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Mapping Clouds at the Galactic Center

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This image appears at first to be a naturalistic picture of something: but it is in fact a diagram. The horizontal axis is spatial — a sweep of the area just left and right of the center of the galaxy. The vertical axis, however, is coded — it records the speed at which clouds of Hydrogen are moving toward or away from the galactic center.

The image does not show visible light, but rather records the intensities of radio wave emission at the specific wavelength of 21 centimeters — so it is a non-naturalistic image that records something that is, in any case, invisible to human eyes. (This is even aside from the fact that it shows a very tiny, faint area in the constellation Sagittarius, which is almost beyond the capacity of unaided vision.)

Reading the graph

The image originally appeared in *Scientific American* in 1974, accompanied by the graphical key reproduced on the next page. To interpret the image, imagine the strip that is apparently left and right of the Galactic center: within it, gases are moving at different speeds, and at different distances from us. The red area on the image has little or no velocity: it represents the Hydrogen in our line of sight, left and right of the Galactic center. Negative values on the *y* axis mean gases moving toward us, and vice versa. The bit of orange and yellow at the right margin, below the red center line, named the "3-kiloparsec arm," is a cloud of Hydrogen moving toward us at about 50 kilometers per second. The green area above, labelled "arm expanding at 135 kilometers per second," is moving away from us.

The lower right of the image is very fast-moving Hydrogen — up to 200 kilometers per second — moving toward us, and the upper left is Hydrogen moving away. In both cases, the high velocities mean the gases are near the Galactic center.

The Center of the Galaxy

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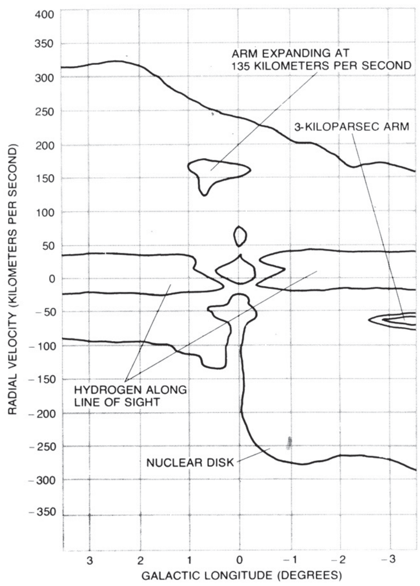
by R. H. Sanders and G. T. Wrixon
April 1974

Coded in the radio, infrared and X-ray emissions from the invisible nucleus of our galaxy is mounting evidence that it is periodically the scene of titanic explosions

Our galaxy is a disk-shaped collection of stars, gas and dust whose components are all bound together by their mutual gravitational attraction. Like an enormous pinwheel it rotates majestically around its mysterious nucleus, or central region. From our vantage near the edge of the disk the nucleus has until quite recently been hidden by clouds of obscuring dust. Within the past 20 years, however, new techniques of "looking" through the dust have been developed, providing us with tantalizing glimpses of the nuclear region. Piecing together observations made through "windows" at wavelengths both longer and shorter than those of visible light, astronomers have become aware of striking similarities between our galactic center and the nuclei of certain bizarre objects called Seyfert galaxies.

Seyfert galaxies are named for Carl K. Seyfert, who in 1943 first classified a group of galaxies according to the unusual properties of their nucleus. They are spiral galaxies (disk-shaped galaxies with luminous spiral arms like our own galaxy) characterized by a small, very bright nucleus embedded in rapidly moving masses of gas that are apparently being ejected from the central region. Seyfert nuclei are also a rich source of infrared radiation and radio waves. Indeed, Seyfert nuclei emit such large amounts of energy and matter that our present laws of physics may be inadequate to explain them.

Quasars, which were discovered in the early 1960's, may be even more extreme examples of the phenomenon seen in Seyfert galaxies. Quasars are very



GAS MOTIONS AT GALACTIC CENTER are displayed in the computer-generated contour map on the opposite page. Based on observations made with the 140-foot radio telescope of the National Radio Astronomy Observatory at Green Bank, W.Va., the map shows the distribution of emission from un-ionized hydrogen at a wavelength of 21 centimeters. The different colors indicate the intensity of the 21-centimeter line, ranging from violet (lowest level) to red (highest level). The vertical axis, as shown at the left, does not indicate galactic latitude but rather the velocity of hydrogen lying in the galactic plane: velocities toward us are negative, velocities away from us are positive. The horizontal red ridge centered at zero velocity represents all the un-ionized hydrogen along the line of sight on either side of the galactic center. The deep hole at the center identifies where 21-centimeter radiation from the powerful radio source known as Sagittarius A is absorbed by un-ionized hydrogen lying between it and us. To the right and just below the central ridge, at a negative velocity of more than 50 kilometers per second, is a fainter ridge produced by emission from the "three-kiloparsec arm." Since the three-kiloparsec arm also produces an absorption line in the output of Sagittarius A, the arm is on this side of the center, and since its velocity is negative it is expanding away from the center and toward us. At the lower right there is a ridge of emission (*blue-and-green feature*) whose maximum velocity exceeds 200 kilometers per second. This ridge is emission from the nuclear disk; its high velocity means that it is very near the galactic center and rotating rapidly. Notice that the velocity approaches zero toward the galactic center. Above and to the left of the center the picture is somewhat ambiguous. The dominant feature is a ridge of emission (*green band*) that crosses the position of the galactic center at +135 kilometers per second; hence it is an expanding arm of gas moving away from us. The absence of an absorption hole at the position of Sagittarius A means that the expanding arm is on the other side of the nucleus. The program for generating the color contour map was devised by Thomas Cram and David Ehnebuske.

In three dimensions

Because we are more or less in the Galactic plane, we see the center edge-on. The image therefore encodes a picture of gases rotating around the center, like the spiral arms of stars in the Galaxy as a whole.

Very high-velocity Hydrogen is rotating close in to the center. Lower-velocity Hydrogen is farther away: one arm swings around toward us, on the right; and a second swings away from us on the left. It is not easy to visualize this, but it is a typical exercise in scientific illustration.

The limits of the image

There are, perhaps, two limitations to this image. First, it has relatively few data points. The isobars are really line segments (made jagged by the large pixels) that connect one data point to the next. That is an insuperable limitation because 21-centimeter radio emissions cannot be made more detailed.

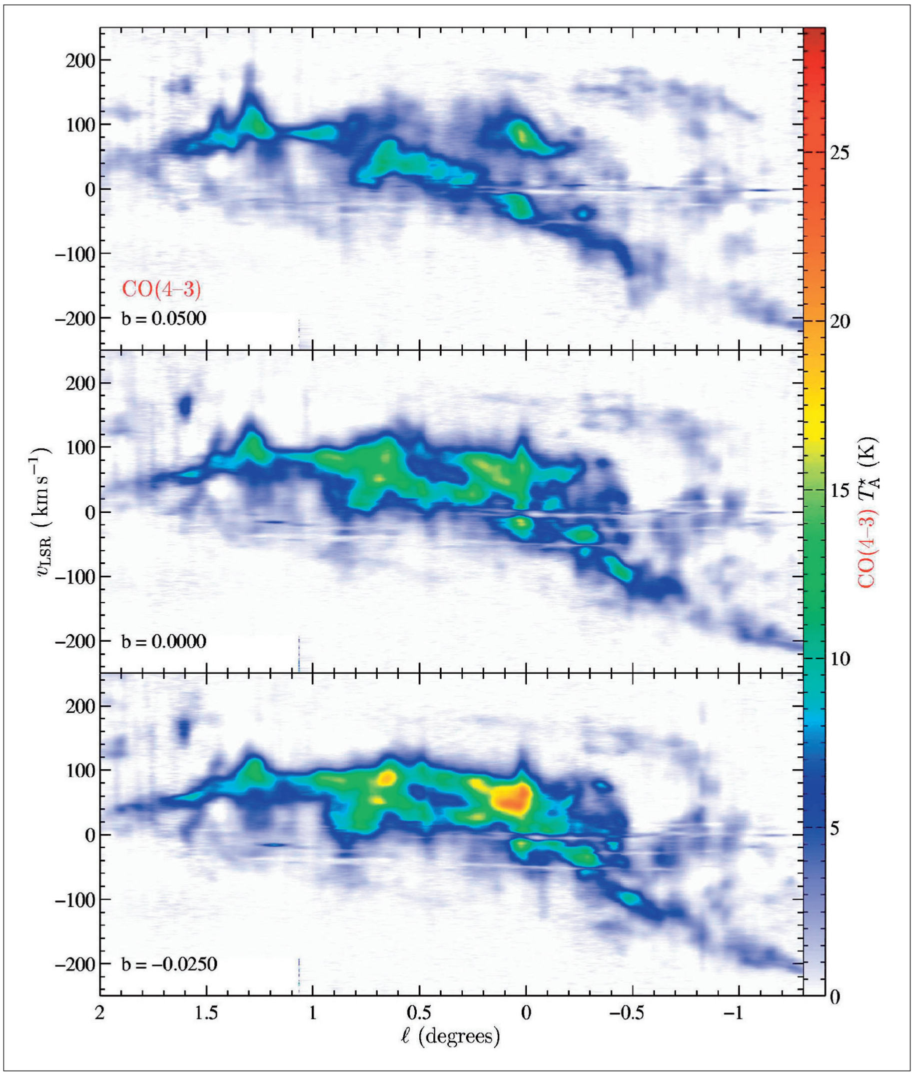
Another limitation comes from the *use* the image was meant to have. In 1974 the idea of black holes was new. To test whether or not a black hole might be present, Sanders and Wrixon made a "model galaxy" simulation on a "large electronic computer" and "observed" it as they observed the actual Galaxy. By changing the mass of the central object, and seeing how the model matched their image, they concluded that whatever lies at the Galactic center could be as large as 200 million solar masses — within the range of a black hole. Thus the image was augmented by a computer model, and would have been incomplete without it.

2004

The first of these limitations — resolution — is easily improved by searching for emissions other than 21 centimeter Hydrogen emissions. Carbon monoxide, for example, has several characteristic emission wavelengths, among them 0.065 centimeters (461 GHz), which are caused by a particular quantum jump in the atoms, from $J = 4 \rightarrow 3$.

In 2004, thirty years after Sanders's and Wrixon's study, a team led by Christopher Martin produced the images reproduced below. Each frame is a longitude-velocity graph like Sanders's and Wrixon's; the middle one samples the Galactic center, and the others show the level (galactic latitude) just above and below it.

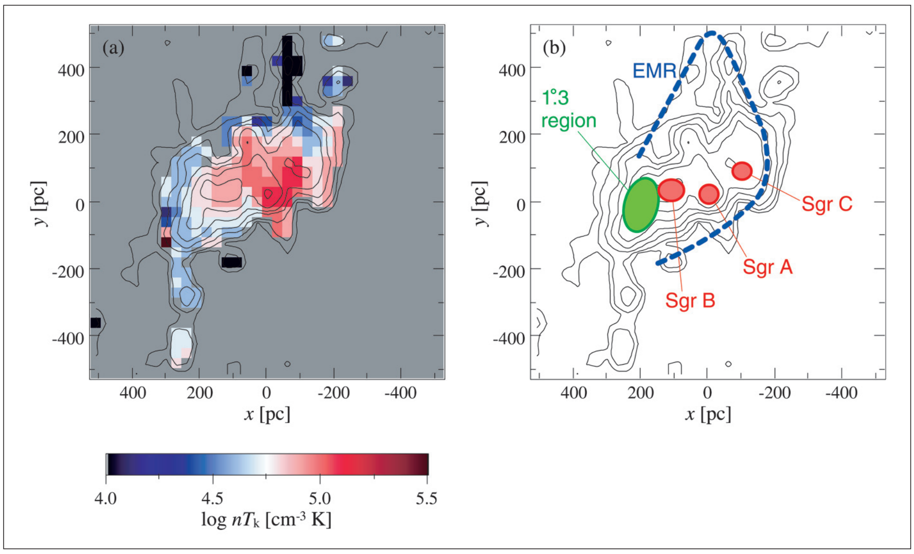
The left-right range in degrees is about the same as Sanders's and Wrixon's diagram, but the smaller wavelength allows much higher resolution. Because these images sample carbon dioxide clouds and not hydrogen, they are hard to compare with the 1974 diagram — and they hint at the complexity of the region.



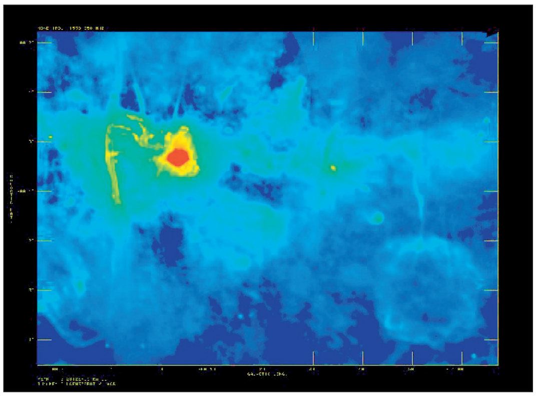
Face-on views

Another recent development is the computer-aided calculation of face-on views, showing the Galactic center "from above." One is shown here.

The center is now known to be comprised of at least three sources, known as Sgr A*, B, and C, and they orbit the Galactic center. This image records gas thermal pressure in another emission line of carbon monoxide. The authors of the study posit a model with four bodies (Sgr A*, B, C, and an object known as the "1.3° region") rotating around one another in two or more spiral arms.



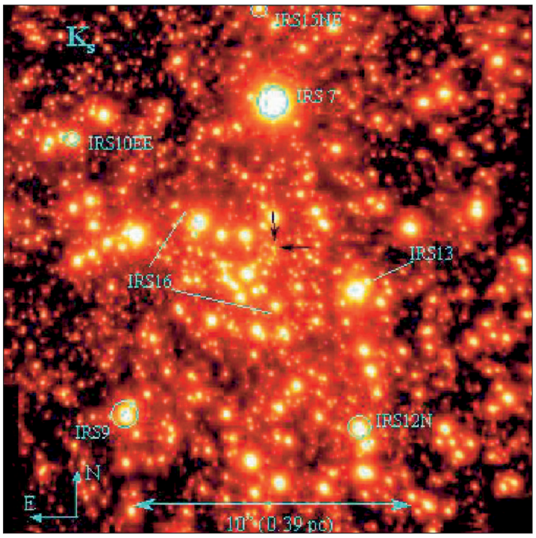
Clouds, shells, arcs…



Martin notes that the region close to the Galactic center has "a complex distribution of emission, which is chaotic, asymmetric, and non-planar, [with] hundreds of clouds, shells, arcs, rings, and filaments." (A little farther from the center, at the distances studied by Sanders and Wrixon, the new study confirms "the gas is loosely organized around closed orbits.") There are even star clusters near the center, named "the Arches" and "the Quintuplet." The picture is gradually becoming more complex, if not clearer.

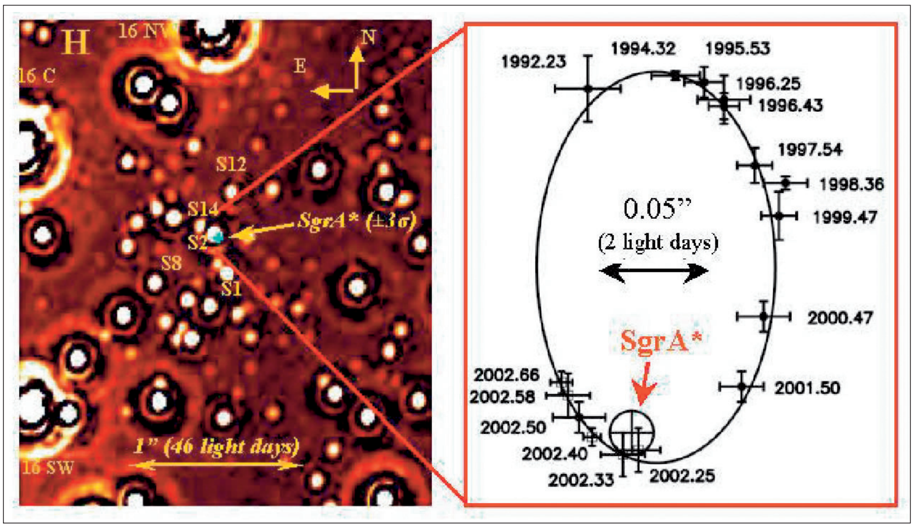
This photo is another radio-frequency image, at 1.4 GHz. F. Yusef-Zadeh, who published this image on January 15, 2005, compares the Galactic center to "a jungle where many species evolve, share the same resources and interact with each other."

Optimal resolution



Recently, too, there has been interest in "non-thermal filaments" (NTFs), long, thin clouds that are only found near the Galactic center. Astronomers have managed to map them in detail even though they are less than an arcminute in apparent length — that is less than one-sixtieth the width of one of the grid squares in the *Scientific American* graph. (For comparison: one arcminute is one-thirtieth the diameter of the full Moon — a tiny portion of the sky.) Yet there is no way to achieve perfect resolution of nebulous objects, because the objects themselves have arbitrarily defined boundaries.

Point-like objects are another matter, and studies of stars at the Galactic center are well advanced. Infrared studies of stars have achieved amazing resolutions. Photo above is about 20 arcminutes wide, about the size of the central black area in the first image.



The bottom photo on the last page, in turn, is a detail of that tiny portion, zooming in on the enigmatic Sagittarius A (marked Sgr A*). The arrow shows the scale: one arcsecond, which is one-sixtieth of the width of one of the squares in the 1974 image. At that resolution it is possible to plot individual stars as they orbit around Sgr A*. (As this book goes to press, scientists at the Max-Planck-Institut für extraterrestrische Physik have released a movie of the motion of the stars in this region, pushing the limits of resolution still further).

What comprises a perfect image?

The conundrum here is the resolution of irresolvable objects. The same problem is of concern in images of the earliest pre-galactic objects at the edge of the visible universe, which will be targets of the Next Generation Space Telescope: they overlap and have no distinct boundaries. What is required is a mathematical constraint on what counts as an "object": a situation far from the concerns of image making in daily life or in art.

Of these images, the one that is most strongly counter-intuitive is the first, because it only appears to be a picture like some later ones. It is, rather, a graph posing as a naturalistic picture — asking to be read, illegitimately, as a picture — a theme that recurs in several of these chapters.

For further reading

Chrisopher Martin et al., "The AST/RO Survey of the Galactic Center Region. I. The Inner 3 Degrees," *ApJS* 150 (2004): 239, plate 6; Tsuyoshi Sawada et al., "A Molecular Face-on View of the Galactic Centre Region," arXiv:astro-ph/0401286 v1 15 Jan 2004, Fig. 11; F. Yusef-Zadeh et al., "Starburst Driven Thermal and Non-thermal Structures in the Galactic Center Region," Fig. 1; T. Ott et al., "Inward Bound: Studying The Galactic Center With Naos/Conica," figs. 1 and 4. See also T. Viehmann et al., "*L*- and *M*-band Imaging Observations of the Galactic Center Region," arXiv:astro-ph/0411798 v1 30 Nov 2004, and Johannes Staguhn et al., "350 µm Galactic Center Dust Observations with SHARC II," arXiv:astro-ph/0412148 v1 6 Dec 2004. For the movie of the stars and the galactic center, see www.mpe.mpg.de/ir/GC/prop.html.