernovae and new asteroids, for days or weeks.

### LSST

**Collection area:** 35 square metres  
**First light:** 2015  
**Cost:** \$390 million to first light  
**USP:** All of space, in real time

# SUPERSIZING THE HEAVENS

## The European Extra Large Telescope

Space-based observatories have much to recommend them; they see in wavelengths forever hidden from observers on Earth's surface, and with the crystal clarity of an airless sky. But they are hard put to compete in one of the most important aspects of telescope design: size. Whether you want a telescope for a backyard or a mountain top, the larger the light-gathering surface, the more photons you will catch. With a primary mirror measuring 42 metres across, the European Extremely Large Telescope (E-ELT) is

designed to pick out features only hinted at in the best images made by orbiting telescopes, detecting objects as faint as the planets around other stars. Its backers think that such a telescope could put satellites out of the optical-and-near-infrared business until similar sized behemoths can be assembled in orbit — or on the Moon.

Today E-ELT, a project of the European Southern Observatory (ESO), is halfway through a 3.5-year, €57.2-million (\$72.5-million) detailed design phase. Construction could start as soon as mid-2010.

It is not the only such giant planned: the Thirty Meter Telescope is being built by a public-private consortium including universities in North America, and the Giant Magellan Telescope is a collaboration between several US and Australian universities and research institutes (see *Nature* 452, 142–145; 2008). But E-ELT is the most audacious in scope and, with a budget of €950 million, the most expensive.

That said, the current E-ELT design is a scaled-down version. When originally discussed as the Overwhelmingly Large

Telescope (OWL), it was to have had a mirror 100 metres in diameter. The current 42 metres is more pragmatic. But if adaptive optics that constantly correct the mirror's shape to offset atmospheric turbulence work for a system of this size, as its designers hope, E-ELT should still have a spatial resolution 18 times better than that of the Hubble Space Telescope. Today's largest mirrors are those of the twin 10-metre Keck telescopes on Mauna Kea; E-ELT would have a light-gathering area almost nine times larger than both of them put together.

When it comes to thinking big, E-ELT's designers have the advantage, not shared by astronomers in the United States, of steady annual funding. ESO's management hopes to build the giant without asking the organization's 13 member states for more money, or having to hunt around for new partners. That could still change though: the telescope's optical design is not finalized, nor is its ultimate location. The Canary Islands, Morocco, Argentina and two sites in Chile are all under discussion.

All this is just background noise to Roberto Gilmozzi, E-ELT's principal investigator, who already has his eye on the telescope's potential discoveries. "One of the key goals of the telescope will be the quest for Earth-like planets around other stars," he says, "both by indirect methods — such as measuring radial velocity variations in the parent star — and by direct imaging and spectroscopy of their atmospheres." It will also aim to study proto-planetary systems around young stars in unprecedented detail.

"E-ELT will provide a 'quantum jump' in sensitivity over the present generation of telescopes — comparable to that of Galileo's telescope over the naked eye," says Gilmozzi, and that will affect astronomy at all scales. Galaxies that are now blurs will turn into fields of distinct stars. And on the largest of scales the telescopes will carry out a "physics experiment" that would not be possible with any other telescope, Gilmozzi says. By comparing ultra-precise velocity measurements of very distant objects taken several years apart E-ELT will make the first direct observations of how fast the Universe is expanding.

### E-ELT

Collection area: 1,385 square metres

First light: 2010s

Cost: \$1.4 billion to first light

USP: The clue is in the name

### Other ways to other planets

The international COROT mission, launched in 2006, has spent two years trying to detect dips in the brightness of stars caused by intervening planets. Later this year it will be joined by NASA's Kepler mission, and a follow-on European mission, PLATO, is planned for the middle of the next decade. All aim to discover Earth-sized and

smaller planets, particularly in or near the 'habitable zones' around stars where liquid water is possible on the surface. E-ELT might be used to confirm and follow up the findings of such missions — perhaps making spectroscopic measurements of a newly discovered planet's atmosphere, for instance. The combination of detection

from space with such satellites and study from Earth with a new generation of very large telescopes such as E-ELT means that astronomers will be able to start putting together profiles of other planetary systems, some of which may be similar to the Sun's, some of which will doubtless prove very different.

# LOOKING EVERYWHERE

## The Square Kilometre Array

It hasn't yet got a site; it hasn't yet got funding. But what the Square Kilometre Array (SKA) lacks in these pragmatic matters it more than makes up for in ambition: it will be the largest telescope of any kind in the world. Today's biggest single-aperture radio telescope, the Arecibo Observatory in Puerto Rico, has just 73,000 square metres of collecting area. SKA is aiming for a million. This collecting area will be distributed between thousands of small dishes, some grouped together in a central core, some trailing out along a vast crop-circle-like, multi-armed spiral to provide a total radius of a couple of thousand kilometres. That vast radius will give the system a resolution to match the incredible sensitivity provided by all that collecting area.

The result is a telescope that works over a frequency range of from 70 megahertz to 10 gigahertz, and boasts a huge field of view — 200 square degrees at frequencies of under 1 gigahertz, 1 square degree or so at higher frequencies. The telescope's final design will incorporate dishes for higher frequencies and flat 'phased-array' panels for the lower frequencies. An advantage of the phased-array approach is that observers can study different parts of the sky simultaneously. This design will allow the instrument to survey the sky 10,000 times faster than any radio telescope producing similar images. Research topics will cover more or less the whole reach of astronomy, from galaxy evolution and the cosmic jets spewed

out by quasars to the study of pulsars and supernova remnants.

The array is a truly international collaboration between institutions in 19 countries, including much of Europe, Argentina, Australia, Brazil, Canada, China, India, South Africa, Sweden and the United States. The consortium members hope to see it completed in 2020, and to keep producing science for 50 years. Taking into account the all-but-inevitable delay, later upgrades and the like, SKA could well last long enough to be the first great telescope of the twenty-second century.

According to James Cordes, chair of the US SKA Consortium, SKA will revolutionize understanding of the first galaxies, and of how the Universe developed its 'metals' (astronomers speak for all elements heavier than helium). Previous work has shown that just half a billion years after the Big Bang, galaxies were awash in carbon monoxide gas that could only have come from earlier stars. The array will be able to map that spread, and to measure CO molecules in the interstellar media of 'pregalactic objects' — the seeds of galaxies. But like everyone with a big telescope that they have fallen in love with, Cordes is also keen to stress the capacity for surprise inherent in the object of his affection. SKA, he says, will be a discovery machine. Who knows what it will see that lesser eyes on the sky have missed: "Perhaps extrasolar planets and flare stars of new types. Perhaps even exotica — such as evaporating black holes and extraterrestrial civilizations." ■



### SKA

**Collecting area:** Up to 1 million square metres

**First light:** 2020s

**Cost:** \$1.4 billion or more

**USP:** All things radio, better

### Back to space

Earth-based telescopes find it relatively easy to grow to a giant size; in space things are more constrained. But astronomers at the Space Telescope Science Institute in Baltimore, Maryland, who are looking for the next big thing are thinking that it should be exactly that: big.

The Advanced Technology Large-Aperture Space (ATLAS) telescope is a proposed telescope that could only be launched on NASA's planned Ares V heavy-lift launch vehicle, the humans-to-the-Moon launcher that will be the largest rocket since the days of Apollo. ATLAS would have a larger mirror than the largest Earth-based telescopes today, with a diameter of perhaps 16 metres and a sensitivity some 40 times that of the Hubble telescope. It would provide yet another set of perspectives on dark matter and galactic evolution. Perhaps most exciting, though, would be its role in characterizing habitable planets — perhaps even inhabited ones — around other stars.