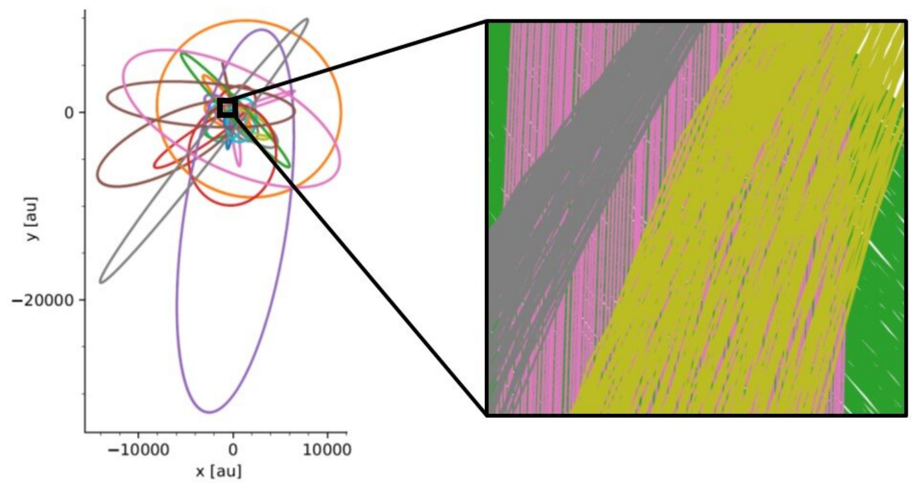
Motion of stars near Milky Way's central black hole is only predictable for a few hundred years

September 13 2023



Simulation of the motions of stars around the black hole at the center of the Milky Way. On the left are shown the orbits of the stars. These orbits have been calculated for 10,000 years. It seems that the stars do not diverge from their orbits. The right panel is a zoom-in near the crowded center. It reveals that the stars have considerable variations along their orbits. The yellow orbit, for example, fluctuates in those 10,000 years in a range of forty times the distance from Earth to sun. Credit: Simon Portegies Zwart et al

The orbits of 27 stars orbiting closely around the black hole at the center of our Milky Way are so chaotic that researchers cannot predict with confidence where they will be in about 462 years. This finding emerges from simulations by three astronomers based in the Netherlands and the United Kingdom. The researchers have published their findings in two papers in the *International Journal of Modern Physics D* and in the *Monthly Notices of the Royal Astronomical Society*.

Simulating 27 stars and their interactions with each other and with the black hole is easier said than done. For centuries, for example, it was impossible to predict the motions of more than two interacting stars, planets, rocks, or other objects. It was only in 2018 that Leiden researchers developed a computer program in which rounding errors no longer play a role in the calculations. With this, they were able to calculate the motions of three imaginary stars. Now the researchers have expanded their program to deal with 27 stars that, by astronomical standards, move close to the black hole at the center of the Milky Way.

The simulations of the 27 massive stars and the black hole resulted in a surprise. Although the stars remain in their orbits around the black hole, the interactions between the stars show that the orbits are chaotic. This means that small perturbations caused by the underlying interactions change the orbits of the stars. These changes grow exponentially and, in the long run, make the star orbits unpredictable.

Black hole relays shock

"Already after 462 years, we cannot predict the orbits with confidence. That is astonishingly short," says astronomer Simon Portegies Zwart (Leiden University, the Netherlands). He compares it to our solar system, which is no longer predictable with confidence after 12 million years.

"So, the vicinity of the black hole is 30,000 times more chaotic than ours, and we didn't expect that at all. Of course, the solar system is about 20,000 times smaller, contains millions of times less mass, and has only eight relatively light objects instead of 27 massive ones, but, if you had asked me beforehand, that shouldn't have mattered so much."

According to the researchers, the chaos emerges each time in roughly the same way. There are always two or three stars that approach each other closely. This causes a mutual pushing and pulling among the stars. This in turn leads to slightly different stellar orbits. The black hole around which those stars orbit is then slightly pushed away, which in turn is felt by all the stars. In this way, a small interaction between two stars affects all 27 stars in the central cluster.

Zooming in on orbits

"We run our simulation for 10,000 years each time. From a bird's eye perspective the stellar orbits seem to remain unchanged with time," says Tjarda Boekholt (a former graduate student of Portegies Zwart in 2015 and now working at the University of Oxford, U.K.). "It is only when you start zooming in on a segment of an orbit that chaotic variations become visible. These variations can reach large values up to forty astronomical units, which is forty times the distance of the Earth to the sun."

The researchers like to compare the chaos at the black hole to cycling through a city. You know approximately how long it takes, but exactly how long is impossible to predict. If a bridge is open, or if somebody jumps in front of your bike, you may arrive minutes later.

"And that's kind of how it works with the stars around the black hole, too," says Portegies Zwart. "You are aware that unexpected events take place regularly, and those cause an exponential change, which we can now measure. But the implication is that the center of the Milky Way with the black hole and the 27 stars orbiting it is no longer predictable with confidence after 462 years. We can no longer reliably predict the positions and velocities of those stars."

For Portegies Zwart and his colleagues, it is not so much the 462 years that matters. "462 years is of course very short, but our point is that as astronomers we have to look differently than we did before at what happens in the vicinity of a black hole," Portegies Zwart said. "And we have to find new words for it. For example, I started building a glossary of definitions with Tjarda Boekholt, simply because there weren't any existing terms that accurately captured this new type of chaotic behavior we were observing."

Punctuated chaos

The researchers coined the phenomenon "punctuated chaos." The term is inspired by evolutionary biology where the opposite occurs: the so-called punctuated equilibrium. That is about evolution within species where there is often a long-term equilibrium that is interrupted only very sporadically by a shocking event.

"Before this research, you didn't know if the chaos in simulations had a physics origin, or if it stemmed from rounding errors and other problems with the calculations," says co-author Douglas Heggie, a retired, but still active mathematician and astronomer at the University of Edinburgh (United Kingdom) and a pioneer in the field of the N-body problem.

"We have put the simulations and the underlying calculations to the test in many ways. Our results hold up as solid. We are now able to make real statements about the chaotic behavior of systems with multiple stars. That's wonderful," Heggie says.

More information: Tjarda C. N. Boekholt et al, Punctuated chaos and indeterminism in self-gravitating many-body systems, *International Journal of Modern Physics D* (2023). DOI: 10.1142/S0218271823420038. On *arXiv*: DOI: 10.48550/arxiv.2308.14803

Simon F Portegies Zwart et al, Punctuated chaos and the unpredictability of the Galactic center S-star orbital evolution, *Monthly Notices of the Royal Astronomical Society* (2023). DOI: 10.1093/mnras/stad2654. On *arXiv*: DOI: 10.48550/arxiv.2308.14817

Provided by Netherlands Research School for Astronomy