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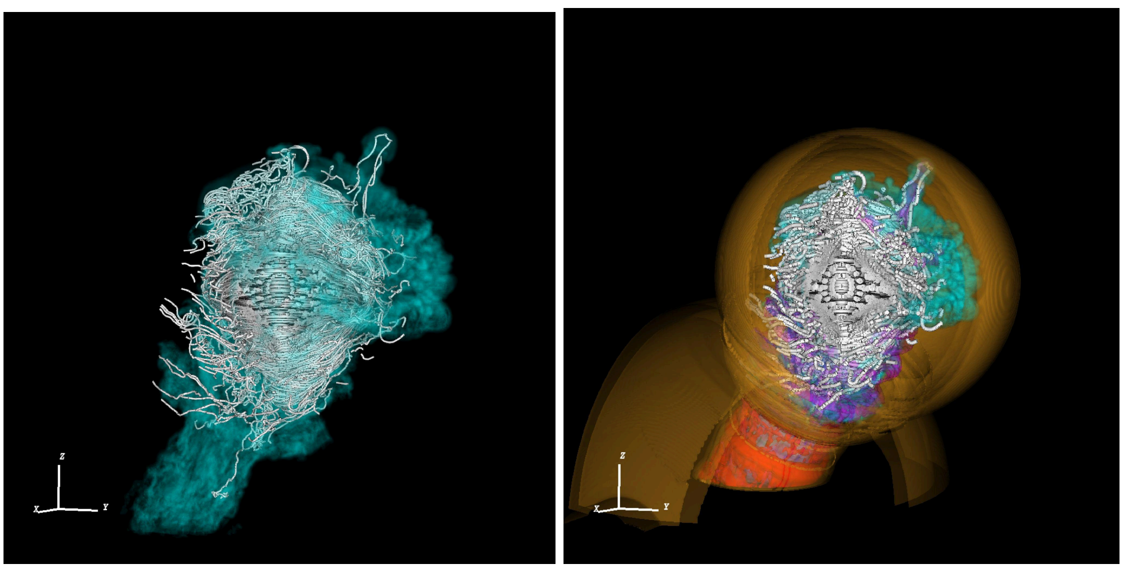
New simulations hint pulsar nebulae are influenced by the evolution of their progenitor stars

- A recent study led by ICE-CSIC researchers shows the shape and emission properties of pulsars' nebulae are directly influenced by the past evolutionary history of their progenitor stars.
- The team used three-dimensional simulations to model the nebula created by a runaway pulsar from a massive star which evolved and died as a red supergiant.



Rendering of the 3D magnetohydrodynamic pulsar wind nebula models, considered without and with their complex environments shaped by their progenitor star before the explosion. The various colors highlight the stellar wind bubble created by the pulsar's massive progenitor star throughout its life and the materials therein. The white tubes trace the magnetic field lines in the pulsar wind. Credits: Meyer, et al. (2025). 3D magnetohydrodynamic simulations of runaway pulsars in core-collapse supernova remnants. A&A, 696, L9.

Pulsars are a type of neutron star with a very fast rotation and strong magnetic fields that form following a supernova explosion. When a supernova explosion is asymmetric, it can give the pulsar a powerful 'kick', accelerating it to supersonic speeds. As the pulsar moves, the nebula formed by its wind interacts with the surrounding environment, significantly altering its shape. A new study led by the Institute of Space Sciences (ICE-CSIC) published in a letter to the editor of the *Astronomy & Astrophysics* journal proves that the shape and emission properties of these nebulae are directly influenced by the past evolutionary history of their progenitor stars.

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Initially, the pulsar crosses the expanding remains of the supernova, and then encounters different layers of gas and dust expelled during the progenitor star's evolution. The team modelled the nebula created by a runaway pulsar from a red supergiant using three-dimensional magnetohydrodynamic simulations with the PLUTO code, a numerical code for computational astrophysical fluids. It is a widely-used software which permits to simulate astrophysical plasma in general and those of stellar environments in particular.

The team, composed by researchers from ICE-CSIC and the Observatory of Paris (France), used the MareNostrum Supercomputer at the Barcelona Supercomputer Centre (BSC) and the Lise supercomputer, a high-performance computing system operated by the North German Supercomputing Alliance (HLRN). The final models took 500,000 cpu-hours each to process.

"Those simulations, the most computationally-intensive of my career, show that the fields of massive star evolution and pulsar physics are intrinsically linked together, which opens a wide avenue to explore", says Dominique Meyer, ICE-CSIC postdoctoral researcher.

This study proves the physical properties and physical appearances of the wind nebulae forming around young fast-moving pulsars depend strongly on the past stellar evolution history of their progenitor star. The new 3D results show the progenitor history must be definitely taken into account to better constrain the environments of pulsars. So far, this element has been ignored in scientific studies.

"The stellar history upon the nebula environment was never considered before, since at most fixed, constant densities in the interstellar medium were assumed. However, what the nebula finds when colliding with the medium is significantly dependent over the full history of the progenitor star, ultimately affecting its morphology. We need ways to deal with these effects in a computationally effective fashion", explains Diego F. Torres, Research Professor from Catalan Institution for Research and Advanced Studies (ICREA) at the ICE-CSIC and the Institute of Space Studies of Catalonia (IEEC).

Pulsar wind nebula

Pulsars are among the possible final evolutionary stages of massive stars. A pulsar also has a wind and charged particles that form a nebula around it: a pulsar wind nebula. The structure of its surrounding area confines and reshapes the nebula, bending its side jets inward and giving it an arched shape. This has been observed in pulsars, such as: PSR J1509–5850 —located about 12,000 light years from Earth, that generated a long tail of X-ray emission trailing behind it—

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and Geminga, —about 500 light-years from Earth, it has one long, narrow particle structure directly behind it and arching trails of particles spanning a distance of half a light-year—.

“What’s fascinating about this work is the possibility to discover to what extent the evolution of a massive star has an impact on the environments of pulsars through the wind nebula formed afterwards. And this even though massive stars blew their strong winds millions of years before dying as a supernova”, explains Meyer. This research proves not only their fast motion shape the nebulae, as believed so far, but the way its massive ancestor lived too.

Therefore, the results obtained imply the need for a reconsideration of the numerical simulations of pulsar wind nebula performed so far, such as those modelled of the Crab nebula (the most famous example of a pulsar wind nebula), as well as a revision of current interpretations of observations of pulsar wind nebulae and plerionic supernova remnants (a nebula powered by the relativistic wind of its central rotating compact object).

The results shown in the study bring the field of stellar evolution of massive stars together with the field of pulsar wind nebulae, letting the door open to new research possibilities. For instance, studying the stellar history of historical pulsar wind nebulae like Gemina or Crab nebula.

“The pay-off of this pilot model is enormous, as it calls for a complete revision of the knowledge on pulsar wind nebulae”, adds Meyer.

More information

Meyer, D. M.-A. et al., incl. Torres, D. F. Torres (2025). *3D magnetohydrodynamic simulations of runaway pulsars in core-collapse supernova remnants*. A&A, 696, L9. https://doi.org/10.1051/0004-6361/202452991

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