ALMA observations show how double, triple, quadruple and quintuple star systems form simultaneously in a molecular cloud

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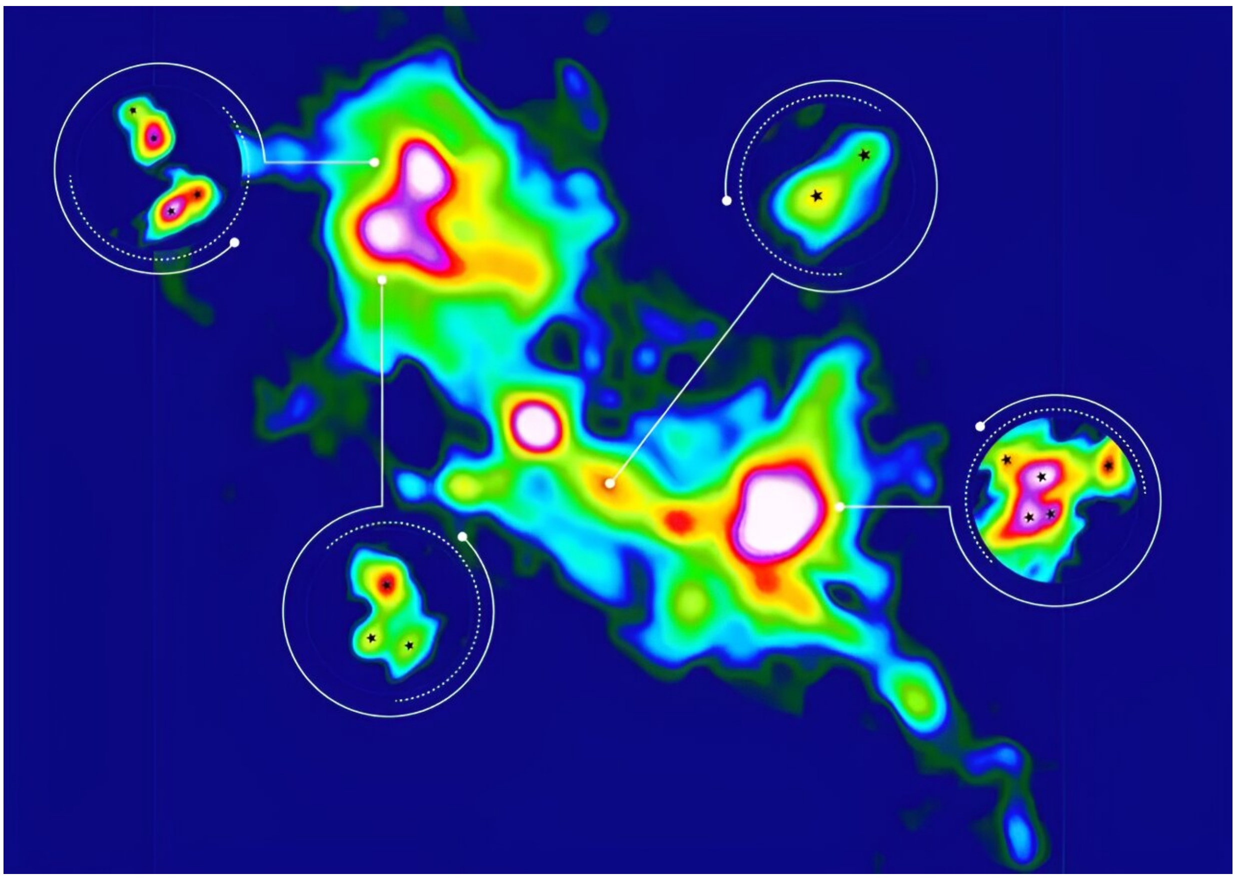

False-color image of the massive star formation region G333.23–0.06 from data obtained with the ALMA radio observatory. North is to the left. The insets show regions in which Li et al. were able to detect multiple systems of protostars. The star symbols indicate the location of each newly forming stars. The image covers a region 0.62 by 0.78 light-years in size (which on the sky covers a mere 7.5

times 9.5 arc seconds). For comparison: If you look at the sky along an outstretched thumb, it spans a viewing angle of around two degrees. One degree corresponds to 3600 arc seconds. Credit: S. Li, MPIA / J. Neidel, MPIA Graphics Department / Data: ALMA Observatory

For humans, the chance of giving birth to multiples is less than 2%. The situation is different with stars, especially with particularly heavy stars. Astronomers observe stars that are many times heavier than the sun in more than 80% of cases in double or multiple systems. The key question is whether they were also born as multiples, or whether stars are born alone and approach each other over time.

Multiple births have long been the norm for massive stars. At least on the computer, because in theoretical simulations huge clouds of gas and dust tend to collapse and form multiple systems of massive stars. These simulations depict a hierarchical process in which larger cloud portions contract to form denser cores, and where smaller regions within those "parent cores" collapse to form the separate stars: massive stars, but also numerous less massive stars.

And astronomers do indeed find a wealth of fully formed multiple star systems, especially stars that weigh many times more than the sun. However, this does not yet prove that multiple systems with massive stars are already forming in the primordial cloud, as predicted by simulations.

ALMA observes a massive star cluster

Systematic observations with the ALMA radio observatory, a network of sensitive radio telescopes that can observe the cold molecular gas from which stars are formed at very high resolution, have now shown for the first time that the computer simulations are correct. The images from the ALMA telescope show that a single molecular cloud does not only give rise to binary star systems. They observe the beginnings of a wealth of different multiple systems. Our sun was probably also formed in such a mixture.

It is very difficult to observe star formation regions in sufficient detail. Observations had, up to that point, been able to show only a few candidates for isolated multiples in massive star clusters, but nothing like the teeming crowd of multiples predicted by the simulations.

In order to confirm or rule out the current models of massive star formation, it was clear that more detailed observations were needed. This became possible once the ALMA observatory in Chile became operational. In its present form, ALMA combines up to 66 radio antennae to act as a single gigantic radio telescope, allowing radio observations that show exquisitely small details.

Led by Patricio Sanhueza of the Japanese National Observatory NAOJ and the Graduate University for Advanced Studies in Tokyo, and including several researchers from the Max Planck Institute for Astronomy in Heidelberg, a group of astronomers set out to observe 30 promising massive star-formation regions with ALMA between 2016 and 2019.

Analyzing the data proved a considerable challenge, and took several years. Each separate observation yields around 800 GB of data, and reconstructing images from the contributions of all the different antennae is a complex process.

The result that has now been published is based on the analysis of one of the star-formation regions, which has the catalogue number G333.23–0.06. The analysis was led by MPIA's Shanghuo Li, who is also the lead author of the resulting paper that has now been published in *Nature Astronomy*. It is titled "Observations of high-order multiplicity in a high-mass stellar protocluster."

The resulting reconstructed images are remarkable: They show details down to about two hundred astronomical units (200 times the Earth-sun distance) for a large region about 200,000 astronomical units across.

How stars are forming

The results are excellent news for the current picture of massive star formation. In G333.23–0.06, Li and his colleagues found four binary proto-stars, one triple, one quadruple and one quintuple system—consistent with the expectations. In fact, the observations of the environments bolster a particular scenario for high-mass star-formation. They provide evidence for hierarchical star formation, where the gas cloud first fragments into "cores" of increased gas density, and where each core then fragments into a multiple proto-star system.

Henrik Beuther, who leads the Star Formation group in the Planet and Star Formation department at the Max Planck Institute for Astronomy, says, "Finally, we were able to take a detailed look at the rich array of multiple star systems in a massive star formation region! Particularly exciting is that the observations go as far as to provide evidence for a specific scenario for high-mass star formation."

Shanghuo Li, an astronomer at the Max Planck Institute for Astronomy and the current publication's lead author, adds, "Our observations seem to indicate that when the cloud collapses, the multiples form very early on. But is that really the case? Analyses of additional star formation regions, some of them younger than G333.23–0.06, should give us the answer."

Specifically, the astronomers are currently working on a similar analysis for the additional 29 massive star formation regions they had observed—soon to be joined by 20 more, with new ALMA observations led by Li. That should allow farther-reaching statistics on the properties of such regions, and insight into the evolution of the multiples. But even with the present results, the role of multiples in massive star formation is now firmly anchored in observation.

Huge explosions and the shaking of space–time

Massive stars with more than eight times the mass of the sun, which form multiple star systems, are of particular interest to astronomers: The most massive stars shine much brighter than our sun and are wasteful with their energy supply. They die up to a thousand times earlier than lower-mass stars like our sun.

If the star system remains bound after the stars die with supernova explosions, neutron stars and black holes remain, orbiting each other. When black holes merge, they emit gravitational waves, which detectors been able to measure since a few years. Collisions of neutron stars are also particularly exciting. The heaviest elements known to us, such as gold, are demonstrably formed in such kilonovae.

More information: Shanghuo Li et al, Observations of high-order multiplicity in a high-mass stellar protocluster, *Nature Astronomy* (2024). DOI: 10.1038/s41550-023-02181-9

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