SPACE INVADERS

A huge radio telescope called the Square Kilometre Array (SKA) may help solve some of the most fundamental cosmic mysteries surrounding the birth and growing pains of our Universe – including the possibility of extraterrestrial life.

> BY ALAN DUGGAN

SCIENTISTS have learned so much about the workings of our inconceivably vast Universe that one might be forgiven for thinking there's little left to discover. That assumption is so wrong as to be ludicrous.

Some disconcerting gaps in our knowledge: Big Bang theory, compelling though it is, remains a theory. In fact, some cosmologists believe our Universe may be just one in an infinity of universes. Others, such as South African-born theoretical physicist Neil Turok, suggest we may be living in a sheet-like "brane" that periodically touches another brane, setting off Big Bangs in a never-ending cycle.

How do pulsars work? What does it take to make a black hole radiate energy? Can we test the limits of Einstein's General Relativity? How much do we really know about the adolescence of our Universe, when the first stars coalesced from the primordial gas?

There's more. We still have no idea what dark matter is, even though it constitutes a significantly bigger portion of the cosmos than all the stars and galaxies (so-called baryonic matter) put together. As for dark energy, well, that's an even bigger mystery. Since it makes up a resounding two-thirds of the "stuff" of the Universe, and is apparently responsible for accelerating its expansion, we have a compelling reason to find out.

Then there's the ET thing. Although astronomers have yet to discover firm evidence of extraterrestrial life, they are finding its chemical building blocks – not to mention extra-solar planets that could theoretically harbour life – all over the place.

Bottom line: many of the most fundamental questions about the laws of nature and the functioning of the Universe – including its beginning and its likely end (if any) – remain unanswered. Having evolved into the most intelligent and insatiably curious species in the 3,8 billion-year history of life on planet Earth, we really need to know – and the Square Kilometre Array (SKA), the largest and most sensitive radio telescope ever conceived, is a giant leap in the right direction.

South Africa and Australia are the only two countries remaining on the shortlist for hosting this mega-telescope. The European Union's Framework 7 Programme recently awarded funding to a consortium of 20 signatories to finalise the design of all the sub-systems between now and 2010. This programme will not only consider technical design issues and science cases for the SKA, but will also investigate the most appropriate governance structures, intellectual property issues, ownership of data and long-term operational issues for the lifetime of the telescope. A final decision on the location of the telescope is expected by 2011, and construction is expected to start soon afterwards, around 2014.

If it is built in South Africa, the core of the SKA will be in the Karoo region of the Northern Cape. SKA will consist of an interferometer array with a total receiving area of about one square kilometre, of which 50 per cent will be contained within a core site more or less 5 km in diameter. Stations of antennas will fan out from the core in a spiral pattern, with proposed remote stations in several other African countries and on neighbouring islands up to 4 500 km from the core. The potential benefits for the southern African region are huge: the telescope would attract top scientists from around the world, boost local scientific and engineering skills, and seed a host of high-tech industries.

Some key reasons why the Karoo is an appropriate location for the SKA:

- Low levels of radio frequency interference and the certainty of a future radio quiet zone protected by tough legislation.
- Basic infrastructure of roads, electricity and communication in place.
- Ideal geographical location, sky coverage and topography.
- Safe and stable area, with very few people and no conflicting economic activities.
- Required land, labour and services available and very affordable.
- Excellent academic infrastructure to support SKA science and technology.
- The astronomical richness of the southern skies, and a strong tradition of astronomy.

Unless current research and development programmes reveal fatal flaws in technologies of choice, the SKA will consist of thousands of dishes, each 10-15 m in diameter. We're talking Big League astronomy here: the joint receiving area of all these dishes and panels will add up to about 1 million m². Special antenna tiles in the core of the array will form a "radio fish-eye lens" for all-sky monitoring at low frequencies, allowing many independent observations at the same time. The SKA will require super-fast data transport networks and more powerful computing than ever before.

It won't be cheap. According to the latest estimates, the telescope instrument alone (excluding infrastructure) will cost about 1,5 billion euro (about R14,5 billion at current exchange rates) to build, with contributions from partner countries around the globe. Many international teams are working together to develop the technology solutions that will make the SKA possible and feasible. They are also participating in multinational studies to trade off projected costs against the instrument's technical performance specifications.

An independent international committee will ultimately select an optimal site for the SKA based on comprehensive technical, scientific and financial considerations. A final decision is expected only in 2011, after which the telescope will be built in phases, with construction on Phase 1 (representing about 10 per cent of the total telescope) starting in 2014 and slated for completion by 2016.

Operation of the full SKA (called Phase 2) should start by 2020, but scientific observations will be possible throughout the construction phases. This ability to perform "early science" using a subset of the full instrument is a powerful feature of radio interferometer arrays.

To construct an affordable SKA with the requisite technical specifications, it will be necessary to develop technologies that are not currently employed in existing radio telescopes. These technologies are

SKA/Hubble Space Telescope

This composite image shows just a few of the thousands of dish-shaped antennas that will eventually comprise the Square Kilometre Array (SKA), the world's biggest and most sensitive radio telescope, against the backdrop of a star-forming region in the Large Magellanic Cloud.

being driven by various design studies and "demonstrator" projects around the world.

As an important first step, South Africa has launched an ambitious – and by all accounts, thoroughly successful – demonstrator project known as meerKAT (KAT refers to Karoo Array Telescope). The underlying intention may be to show the astronomical community that this country is capable of building and operating a world-class facility, but it goes a lot further than that: irrespective of who gets the big prize, meerKAT is destined to become one of the world's premier mid-frequency radio astronomy facilities, and as such, will put South Africa right at the cutting edge of radio astronomy.

About meerKAT

According to the project management, the telescope – funded by the Department of Science and Technology via the National Research Foundation – will be constructed in several phases to ensure the best value for money and sound technology choices. In fact, the government has taken a big leap of faith here, committing R860 million to the SKA effort, including the design and construction of meerKAT.

Winning the SKA bid would be a major step forward for the government's Astronomy Geographical Advantage Programme (AGAP). Other major astronomy players in the region include the Southern African Large Telescope (SALT) outside Sutherland and the HESS gamma ray telescope in Namibia.

- The first prototyping phase, a single-dish system, has already been built at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) in Gauteng.
- KAT-7, a seven-dish engineering test bed and science instrument near Carnarvon in the Northern Cape, will be commissioned from the end of 2009.
- The full array of 80 dishes should be operational and doing science from the end of 2012. A high-speed data transfer network will link the telescope site in the Karoo to a remote operations facility.

The Karoo region is ideal for radio astronomy, since it is remote and sparsely populated, with a very dry climate. There is minimal radio frequency interference from sources such as cellphones, broadcasting and air traffic.

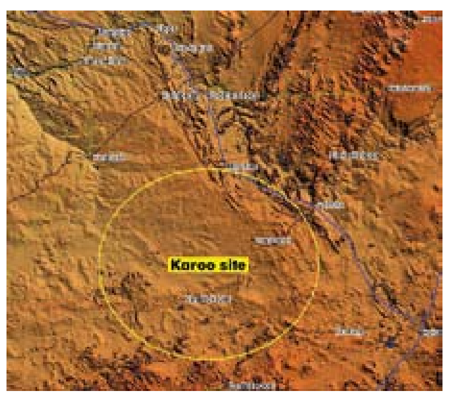
MeerKAT will explore celestial mysteries such as cosmic magnetism, the evolution of galaxies and the large-scale structure of the Universe, dark matter, and the nature of transient radio sources. It will also study pulsars, and allow scientists to carry out novel astrophysics and astrobiology experiments. South African engineers and astronomers are working closely with teams around the world on the advanced technology required to make meerKAT work, and on the science programmes at which this telescope is expected to excel.

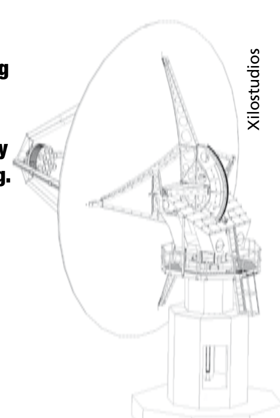
Says project leader Anita Loots: "Looked at one way, it's an experiment in mission-driven innovation. The government is recognising the importance of the high-tech economy and is seeding new industries, playing a critical role in the 'knowledge economy' by backing an important tool for the advancement of physics. Part of that commitment is reflected in its backing of 52 post-graduate bursars who are destined to make important contributions of their own.

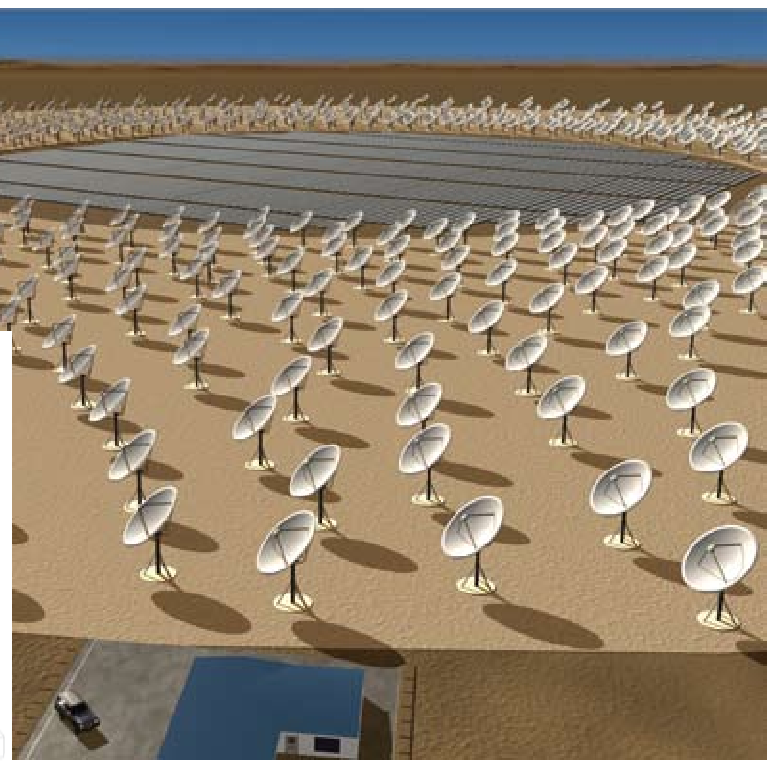
"In fact, the government took a unique approach to the project. It said: 'We will allocate money to the project, but you have to build a world-class facility – and you have to be ready to press the button by the end of 2009.' It was a scary proposition, but we knew we could do it.

"From the very beginning, we took a system engineering approach, and although it's early days, all indications are that it is working. A year ago, I stood up at a conference in Paris and told them we were going to build a dish within a time frame they considered impossible. They actually laughed at me in disbelief. Today, I think, they are less inclined to laugh – because we've done it."

The meerKAT digital signal processing team is working closely with UC Berkeley (two people based at that university), and the collaboration includes teams from several other coun-







Above: A single-dish system, representing the first prototyping phase of the meerKAT project, has already been built at the Hartebeesthoek Radio Astronomy Observatory (HartRAO) in Gauteng. Left: If all goes according to plan, the core of the SKA will be built in a remote part of the Karoo. Right: Tile-shaped antennas will make up the central focal plane array, surrounded by dish-shaped antennas.

The science of the SKA

Astronomers explore the universe by passively detecting electromagnetic radiation and cosmic rays emitted by celestial objects. Earth's atmosphere and ionosphere shield us from much of this radiation, so modern astronomy is conducted from large optical telescopes on mountain tops, or from orbiting satellite observatories.

Radio astronomers, on the other hand, concentrate on the relatively long-wavelength (or low-frequency) radio waves that penetrate the atmosphere with little impediment or distortion. These radio signals have frequencies between about 30 Megahertz (below this frequency, the ionosphere distorts and attenuates the signals), and 10 Gigahertz, or equivalently, wavelengths from 10 metres down to 3 mm.

History has shown that for any scientific discipline to remain active and productive, the power of its instrumentation must grow exponentially with time. Without this growth, the discipline tends to stagnate, and new discoveries become rare. Most of the currently used radio telescopes were built 10 to 30 years ago. For radio astronomy to progress, a new telescope with 100 times the collecting area of existing telescopes will be needed in about 10 years' time.

The Square Kilometre Array (SKA) was conceived as a new international project to meet the future needs of radio astronomers. One of the prime objectives of the SKA is to probe the so-called "Dark Ages", when the early Universe was in a gaseous form before the formation of stars and galaxies. At present, astronomers do not have the necessary tools to observe radiation from this period of the Universe, which extends from about 300 000 years until 1 billion years after the Big Bang.

Because electromagnetic radiation travels at a fixed speed of about 1,08 billion km/h, very distant objects are observed as they were in the distant past. Astronomers are therefore able to look back in time to observe the early stages of the evolution of the Universe.

For example, recent results from the WMAP Cosmic Microwave Background Radiation satellite observatory provide us with a view of the universe 300 000 years after the Big Bang, at the time when radiation and matter became separated. The Hubble Deep Field (HDF) image produced by the Hubble Space Telescope shows us what the early galaxies looked like some billion or more years later. We need to know how the "lumpy" galaxies seen in the HDF were born during the "Dark Ages" out of the "smooth" early Universe observed by WMAP.

Radiation reaching us from the "Dark Ages" has travelled a huge journey through space, and is in the form of radio signals emitted by the neutral hydrogen gas that dominated the Universe during this period. The signals are, however, extremely faint, and require a telescope with the planned sensitivity of the SKA to be detected. The SKA will map the time evolution of this cosmic web of primordial gas as it condenses to form the first objects in the Universe.

It will also chart the development of these adolescent stars and galaxies, which will provide us with information about our own origins. The atoms in our bodies, our planet and our star were formed by the nuclear reactions that powered these early stars.

The SKA will provide data for a whole range of astronomical investigations, complementing other planned instruments in the optical, infrared and millimetre wavebands. It will provide sharp radio images of all categories of astronomical objects, investigate the nature of the enigmatic gamma-ray burst sources, detect the gravitational waves predicted by Einstein's theory of General Relativity (by using radio pulsars as cosmic clocks), detect extra-solar planets, and may even detect signals transmitted by intelligent extraterrestrial civilisations (SETIs).

With a resolution of one-tenth the Earth-Sun separation at 300 light-years' distance, the SKA should detect emission from the centimetre-sized "pebbles" thought to be the first step in assembling Earth-like planets. Observing the process of planet building will tell us how these other worlds are formed. Biomolecules tracing the existence of life may also be detected.

- Source: SKA South Africa/meerKAT (*www.ska.ac.za*) tries around the globe. The meerKAT team also enjoys a close relationship with scientists at SETI's Allen Telescope Array (ATA) in the US, which has pioneered many technologies required by meerKAT. For the RF systems, they work with several international teams, most notably the Jodrell Bank Observatory in the UK, Caltech and Cornell in the US, Onsala Space Observatory and Chalmers University in Sweden, and ASTRON in the Netherlands.

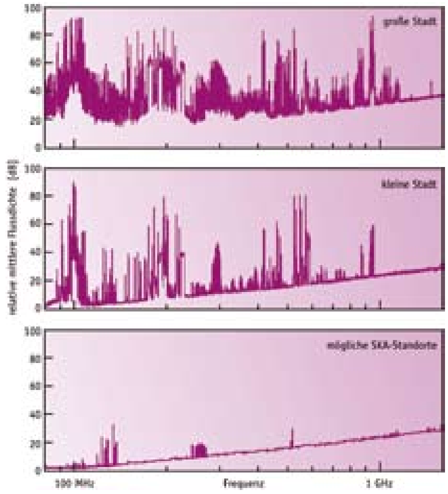
Says Loots: "Funnily enough, we're even working with our rivals, the Australians, in a formal collaboration focusing on software and computing issues. But cryogenics is the issue that keeps us awake at night.

"The technological challenges of the SKA are bigger than any one nation can handle, but there's no doubt about the value of our contribution. For example, we're very strong in terms of correlator development and the antenna solution, and we're making excellent progress in software and computing."

Calibrating the full system dishes will pose a number of serious challenges, says Dr Alan Langman, sub-system manager for the digital signal processing team of the Karoo Array Telescope. "There are several levels of calibration. For example, you have to allow for significant differences in temperature during the course of the day, wind and other weather phenomena, and even the effect of gravity, which distorts the dish as it moves. Because the tolerances are so tiny, any of these factors could compromise the signal."

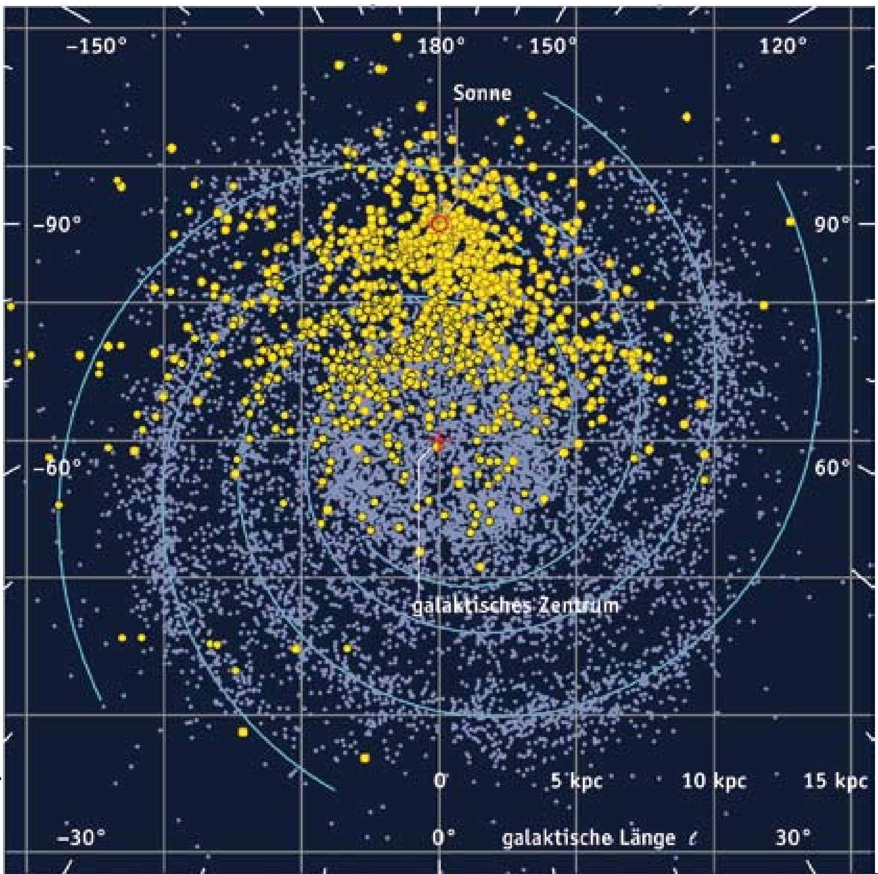
And it doesn't end there, says Langman. "You have to filter out a lot of 'noise' from satellites and other stuff to get to your astronomical object. This is where the correlator comes in, improving the noise signal quite dramatically. In essence, it's a very serious computer, albeit an unusual one that uses Field Programmable Gate Array (FPGA) processors to correlate data from the dishes according to frequency, averaging the results.

"We're talking about a lot of data here: each dish transmits 2 gigabytes of data a second, which means meerKAT's full array of 80 dishes will be producing 160 GB of data each second. That requires rather a lot of number crunching. Our system will be scalable and upgradable, which makes it very effective.



A graph showing man-made radio frequency interference from 80 to 2 000 MHz in a big city (top), a small city (middle) and on an SKA site (bottom).

"Ours is essentially next-generation technology, and solving these challenges should ultimately have a myriad potential applications outside the sphere of radio astronomy. For example, better



Simulation by Jim Cordes/SuW

Known pulsars (yellow) and pulsars expected to be found with the SKA (blue).The faint red cross in the centre indicates the galactic centre, the red circle the position of our Sun. The grid distance is 5 kpc, or 16 000 light-years.

broadband Internet access will be a direct benefit, since the infrastructure that the telescope will require far exceeds the total Internet traffic of the country as a whole."

Langman is distinctly upbeat about the potential of the project that occupies his every waking moment: "Aside from the obvious scientific and economic benefits to South Africa and the rest of the world, our work will hopefully come across to young people as 'cool', and may perhaps even inspire some of them to follow a career in science, engineering or technology."

● As part of its student recruitment efforts, the South African SKA project office has produced a student recruitment poster for the meerKAT project. The poster (download it at *www.ska.ac.za*) highlights the different skills and disciplines required for the science and engineering of building and operating a world-class radio telescope. For a copy, e-mail *kdeboer@ska.ac.za* **PM**