

A Journey to the Center of the Milky Way: Stellar Orbits around its Central Black Hole

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Abstract—The Advanced Visualization Lab at the National Center for Supercomputing Applications created a cinematic scientific visualization showing a flight through the Milky Way galaxy, to the galactic center where stars are orbiting around a supermassive black hole. The visualization required a number of steps including: data processing; data fusion; virtual scene design; camera choreography; compositing; rendering on the Delta supercomputer; and focus groups and surveys with test audiences.

The tour summarizes results from Andrea Ghez's Galactic Center Group: their study of the motions of stars around the Milky Way's central black hole reveals a rich and surprising environment, with hot young stars (coded as purple) where few were expected to be, many orbiting in a common plane; a paucity of cooler old stars (yellow); a population of unexpected "G-object" dusty stars (red); and an eclipsing binary star (teal). The black hole itself, shrouded in mystery, is seen only as a tiny faint twinkling radio source. But the movement of these nearby stars, especially the S0-2 "hero" (pale blue ellipse), probe the black hole's gravity, exposing its massive presence.

Index Terms—scientific visualization, cinematic visualization, explanatory visualization

I. INTRODUCTION

The "Flight to Milky Way Galactic Center Star Orbits" visualization is a collaboration between Dr. Andrea Ghez, Nobel laureate for her discovery of the supermassive black hole residing at the heart of the Milky Way [2], and the Advanced Visualization Lab (AVL) at the National Center for Supercomputing Applications, a Renaissance Team of artists, programmers, and scientists known for crafting cinematic scientific visualizations tailored for public engagement. This

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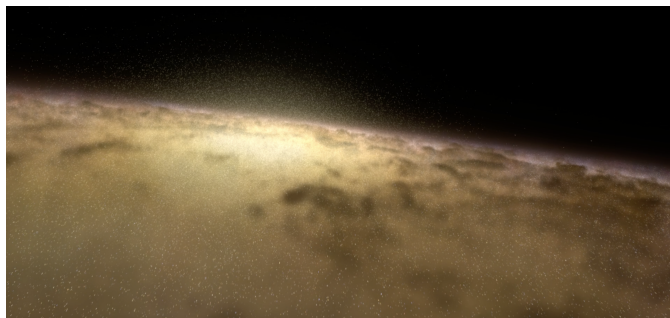


Fig. 1. An early frame in the visualization video, panning over the Milky Way galaxy.

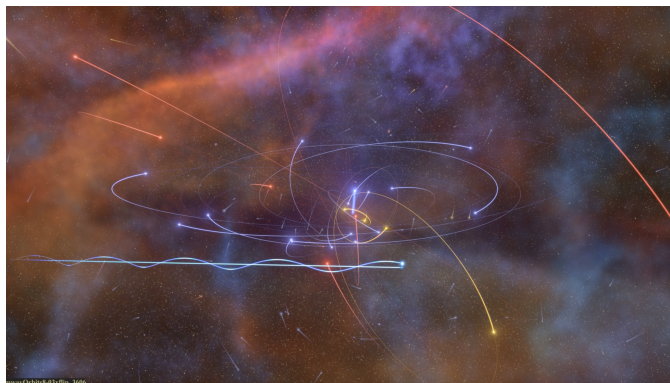


Fig. 2. A later image from the visualization video, showing stellar orbits around our galaxy's central black hole. A binary star system is shown in the foreground.

expedition commences with a view of the entire Milky Way galaxy. From this vantage point, the visualization embarks on a celestial journey toward the enigmatic galactic center, unveiling veils of cosmic clouds and dust that shroud the secrets concealed within. As the voyage unfolds, the focus tightens, revealing a tapestry of stellar orbits ensnared by the gravitational forces emanating from a central supermassive black hole. Among this stellar ballet, a binary star system emerges as time slows, inviting observers to witness the intricate interplay of a colossal, cool star entwined with its diminutive, searing-hot counterpart.

The black hole is represented as a flickering point of light, a tribute to the genuine experience of discovery. This artistic choice resonates with the initial observations of scientists – a faint, enigmatic glimmer that would ultimately unveil itself as the supermassive black hole. This choice, made in collaboration with Dr. Ghez, preserves the mystique surrounding this extraordinary cosmic entity.

Central to the creation of this visualization was a comprehensive scientific endeavor underpinned by a unique social science dimension. Over the span of approximately two years, a dedicated social scientist led the orchestration of focus groups, facilitating a continuous dialogue between the visualization creators and diverse audiences. This strategic emphasis on science communication research ensured that the final visualization not only conveyed scientific authenticity but also captivated a broad spectrum of viewers, from seasoned astronomers to novices exploring the cosmos for the first time.

The visualization video is available online at <https://youtu.be/37fVIgbT4UQ>

II. TECHNICAL DETAILS

The data visualization was created using a combination of tools. The flight through the Milky Way camera choreography was designed in AVL's proprietary Virtual Director software, and rendered with StarRenderer. As we arrive at the Milky Way center, we transition to renders using SideFX's Mantra in the Houdini software, together with Maxon's GPU-accelerated Redshift. The scene was rendered in layers and composited using Foundry's Nuke software. The renders were run on a combination of AVL's local cluster and the Delta supercomputer at the National Center for Supercomputing Applications. Image rendering required about 2000 GPU hours, much of it spent simulating light scattering within clouds of gas in the neighborhood of the galactic center.

III. ASTRONOMICAL INFORMATION UNDERLYING THIS VISUAL PORTRAYAL

The first two minutes of animation carry the viewer through a digital model of our Milky Way, starting about 9500 parsecs from the galactic center. (For comparison, Earth is about 8000 parsecs from that center.) Aspects of the Milky Way disk and bulge – spiral arms, star clusters, dust clouds, ionized-hydrogen regions and so on – were patterned after those of another spiral galaxy generally similar to ours, named M83.

As the tour continues, we pass features in the innermost few hundred parsecs which were created to resemble objects near our own galaxy's center as determined from infrared and radio observations, such as molecular clouds, supernova remnants, radio arcs, and star clusters.

In the innermost 0.1 parsec around the center, the tour encounters the dozens of stars whose orbits and other properties have been mapped by Ghez et al.[2] over more than a quarter century of observation. As the group refined their techniques, they were able to measure not just precise positions of the stars, but also their spectra, yielding new richness of understanding, and new surprises.

The expectation had been that stars near the galaxy's supermassive black hole would all be relatively old, as its tidal influence was expected to disrupt formation of new stars; and that the orientations of orbits would be fairly uniformly distributed. Observations showed otherwise.

In this visualization, "early type" (hot, bluish, presumably young) stars are shown in bluish-purple; "late type" (cool, yellowish, presumably older) stars are shown in yellow; and in red is an unanticipated new class of objects, labeled "G-objects", which have spectra that resemble gas clouds but gravitational behavior that makes them seem like stars (<https://www.keckobservatory.org/g-objects-2>).

Old late-type stars are surprisingly scarce, and young early-type ones surprisingly numerous. Further, we see that the orbits of most of the young stars are arranged in a common plane, suggesting that they had formed in a single cluster of stars which was disrupted by tidal forces. Portraying this plane, and the distribution of stellar types, were specified by the scientists as important aspects of the visual story.

The tour approaches another aspect of this astrophysically rich environment, an eclipsing binary star, briefly slowing down the animation's time scale to show it clearly as we pass. The G-objects are also thought to be related to binary stars: they may be the product of two stars in close orbit about each other which have merged into a single star, surrounded by a loosely-bound, extended cloud of gas.

Around what center do all these stars orbit? It is deliberately not clearly shown in this animation. We see the putative black hole as an inconspicuous flickering point, the radio source Sagittarius A*.

As we approach that center, one particular highly elliptical orbit stands out: the star S0-2, in bright blue, with an orbital period of only about 16 years. This star is the hero of our story. On its first observed close approach, in 2002, it was determined to have come within about 15 billion kilometers of the central massive object – a distance only a couple of times larger than our solar system. Given that that object was known to have around 4 million times the mass of our Sun, this measurement ruled out other explanations for what it might be, clinching the case that it must indeed be a black hole. In 2018, when S0-2 again passed at its closest to the black hole, its motion was used as a test of General Relativity[1].

For the discovery of this supermassive black hole at the center of our galaxy, Andrea Ghez, and Reinhard Genzel whose

group in Germany has been doing similar work, shared half of the 2020 Nobel Prize in Physics (<https://www.nobelprize.org/prizes/physics/2020/summary/>).

A note on scales of space and time: the binary star seen earlier is about 0.1 parsec from the central black hole; S0-2, at its farthest, stands about 0.01 parsec from it, and at closest approach about 0.005 parsec. At that point, the star is moving almost 3% of the speed of light.

During most of this animation, time elapses at about 5 years per animation second, so that each orbit of S0-2 lasts about 3 seconds.

IV. AUDIENCE TESTING

A pivotal aspect of crafting the "Flight to Milky Way Galactic Center Star Orbits" visualization was the integration of participatory audience research [3]. In recognition of the intricate balance between scientific accuracy and captivating engagement, AVL embarked on a qualitative study, a collaborative endeavor between AVL and Science News¹, a renowned science communication organization in the United States. This participatory research aimed to illuminate design choices that would resonate with diverse audiences and enhance the visualization's potential for effective science communication.

Guided by a commitment to inclusivity, the audience researcher from Science News orchestrated participatory focus groups, recruiting participants primarily from STEM organizations, and focusing on Black American youth aged 11 to 17, representing middle and high school students. This approach ensured a broad cross-section of perspectives, fostering a diverse dialogue surrounding the visualization's design choices.

The focus groups followed a meticulous A/B testing structure, an approach chosen to maintain a neutral moderator stance and encourage participants to candidly express their opinions. Within this framework, participants were presented with pre-recorded video options, showcasing alternative design choices that the AVL team was considering. This approach enabled participants to engage with and compare the options, facilitating their involvement in shaping the visualization's narrative.

One critical design choice that engaged the focus groups was the camera path – the visual trajectory guiding the viewer's journey from Earth to the galactic center. Two options were presented: a direct route that traversed the Milky Way's celestial expanse (Camera Test A) and an alternative path that first provided an overview perspective before delving into the galactic center (Camera Test B). The focus group discussions highlighted a clear preference for Camera Test B, which provided an initial context for the viewer and alleviated the sense of disorientation that some participants felt with Camera Test A. The overview perspective of Camera Test B was deemed more self-explanatory, enhancing the audience's ability to comprehend the journey's context.

Additionally, the focus groups engaged with design choices related to color. Two color palette options were presented:

a more intense, saturated palette (Color Test A) and a paler alternative (Color Test B). The consensus among participants was overwhelmingly in favor of the intense color palette (Color Test A), as it was perceived as more vibrant and original, aligning with their expectations of a captivating visualization. This preference extended to color choices that conveyed a stronger sense of authenticity, positively impacting the audience's perception of the visual journey's credibility.

The evidence gathered from these participatory sessions influenced choices related to camera path orientation and color palette selection, resulting in a visualization that harmonized scientific accuracy with audience engagement. Incorporating an audience researcher into the project for its approximately two-year duration underscored AVL's dedication to robust science communication research. This approach facilitated a continuous, real-time feedback loop, allowing AVL to iteratively adapt and refine the visualization in response to the diverse perspectives garnered from the focus groups. As a result, the "Flight to Milky Way Galactic Center Star Orbits" visualization emerged as a collaborative endeavor that marries scientific discovery with effective communication.

REFERENCES

- [1] Tuan Do et al. "Relativistic redshift of the star S0-2 orbiting the Galactic Center supermassive black hole". In: *Science* 365 (6454 2019), pp. 664–668. DOI: 10.1126/science.aav8137. URL: <https://www.science.org/doi/10.1126/science.aav8137>.
- [2] A. M. Ghez et al. "Stellar Orbits around the Galactic Center Black Hole". In: *The Astrophysical Journal* 620.2 (Feb. 2005), p. 744. DOI: 10.1086/427175. URL: <https://dx.doi.org/10.1086/427175>.
- [3] Eric A. Jensen et al. "Evidence-Based Methods of Communicating Science to the Public through Data Visualization". In: *Sustainability* 15.8 (2023). ISSN: 2071-1050. DOI: 10.3390/su15086845. URL: <https://www.mdpi.com/2071-1050/15/8/6845>.

¹www.sciencenews.org