Into the abyss: Understanding black hole formation through natal kicks and neutrino emission

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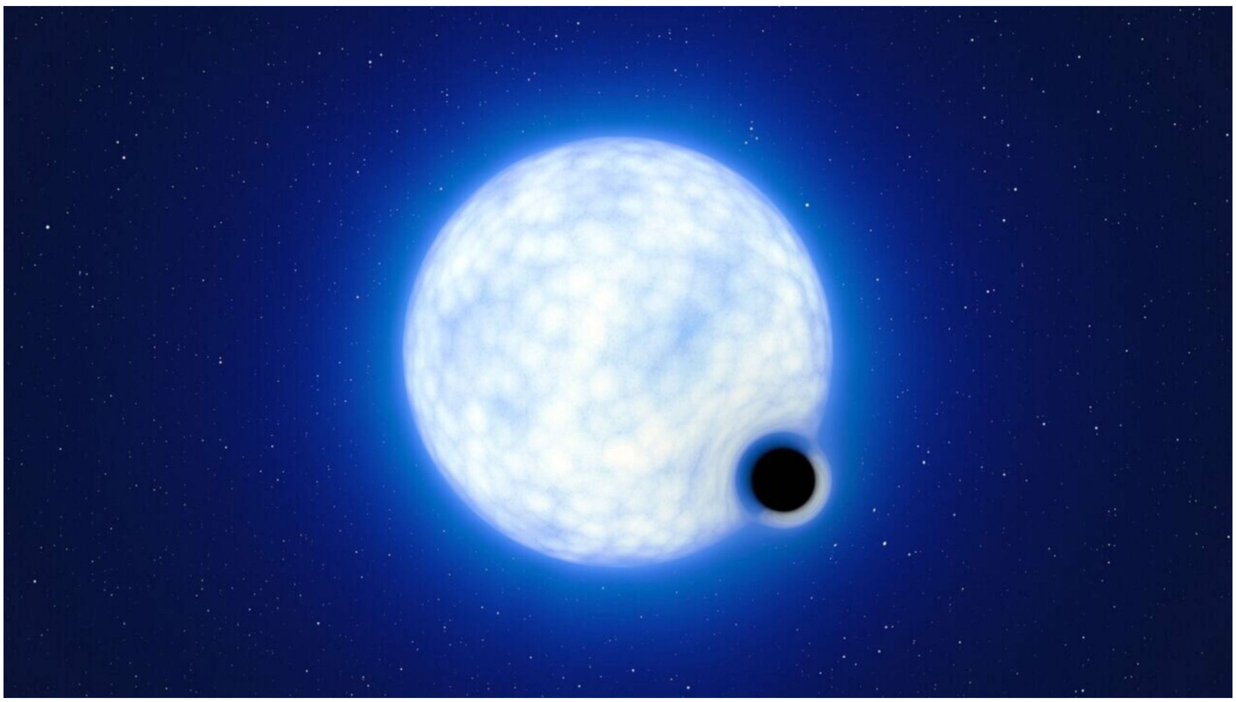

An artist's impression of VFTS 243 in the Tarantula Nebula. Credit: ESO/L. Calçada. eso.org/public/images/eso2210a/

A new study in *Physical Review Letters* explores the conditions of black hole formation from dying stars, particularly the role of neutrino-induced natal kicks in the formation process.

Black holes are some of the most mysterious objects in the universe, with gravitational forces so strong that even light can't escape them. As of now, with the evidence we have, black holes are stellar corpses, meaning they are born when stars die.

However, the exact mechanisms of their formation are still a mystery. The new study addresses some of these mysteries by studying processes like stellar mass ejection and neutrino emission, which play a crucial role in black hole formation.

Phys.org spoke to first author Dr. Alejandro Vigna-Gómez, a postdoctoral fellow at the Max Planck Institute for Astrophysics in Germany.

When asked about his motivation to study black hole formation, he said, "Over the past decade, my work has revolved around the intersection of binary star and supernova physics."

"My interest has grown in the wake of recent breakthroughs in black hole astronomy. In recent years, I realized that heavy black holes could offer significant insights into the processes of stellar collapse that result in their creation."

Natal kicks and neutron stars

When a star bigger than our sun reaches the end of its life, it leads to an extremely bright and violent explosion called a supernova explosion. These explosions are so bright that they can outshine the luminosity of an entire galaxy briefly and release a large number of neutrinos to leave behind a neutron star.

The stellar mass ejected during the explosion has a velocity of thousands of kilometers per second but is not always equally distributed. This asymmetry leads to large-scale asymmetries in the remnants of the explosion, which has been observed for neutron stars.

This asymmetric ejected mass causes a recoil to the neutron star called a natal kick, which causes it to move at high speeds throughout a galaxy. Natal kicks have been previously seen for neutron stars but not for black holes.

Black holes are formed when, instead of an explosion, a dying star collapses in on itself. So, we come to the question posed by the researchers: Could natal kicks also play a role in the formation of black holes?

Black hole binaries

"In recent years, several black-hole binaries have been discovered within our galaxy and its surroundings. They are usually detected via X-ray emission, but only a few have been detected via single-lined spectroscopy [a different method] as X-ray-quiet binaries," said Dr. Vigna-Gómez.

These binary systems do not emit significant amounts of X-rays, which can be indicative of the stages of evolution of the stars in the binary system.

The researchers chose the galaxy VFTS 243 for their study as it houses one of the most massive black holes among these binaries.

The binary system consists of a black hole and a massive star. The researchers wanted to study the conditions under which the black hole was formed like the stellar mass lost and the natal kicks associated with its formation.

The researchers were building on recent observations of disappearing stars, which are stars that died and became black holes without an explosion. Additionally, these stellar-mass black hole binaries (this is the official term) are inert, meaning that there is little interaction between the star and black hole after the black hole is formed.

Constraints on natal kick

The researchers used a semianalytic approach to calculate the probability that a natal kick during the formation of the black hole would lead to the observed configuration of the system.

For analyzing the formation of the system, the researchers used various constraints like orbital period, eccentricity, and systemic radial velocity of the system. They additionally performed estimations for long-term neutrino asymmetries during the formation of the black hole (assuming that it happened due to a complete collapse and not an explosion).

Dr. Vigna-Gómez summarized the findings, saying, "We find that the black hole of VFTS 243 formed without an explosion and had a low neutrino natal kick, if any. This suggests that neutrinos were emitted nearly equally in all directions when the massive progenitor collapsed into a black hole."

For VFTS 243, the researchers constrained the natal kick velocity to be less than or equal to about 10 kilometers per second. They found that the most likely scenario is that approximately 0.3 solar masses were ejected, presumably in neutrinos, and the black hole experienced a natal kick of about 4 kilometers per second.

Future work

These findings have implications for the formation of other black holes, suggesting that some can be formed via complete collapse, with no explosion.

Further, long-term neutrino emission is preferentially spherically symmetric (equal in all directions), which explains the lack of a strong natal kick to the binary system.

Dr. Vigna-Gómez added, "It seems that the theoretical intuition we have built on black holes having reduced natal kicks with respect to neutron stars was right."

"This analysis shows that VFTS 243 can be used as a benchmark system for the simulation of core-collapse supernovae, i.e., simulations of stars that collapse into black holes that are around ten solar masses should align with the small neutrino asymmetries and natal kicks that we inferred for VFTS 243."

Building frameworks for a population of black holes would be the next step for the researchers in their attempt to understand the evolution of massive stars.

More information: Alejandro Vigna-Gómez et al, Constraints on Neutrino Natal Kicks from Black-Hole Binary VFTS 243, *Physical Review Letters* (2024). DOI: 10.1103/PhysRevLett.132.191403.

black-hole-formation-natal.html