A long time ago, in a galaxy not so far away

Vast stellar nurseries, clouds that dwarf the Solar System and lurking swarms of black holes. **Jeff Kanipe** probes the unfolding mysteries at the heart of the Milky Way.

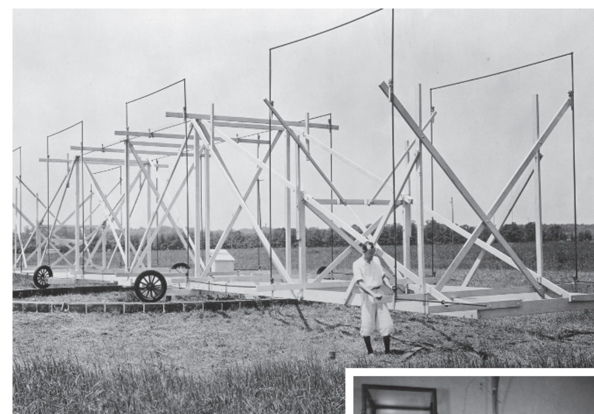
Before it was seen, it was heard. In the early 1930s, a Bell Labs engineer named Karl Jansky was given the job of sorting out where the static interference in radio transmissions came from. With an ungainly but ingenious steerable antenna he tracked a number of sources. Most were thunderstorms, but one wasn't. As Jansky tracked it across the sky from day to day he realized that it was far beyond Earth's atmosphere, and indeed beyond the Solar System — an abiding hiss from somewhere in the constellation of Sagittarius[1].

As constellations go, Sagittarius is modest both in size and in brightness. What sets it apart, on dark, moonless nights, are its background contrasts: brilliant, billowy clouds of stars that are punctuated by dusky rifts and voids. No other place in the sky looks this compelling.

By the time of Jansky's discovery, the behaviour of other objects in the sky had already provided good evidence that something special lay within those beguiling clouds. In 1918, a study of star clusters by Harlow Shapley, an astronomer at the Mount Wilson observatory above Los Angeles, showed that 'open' star clusters were spread throughout the plain of the Milky Way, whereas globular clusters were concentrated in the direction of Sagittarius[2] — some above the Milky Way, and some below it, drawn by some unseen immensity. The globular clusters were like moths batting about a lamp hidden in Sagittarius's dense folds of dust.

Hidden behind the clouds

Jansky's observations provided the first hint of what lay behind those shrouds, but it took decades for further details to become clear. It was not until 1968 that the radio source at the centre of the Galaxy, now called Sgr A* (or 'Sagittarius A-star'), was detected in the infrared, showing that it was 1,000 times brighter than the radio emission had led astronomers to suspect[3]. At shorter infrared wavelengths — which like their longer brethren pass through dust much more easily than visible light — it was even brighter. By this time, astronomers gazing elsewhere in the sky had discovered quasars, bodies so bright and yet so small that it seemed possible they were powered by vast black holes sucking up dust and gas at an incredible rate. In 1969, the British astronomer Donald Lynden-Bell suggested that our Galaxy



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Karl Jansky (right) used a rotating antenna to detect radio waves in the Milky Way.

and its neighbours could all have 'dead quasars' at their hearts[4]. By this line of reasoning, Sgr A* had to be a vast black hole.

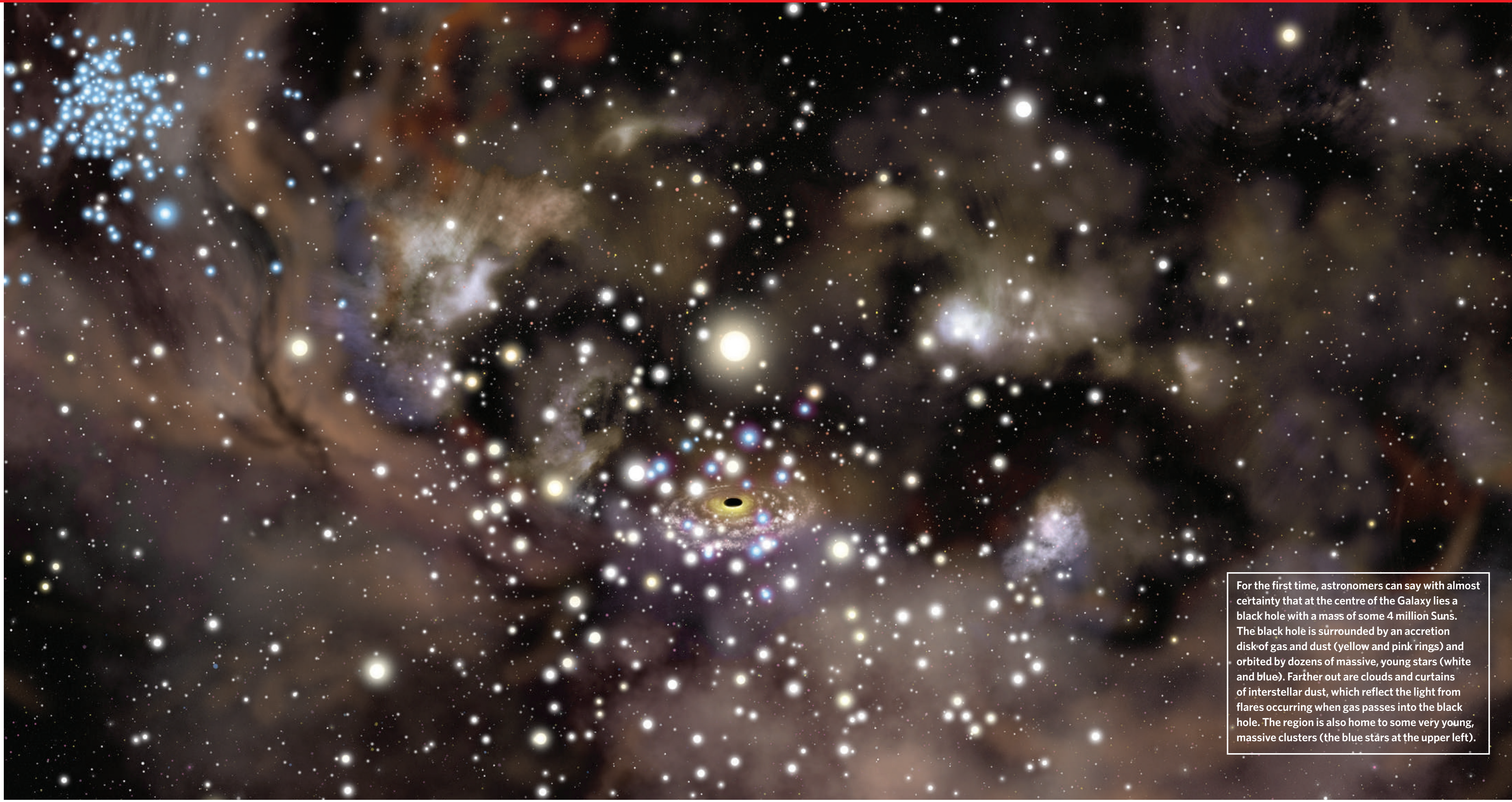
Even with a compelling theory, seeing the details was hard. Telescopes using visible light — even the mighty Hubble — could not see through the clouds of dust. But in the past ten years, powerful radio arrays, new infrared and X-ray telescopes, detectors in orbit and adaptive-optics systems on Earth have revealed strange new structures in and around the Galaxy's central engine: magnetic arcs and filaments, giant clumps of massive stars and whorls of gas. Analysis of the motions and masses of the stars within the central two light years of Sgr A* have shrunk the known heart of our Galaxy down to a region of space no larger than Earth's distance from the Sun, and probably much smaller, containing the mass of four million Suns. For all this insight, the heart of the Galaxy still has mysteries for astronomers to explore — from echoes of outbursts to the silhouette of the event horizon itself.

One problem with observing the very centre of the Galaxy, though, is that it simply isn't very bright — a firefly to the searchlight of a full-blown quasar. The obvious explanation for its lack of luminosity, says Andrea Ghez, principal investigator of the Galactic Center Group at the University of California, Los Angeles, is that even though Sgr A* lies at the heart of a galaxy of hundreds of billions of stars, it may be a bit isolated. The radiation from black holes comes not from the holes themselves, but from matter falling onto the accretion disks that swirl around them. There may just not be much matter around to fall onto the accretion disk at the centre of the Galaxy. Or the disk may be generating a wind of radiation strong enough to stop any more gas and dust flowing into it.

Unexpected echo

Nevertheless, the flow sometimes increases and the central engine heats up. For a couple of years in the 1950s, for example, Sgr A* looked perhaps a hundred thousand times brighter in the X-ray spectrum than it is today, probably because it swallowed a planet's worth of gas in a gulp. Unfortunately, humankind had no X-ray telescopes in the 1950s — the devices only work in space — which might seem a serious impediment to learning from the event. But it is not, it turns out, an insurmountable one.

At the January 2007 meeting of the American Astronomical Society in Seattle, Washington, Michael Muno of the California Institute of Technology (Caltech) in Pasadena announced that his team had managed to see part of the 1950s outburst reflected off clouds on the far side of the Galactic Centre[5]. X-rays that had started off heading away from Earth had bounced back to us, and because the clouds were a few tens of light years away from the centre, the reflected X-rays took half a century longer to get to Earth than did those that had taken the direct route. Half a century



For the first time, astronomers can say with almost certainty that at the centre of the Galaxy lies a black hole with a mass of some 4 million Suns. The black hole is surrounded by an accretion disk of gas and dust (yellow and pink rings) and orbited by dozens of massive, young stars (white and blue). Farther out are clouds and curtains of interstellar dust, which reflect the light from flares occurring when gas passes into the black hole. The region is also home to some very young, massive clusters (the blue stars at the upper left).

isn't much in terms of a journey across the 26,000 light years that separate Earth from the Galactic Centre, but it's enough to make the difference between astronomers stuck underneath Earth's X-ray-absorbing atmosphere and astronomers who, like Muno's team, can use NASA's Chandra X-ray telescope to monitor the centre of the Galaxy.

"This is the first X-ray echo that we have seen propagating through space after an event that we had not originally seen," says Muno. The observations allowed his team to say that the burst must have been 1,000 times brighter and 1,000 times longer than the contemporary ones seen with the Chandra telescope or the Japanese Advanced Satellite for Cosmology and Astrophysics. The intermittency of such events could imply that the disk of material swirling about the black hole is both meagre and unstable, only occasionally dropping a gobbet of matter into the black hole's maw.

But if the black hole's neighbourhood is by and large empty, how can we account for the family of bright young stars that swarms about it? This apparent paradox received prominent attention at the Galactic Center Workshop held in Bad Honnef, Germany, in 2006. The black hole's inactivity suggests that the central few light years doesn't contain enough raw material to make stars. And the enormous gravitational tidal forces around the black hole would seem to prohibit stars from forming even if the material were there: it's hard for a cloud of gas to contract into a star under its own gravity when something that weighs as much as four million stars is sitting next door.

Nevertheless, says Ghez, at the Galaxy's core is a swarm of about 40 massive young stars; they are called 'S stars' because they belong to the Sgr A* cluster. One, called S0-2, has a mass that is some 15 times that of the Sun and orbits Sgr A* with a period of just over 15 years. At its closest, it comes within 17 light hours of the supermassive black hole[6] — as close as the edge of our Solar System is to Earth. After 12 years of monitoring the motions of these stars using the infrared capabilities and adaptive optics of the W. M. Keck Observatory on Mauna Kea, Hawaii, Ghez's Galactic Center Group, has almost seen them make complete circuits of the centre and return to where they started: "We should see S0-2 close [its orbit] in 2010," she says.

The orbits of the central stars of the Galaxy can be used to further refine the mass of the central black hole and to constrain the distribution of mass in the neighbourhood. And their motions might also reveal something about how they got there in the first place.

There are two explanations for the stars' presence. One theory is that the stars formed more or less where they are today, near the black hole. In principle, this could have occurred if the density of the gases in the centre of the Galaxy was much higher in the past. Higher density would allow clumps in the clouds to collapse to form stars, even in the presence of a strong gravitational field.

The alternative explanation is that the stars formed outside the adverse conditions of the central region and migrated there later on as a single massive cluster. However, for this to work the core of the original cluster would have needed a mass that was ten million times greater than that of the Sun, packed into a volume of no greater than 3 light years, which is more compact than any cluster known. At the moment, most astronomers seem to favour the first scenario.

But although young stars may not be migrating into the central zone, very old ones probably are. Theorists at the Galactic Center Workshop described recent simulations that bolster a striking prediction first made by Mark Morris of the University of California, Los Angeles, in 1993. Morris postulated that the inner three light years of the Galaxy's centre might contain as many as 20,000 star-sized black holes. These are the remnants of previous generations of bright young stars, which have sunk slowly in towards the central and much larger black hole over

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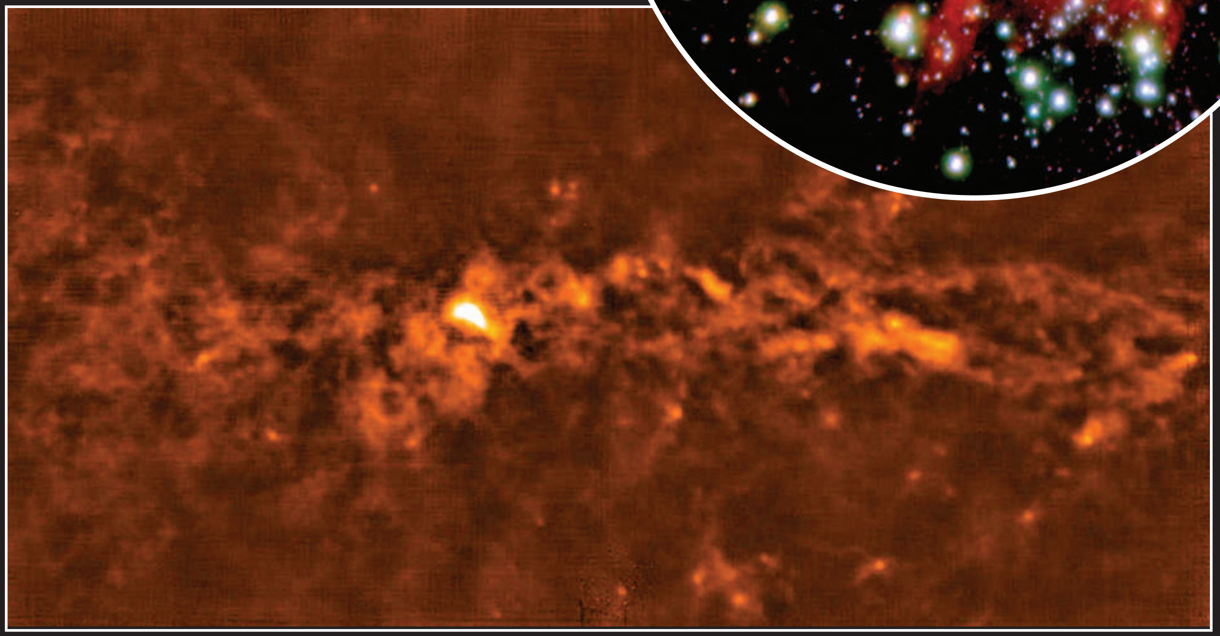
At the centre of the Milky Way (above) is a supermassive black hole called Sgr A* (right), which is surrounded by both hot (blue) and cold (red) stars. The stars form in 'nurseries' (below) as bright cores embedded in giant molecular clouds.

J. BALLY & THE BOLOCAM/CSO GALACTIC PLANE SURVEY TEAM



billions of years. The presence of a close-knit cluster of dead stars is supported by Chandra's discovery of four bright but variable X-ray sources — within 3 light years of Sgr A* (ref. 7). The sources' variability is a characteristic of systems in which matter from a normal star is sucked onto a black hole or an ultradense neutron star. Four fairly easily discerned X-ray sources of this type in such a confined region, say astronomers, provide strong circumstantial evidence that tens of thousands of black holes and neutron stars have settled in and around Sgr A*.

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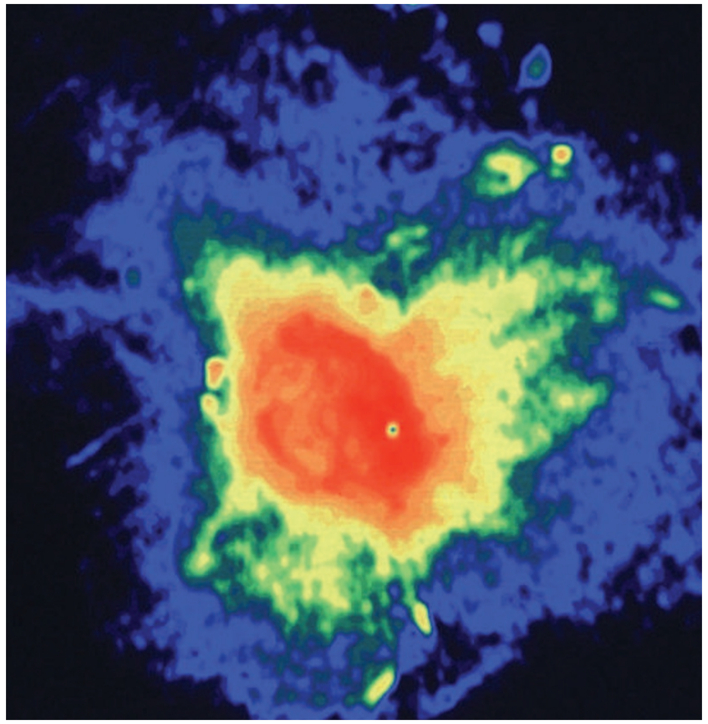

At radio wavelengths, shells of gas surround Sgr A* (point source at centre).

Smouldering stars

To see some real clusters, we have to step back a little. A hundred light years from Sgr A* lie the Arches and Quintuplet clusters — two of the most massive young clusters and unlike either the open or globular clusters seen elsewhere. The stars in the Arches cluster are 50 times closer together than are those in the neighbourhood of our Solar System. At the density seen in the Arches cluster, the space between the Sun and its nearest neighbour would contain 100,000 stars. The other cluster, the Quintuplet, is a bit older and more dispersed, but it has one of the biggest and potentially most volatile stars known, called the pistol star (so named for the pistol-shaped nebula in which it lies).

The source of these mammoth star clusters are giant molecular clouds — cool, dense complexes of dust and hydrogen gas up to 130 light years in breadth and containing the mass of between 10,000 and 500,000 Suns. Instruments such as those on NASA's Spitzer space telescope can see the parts that contain young stars, which glow brightly in the infrared. Astronomers working at longer wavelengths can see even earlier stages of the star-birth process. New maps of the Galactic Centre made at the Caltech Submillimeter Observatory (CSO) on Mauna Kea, Hawaii, reveal objects so early on in their development that they can't yet be called stars. "What we see are usually cores of clouds that have not necessarily begun to form stars yet, or are in the early stages of doing so," says Elisabeth Mills, who is a member of CSO's Bolocam Galactic Plane Survey. "With millimetre-wave data you get a more unbiased census of where star formation begins to occur. You see all of these nurseries, and whether or not they have a 'baby' in them yet."

A mosaic of these maps reveals a different side to the Galactic Centre. The bright clusters seen in Spitzer images are diminished; the cores of cooler clouds blossom with light, indicating that they have yet to collapse into massive protostars. These regions, which form a ridge-like structure in images taken at millimetre wavelengths, might one day form a chain of clusters like those in the Arches or Quintuplet, unless gravitational forces from the black hole disrupt their formation. Such structures, says John Bally, the principal investigator of the survey, "are unique to the Galactic Centre region."

The Galaxy's dark heart

The one structure that is absolutely unique, though, is the supermassive black hole itself. Given its apparent size and proximity to Earth, says Geoffrey Bower of the University of California, Berkeley, it affords astronomers their best chance to image the black hole's event horizon — the boundary beyond which no light can escape.

At the moment, the best observations of the black hole and its accretion disk are those made by a technique that links radio telescopes around the world, called very long baseline interferometry. At a distance of 26,000 light years, an interferometer working at radio wavelengths with a baseline the size of a planet should be able to resolve details as small as the orbit of the Earth. Unfortunately, the radio waves from Sgr A* pass through intervening regions of highly ionized gas, which scatter its radio emissions. "These random distortions blur the image of Sgr A*, much like frosted glass blurs an image," says Bower.

Bower and his peers hope that new generations of interferometers working at millimetre and submillimetre wavelengths, which are less subject to intervening distortion, might in the long run actually reveal the black hole's event horizon[8]. How would that look to outside observers? Depending on its orientation, astronomers think that the relativistic effects of the black hole's intense gravitational field would make the event horizon appear as a large shadow or a silhouette cast on a background of bright plasma, in which the shadow is the boundary where light passes into the throat of the black hole itself.

"This image can be made with a network of millimetre- and submillimetre-wavelength telescopes distributed around the Earth," Bower says. Some of these telescopes already exist. Others, including the largest, the Atacama Large Millimeter Array, are under construction. Lashing them together into an ad-hoc interferometer the size of Earth, though, is a daunting technological challenge. That, says Bower, "is part of the thrill of the chase".

Such an observation would, of course, be a milestone — the first direct proof that an event horizon, and therefore a black hole, exists. And observing 'hot spots' orbiting the black hole would allow astronomers a qualitative way to test the effects of relativity in a strong gravitational field, an endeavour that has so far yielded ambiguous results[9]. The Galactic Centre may no longer be the mystery it was in Shapley or Jansky's day, but the better known it is, the more remarkable it looks — and it promises to become even more remarkable before too long. ■

Jeff Kanipe is a science writer based in Maryland.

1. Jansky, K. *Proc. Inst. Rad. Eng.* **232,** 1158–1163 (1935).
2. Shapley, H. *Contributions from the Mount Wilson Solar Observatory* No. 152 (1918).
3. Becklin, E. E. & Neugebauer, G. *Astrophys. J.* **151,** 145–161 (1968).
4. Lynden-Bell, D. *Nature* **223,** 690–694 (1969).
5. Muno, M. P., Baganoff, F. K., Brandt, W. N., Park, S. & Morris, M. R. *Astrophys. J.* **656,** L69–72 (2007).
6. Ghez, A. M. *et al. Astrophys. J.* **586,** L127–132 (2003).
7. Muno, M. *et al. Astrophys. J.* **622,** L113–116 (2005).
8. Bower, G. C. *J. Phys. Conf. Ser.* **54,** 370–376 (2006).
9. Broderick, A. E. & Loeb, A. *J. Phys. Conf. Ser.* **54,** 448–455 (2006).