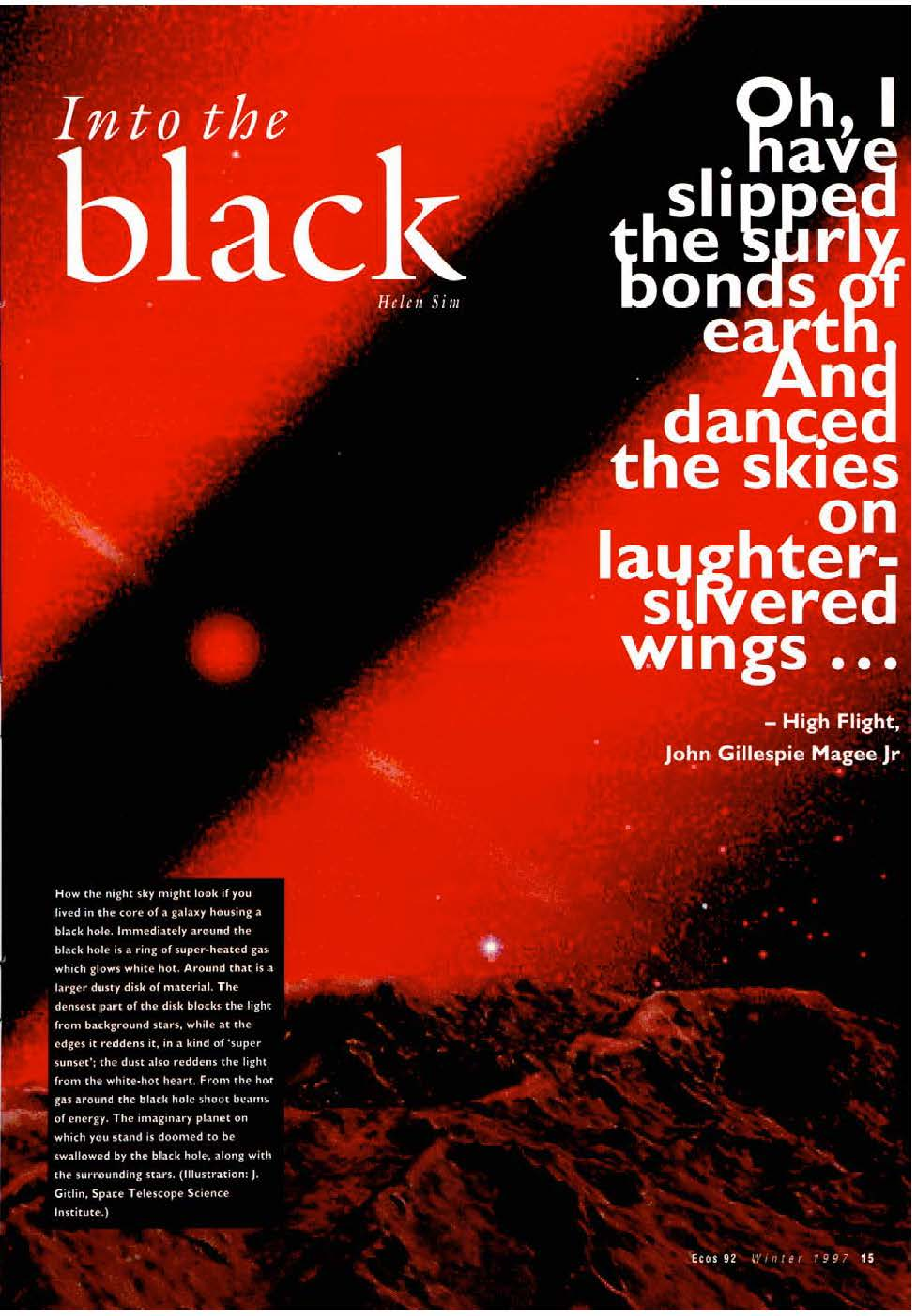
Into the black

Helen Sim



Oh, I have slipped the surly bonds of earth, And danced the skies on laughter-silvered wings . . .

– High Flight, John Gillespie Magee Jr

How the night sky might look if you lived in the core of a galaxy housing a black hole. Immediately around the black hole is a ring of super-heated gas which glows white hot. Around that is a larger dusty disk of material. The densest part of the disk blocks the light from background stars, while at the edges it reddens it, in a kind of 'super sunset'; the dust also reddens the light from the white-hot heart. From the hot gas around the black hole shoot beams of energy. The imaginary planet on which you stand is doomed to be swallowed by the black hole, along with the surrounding stars. (Illustration: J. Gitlin, Space Telescope Science Institute.)

Flying through space, hundreds of kilometres above us, is an eight-metre, golden 'fish-net', spread wide to collect its catch. But its haul will not be Pisces, the heavenly fish, or Cancer, the celestial crab: it will be black holes in the hearts of distant galaxies.

The 'fish-net', the first space radio telescope, was launched by Japan's scientific space agency, ISAS, on February 12, 1997. It is the centrepiece of a project which involves 19 countries and has taken 10 years to reach fruition.

Just before the telescope's launch, CSIRO's Dr Dave Jauncey, co-chairman of the project's international science council, was asked about the contingency plans if it failed. 'I've put 10 years of my life into this,' he said. 'Failure is not something we can contemplate!'

Fortunately he didn't have to worry. The launch, from the island of Kyushu, was flawless. In a mere six minutes the new M-V rocket, trailing a line of flame, ferried the 830-kilogram satellite up through the clouds, down range and out of sight.

Once in orbit the satellite spread wide its solar panels, its only source of energy for the rest of its life. When these die, after years of radiation damage from the Sun, the satellite will fall silent.

Second to emerge was the communications dish, which dutifully made contact with anxious watchers on the ground. Next came the masts and subreflector, extending like insect antennae. And finally, the main reflecting surface, like a giant golden flower blooming.

In fact there was a slight hitch. On the first attempt one of the six arms that underpin the telescope dish's structure wouldn't extend to its full length. But a day later, it worked. At this point, says Jauncey, who was at the launch site, 'the smiles were almost as broad as the telescope itself'.

Astronomers first tested the concept of a space a radio telescope in 1986, with a satellite on loan from NASA. The tests were successful, and so they pushed to get a purpose-built dish into space. The Japanese satellite is the first such dish to be launched.

Because it uses a technique called VLBI, the satellite was originally going to be called VSO–VLBI Space Observatory. But this was quickly changed to VLBI Space Observatory Progamme: VSOP brandy was a favourite drink of Masaki Morimoto, a Japanese astronomer who played a big part in getting the project under way.

Is bigger better?

The radio telescope swoops around the Earth once every six hours and 20 minutes, in a long, elliptical path, its distance from Earth ranging between 575 and 22 000 km.

Unlike the larger Hubble Space Telescope, the space radio telescope has to work with its friends – earth-bound telescopes spread around the world – to make pictures of distant galaxies. Together they are set to out-Hubble Hubble, forming radio images up to a thousand times finer than Hubble can produce. This minor miracle is performed through a technique called Very Long Baseline Interferometry (VLBI).

VLBI is the astronomers' cunning way of overcoming the limitations of their equipment. Modern radio telescopes are used mainly to make pictures of the sky; pictures like photographs, but made from

The M-V rocket carrying the VSOP satellite was launched from the Kagoshima Space Center, Japan. After deployment the satellite was re-named HALCA (Highly Advanced Laboratory for Communications and Astronomy), pronounced in Japanese as 'Haruka', meaning 'far away' or 'distant view'. (Image: ISAS)

radio waves instead of light. The resolution (or sharpness) of the picture depends on the size of the telescope: the bigger your dish, the more detail you can see.

But there is a practical limit to how big a single telescope dish can be made. If you want to point all over the sky, 100 metres across is about as big as you can go. To make a bigger, 'virtual' telescope, astronomers make separate dishes act like fragments of one big dish, taking the signals from each dish and combining them with a bit of mathematical magic.

For the system to work, all the telescopes must observe the same piece of sky at the same time. It's not a perfect substitute for a single, giant dish, but it works well, because, as the Earth turns, more patches are covered on the surface of the imaginary dish. This technique, called interferometry, lies behind the world's most advanced arrays of radio telescopes, including CSIRO's Australia Telescope Compact Array.

Over short distances, linking the dishes is easy: all the signals are run down wires or optical fibres to a central location. But over more than a few kilometres, this becomes impractical. For Very Long Baseline Interferometry (baselines are the distances between the telescopes), the data each telescope takes are recorded on tape, along with high-precision time signals. The tapes are then brought to one location and processed together in a special-purpose computer called a correlator.

While simple in principle, in practice much can go wrong. VLBI experiments typically involve many institutions and telescopes, and dozens of people. They take a long time to arrange – all the telescopes must watch the sky at the same time – a while to carry out, a while to process the data, then the usual long time to interpret and report the results.

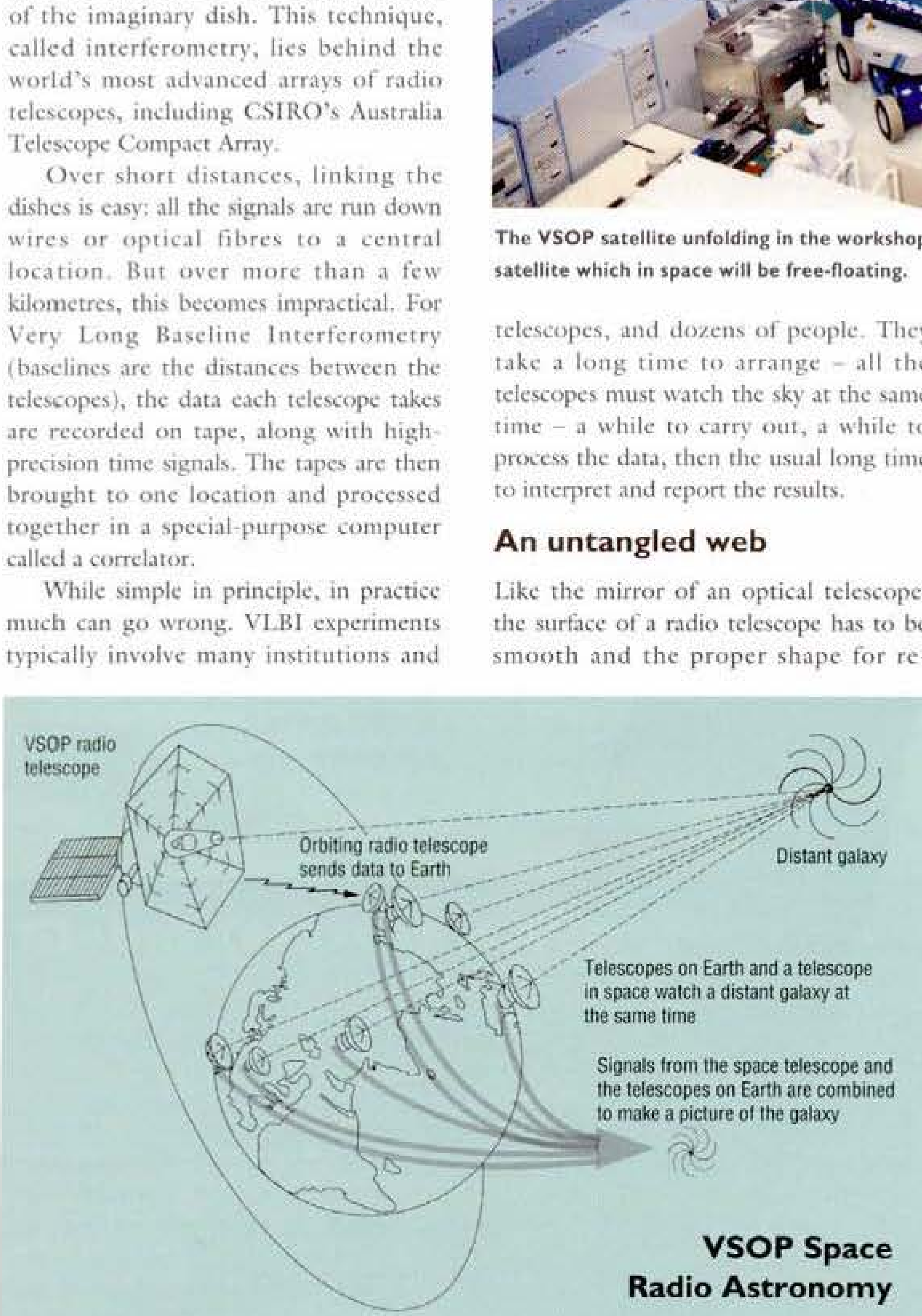
The VSOP satellite unfolding in the workshop. Helium balloons are used to hold up parts of the satellite which in space will be free-floating.

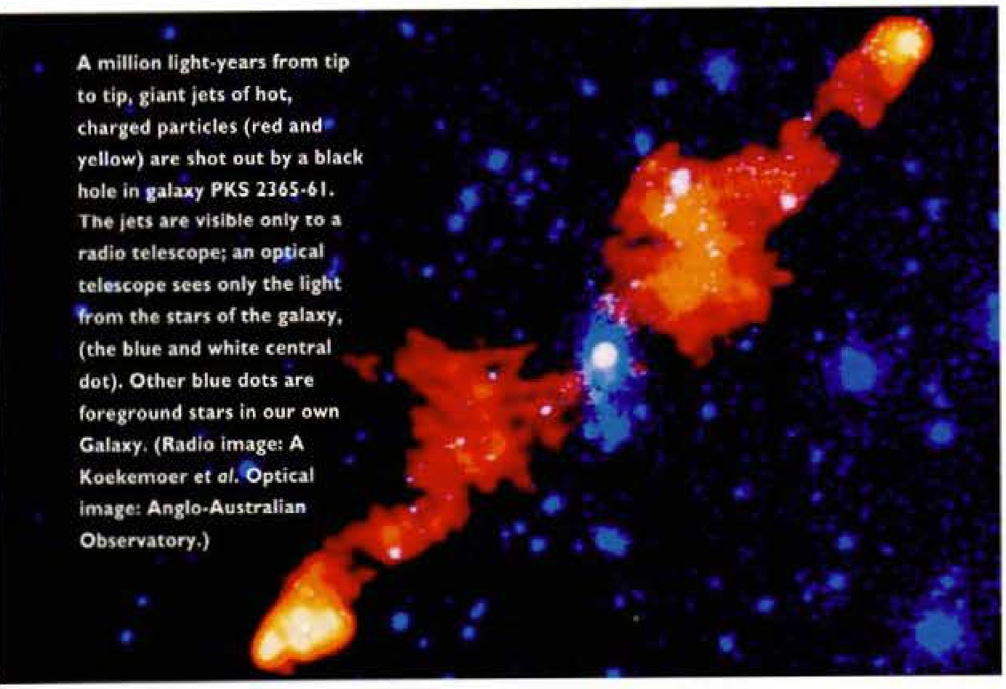
An untangled web

Like the mirror of an optical telescope, the surface of a radio telescope has to be smooth and the proper shape for reflecting. Lumps and bumps are no good. Radio telescopes on the ground are hard, solid things; parabolas of metal plates or mesh panels held in place by ribs and trusses. But a heavy structure like this costs a lot to send into space.

For the VSOP satellite, the Japanese designed an elegant structure of golden mesh – gold-coated molybdenum wire – that to a radio wave looks like a solid surface. To work well, the surface must differ from a perfect parabolic surface by less than 0.6 mm at any point. The mesh surface is supported by a web of Kevlar wire, which in turn is tied at many points to a second web trussed to six radial 'arms' stretched out like a starfish. The wires that tie the two webs together stretch the surface to just the right shape.

Unfolding in the manufacturer's workshop, the satellite was a thing of beauty. The delicate twists and turns of wire that in space would float free were borne up by clouds of red-and-white checked helium balloons. The six arms took more than an hour to creep outwards, gradually straightening out the crinkles in their gold-foil covering. Slowly the surface, a scrunched-up mosquito net, began to unfold. It looked like the crumpled wings of a butterfly fresh from its chrysalis, being pumped taut.





A million light-years from tip to tip, giant jets of hot, charged particles (red and yellow) are shot out by a black hole in galaxy PKS 2365-61. The jets are visible only to a radio telescope; an optical telescope sees only the light from the stars of the galaxy, (the blue and white central dot). Other blue dots are foreground stars in our own Galaxy. (Radio image: A Koekemoer et *al.* Optical image: Anglo-Australian Observatory.)

VSOP works cooperatively with the world's ground-based radio telescopes, but its lifeline to Earth is a set of tracking and control antennas. These are spread around the globe: at Kagoshima and Usuda in Japan, Green Bank and Goldstone in the US, Madrid in Spain and Tidbinbilla, near Canberra, in Australia.

To keep its weight down, the satellite has no on-board data recorders, so the tracking antennas must catch its data streaming down at 128 megabits a second in real time. The satellite also lacks its own ultra-precise hydrogen maser 'clock', so the tracking stations pipe up the time and frequency signals needed for VLBI.

Upon arriving at each ground station, the data will be recorded on magnetic tapes, which will then be whisked away to either Tokyo, Penticton in Canada, or Soccorro in the US, to be processed together with tapes recorded by the ground-based telescopes. There are three different systems for recording VLBI data, and VSOP is going to have to use all of them, translating between different formats if necessary to make the final product.

What VSOP will spy

In the midst of all this technological cleverness it's easy to forget what the satellite is for. The picture's the thing, the sharper the better. If your eyesight were as sharp as the VSOP system, says Jauncey, 'not only would you be able to measure Neil Armstrong's footprint on the Moon, but you would be able to read the name of the manufacturer at the bottom of his sneakers'.

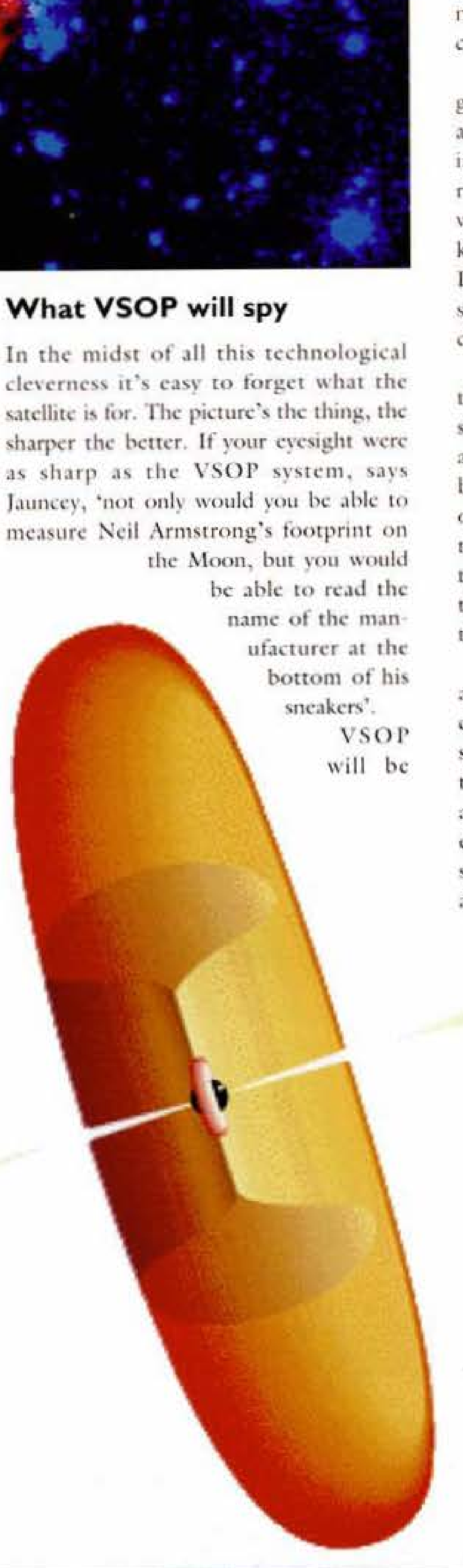
VSOP will be looking at two main groups of radio sources: active galaxies and masers.

Active galaxies are a special class of galaxies: 1-2% of the whole population of galaxies, which shine with more energy than their stars alone can provide. This extra energy comes from something going on deep in their cores. And there can be an awful lot of it, sometimes so much that the galaxy's core outshines the rest of its billions of stars. Since the Universe began, these active galaxies have poured out as much energy as all the other galaxies combined.

There are several species of active galaxies, each with different characteristics and different names. Radio galaxies, for instance, give off energy in the form of radio waves. Astronomers struggle to work out if all these apparently different kinds of galaxies are basically the same. Do they look different because we are seeing them from different angles, or at different stages in their lives?

Amid the chaos, one thing is clear: these galaxies could only be powered by super-massive black holes, sucking in vast amounts of matter. Why? Because only a black hole can squeeze that much energy out of matter. The gas a black hole drags towards it is tortured to unimaginable temperatures, releasing several hundred times more energy than it would in even the nuclear furnace of a star.

From tens of millions of light-years away, VSOP will be zeroing in on the centres of these active galaxies, regions as small as one light-day across – the size of the orbit of Saturn – from which a vast amount of radio energy is being emitted. In active galaxies, squashed into such a region is a



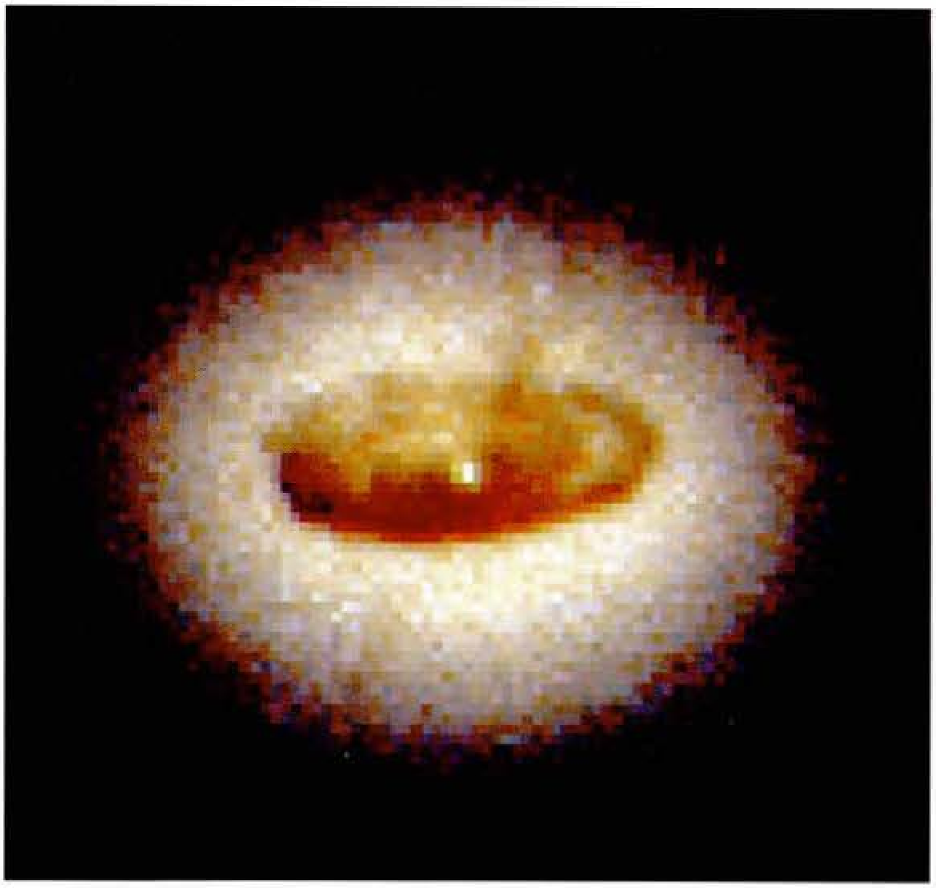
How can a black hole power a galaxy? Just outside the black hole, super-heated gas piles up into a doughnut-shaped ring. This ring forms a nozzle from which blasts a stream of hot gas thousands of light-years long. (Illustration: STSI) mass up to a 100 million times that of our Sun. Here lurks the black hole. We can thank our lucky stars we aren't living near one, because if we did . . . we wouldn't be!

Black holes spit as well as suck. Hundreds of galaxies are known to have fountains of super-heated particles spurting from their centres. These 'jets' eventually billow out into monstrously large structures, millions of light-years long, extending far beyond the galaxy's stars. Astronomers think that in such a galaxy a spinning black hole drags matter towards it, piling it up in a doughnut shaped 'accretion disk', and then somehow shoots some of it out in two oppositely-directed jets.

Galaxy NGC 4258 gives the best evidence for this picture. Around its heart whirls a string of strong radio sources (megamasers), held to their path by the gravity of something like 36 million Suns. NGC 4258 is one of VSOP's key targets. 'VSOP is about proving that we have black holes (in galaxies such as this),' Jauncey says.

There's no problem in coming up with a model to explain how black holes power active galaxies. Rather, the problem lies in deciding between all too many models. How thick is the disk of gas around the black hole? What accelerates the gas into jets? Is it a 'nozzle' formed by the gas disk, a 'funnel' of material, or a combination? Or is the gas revved up by twisted and torn magnetic fields: the so-called 'magnetic slingshot' effect?

Down near the base of some of these jets are sub-regions of gas that seem to be travelling at very nearly the speed of light. What could produce such high velocities? And how are these ultra-speedy jets related to the bigger jets in which they seem to be embedded?



A hole in the heart. This, the central part of the galaxy NGC 4261, probably houses a black hole. The outer white area is the galaxy's core or centre. The brown, spiral-shaped disk inside it has a mass about a hundred thousand times that of our Sun. At the disk's centre is a very heavy object. Because the disk is rotating we can 'weigh' this object at its centre. About the size of our Solar System, but twelve hundred million times more massive than the Sun, this object is almost certainly a black hole. (Image: STSI/NASA)

Not surprisingly, many astronomers would give their eye teeth for a close-up look at the region around a black hole. VSOP won't be able to see right down to the accretion disk itself, but it will get us closer to the base of the jets than any other imaging technique. Particularly intriguing are the jets from a handful of objects which seem to blast out, not straight, but spiralling like a corkscrew. With space VLBI we will be able to see closer to the core, the start of these twisting paths.

VSOP's second main group of targets are masers, natural radio sources powered in the same way as the familiar laser. Masers are found near forming stars and also some old-age stars. VSOP will track the motions of these sources and determine their sizes, to help us understand how they form and evolve.

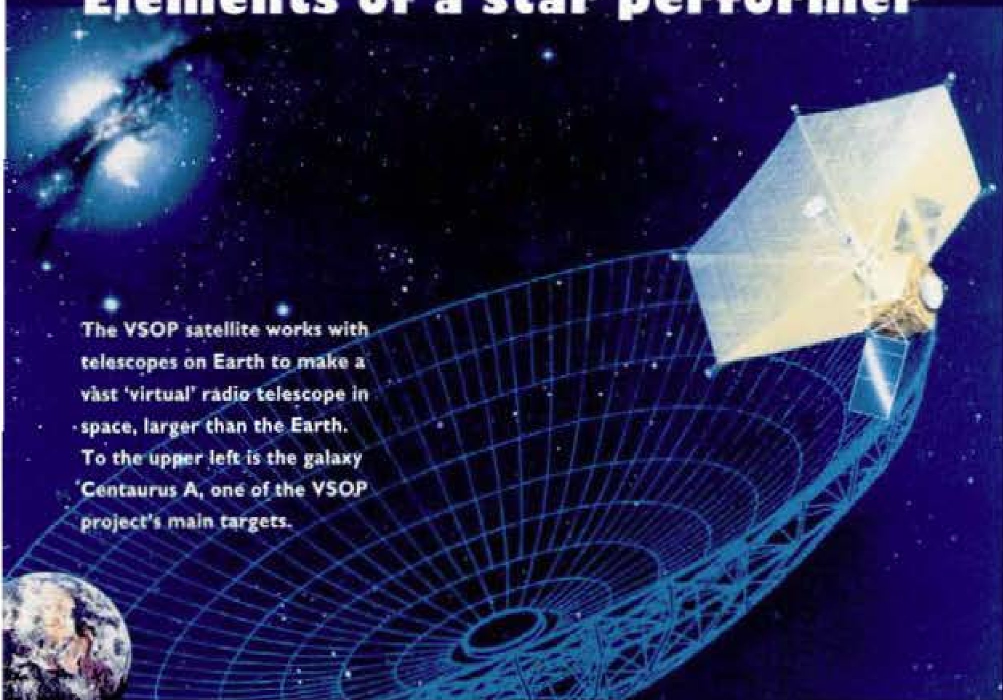
Before this science starts in earnest, however, the telescope must pass many tests. First, all its various operating systems have had to be checked. The next tests, still going on, are to get the satellite and some of the ground-based telescopes working together. The first test observations of a real source – a maser – were made in March.

Global telescopic conspiracies

TELESCOPES around the world for doing VLBI fall into natural 'families', based largely on geography. One group is the Very Large Baseline Array, 10 telescopes strung out across the United States. Another is the European VLBI network, a coalition of independent telescopes spread across Europe and into Asia. The third major grouping has been the Southern Hemisphere VLBI network, running from eastern Australia to South Africa. In the past few years telescopes around the Pacific rim, in Australia, China, Japan and other countries, have banded to form the Asia-Pacific Telescope.

In terms of radio telescopes, Australia is the best endowed country in the Southern Hemisphere. It has the extensive facilities of CSIRO: the Parkes 64 metre diameter telescope, a 22-m dish near Coonabarabran and an array of six dishes near Narrabri, NSW. There are also dishes in Tasmania and South Australia run by the University of Tasmania, and the antennas of the Tidbinbilla space tracking station near Canberra, which often 'moonlight' as radio telescopes. Smaller dishes near Perth and Alice Springs have also been used for some projects. Australia's telescopes are vital for the VSOP project, for only they can give adequate ground-based observations of sources far south in the sky.

Elements of a star performer



The VSOP satellite works with telescopes on Earth to make a vast 'virtual' radio telescope in space, larger than the Earth. To the upper left is the galaxy Centaurus A, one of the VSOP project's main targets.

THE VSOP satellite is equipped to observe in three frequency bands, centred on 1.7, 5 and 22 Gigahertz. The three frequencies give three different 'views', because structures and processes visible at one frequency may not be visible at others.

Each frequency band needs its own receiving system, with low-noise amplifiers boosting the incoming signal before it is further processed. In ground-based telescopes, such amplifiers are cryogenically cooled to near absolute zero to improve their performance; this has not proved practical in the satellite, because it would require extra power and add extra weight.

After being amplified, the incoming signal is mixed with a signal from a 'local oscillator' to convert it to a frequency which can be more easily processed. Ground-based telescopes have their own local oscillators on hand, usually hydrogen masers. But these are too big, too heavy, and too likely to need servicing to put on the satellite, so instead the local oscillator signal will be piped up from the tracking stations, each of which has its own hydrogen maser. Hydrogen masers are ultra-precise clocks, accurate to one second in 30 million years.

Swinging around the Earth, the satellite will be moving towards or away from the tracking station sending these signals. This movement alters the frequency of the signal (by the 'Doppler shift'). To compensate for this, the uplink signal will have to be adjusted in frequency using information about the satellite's orbit. This will be worked out from traditional 'range and range rate' data from the Kagoshima tracking station; a Global Positioning System detector on the satellite, (useful only when it is close to Earth); and the Doppler shift of the data coming down from the satellite.

The satellite orients itself by bright stars. Each day, the star positions needed for that day's observations are sent up to the satellite during one of its passes over the Kagoshima Space Centre. The satellite needs to be able to point accurately, to within an uncertainty of 0.01 degrees.

To observe each new object the satellite must be physically rotated. This is done using magnetic torques. Gas (hydrazine) thrusters are also installed on the satellite, but these will be used for changing its orbit, rather than for routine changing of its orientation.

Much of VSOP's most important work will be done in its early months, probably starting in June, when some of its key sources are going to be in their best positions for observing. One of these sources is the beautiful southern galaxy Centaurus A (also called NGC 5128).

Only 12 million light-years away, Centaurus A is the nearest of the active galaxies and so one of the easiest to study. It has one clear jet, and experiments have found evidence for a second, faint jet, going in the opposite direction: something that's detectable in only a handful of galaxies. The ratio of the brightnesses of these two jets is helping to discriminate between different models of how jets are made. With VSOP astronomers are going to be able to see a region in this galaxy's core that is smaller than our Solar System.

The other two of VSOP's 'three key sources' are NGC 4258, the best black hole candidate, and the galaxy Virgo A, another active galaxy, but further off than Centaurus A. Virgo A (also called M87) has a clearly visible single jet. The galaxy has been studied intensively by the Hubble Space Telescope, revealing the disk of hot gas that probably hides a black hole.

Visions of the future

VSOP has limitations. At any one time, the Sun cuts out a third of its view of the sky. (The Sun puts out a lot of radio waves as well as a lot of light.) The satellite has to be physically rotated to observe each new target. Even with five tracking stations the satellite can't be monitored all the time and, as it can't store its data on board, that means it can observe for only part of any orbit.

An eight-metre dish is not very big as radio telescopes go: it can't see the sky's fainter radio sources. Finally, for the whole system to work, all the telescopes on the ground must do their job without a hitch.

But for all this, the world's astronomers have seized on the project. The first call for observing proposals, made months before the satellite's launch, produced a flood of requests, four times as many as could be fitted in.

With the success of VSOP to ride on, US radio astronomers have already proposed the next generation of space VLBI missions. In 1994 they put together a concept for ARISE (Advanced Radio Interferometry between Space and Earth), which would have greater sensitivity to faint signals. This would be achieved with a bigger dish in space, a 25-m diameter inflatable Mylar dish and a new cooling system for the receiving equipment.

The hope is that, at last, astronomers could zoom down to the base of jets in active galaxies, perhaps detecting the magnetic fields that may give them their shape. But at the moment ARISE is still over the horizon, and what becomes of it will depend on the findings of VSOP.