AstroTalk: Behind the news headlines of July 2017

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Starbirth and violent death: now directly observable in unprecedented detail

Supernovae—the violent end phases of the brief yet brilliant lives of massive stars—are among the most cataclysmic events in the Universe. Although they mark the death of stars, they also trigger the birth of new elements and the formation of new molecules.

In February 1987, astronomers witnessed one of these events unfold in the Large Magellanic Cloud, a small, nearby dwarf galaxy shepherding our Milky Way galaxy. Since then, observations of the remnant of that explosion have revealed never-before-seen details about the death of stars and how atoms created in those stars—like carbon, oxygen, and nitrogen—spill out into space and combine to form new molecules and dust. These newly formed particles may eventually find their way into future generations of stars and planets.

Recently, astronomers used the Atacama Large Millimetre/submillimetre Array (ALMA)—a cutting-edge radio observatory located in Chile—to probe the heart of this supernova, nicknamed SN 1987A. ALMA's ability to see very fine details allowed the researchers to produce an intricate three-dimensional rendering of newly formed molecules inside the supernova remnant. The researchers also discovered a variety of previously undetected molecules in the remnant.

> "*When this supernova exploded, now more than 30 years ago, astronomers knew much less about the way these events reshape interstellar space and how the hot, glowing debris from an exploded star eventually cools and produces new molecules*," said Rémy Indebetouw, an astronomer at the University of Virginia and the U.S. National Radio Astronomy Observatory (NRAO).
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> "*Thanks to ALMA, we can finally see cold 'star dust' as it forms, revealing important insights into the original star itself and the way supernovas create the basic building blocks of planets*."

Prior to the ongoing investigations of SN 1987A, there was only so much astronomers could say about the impact of supernovae on their surrounding, interstellar neighbourhoods.

It was well understood that massive stars, those approximately 10 times the mass of our Sun or more, ended their lives in spectacular fashion. When these stars run out of fuel, there is no longer enough heat and energy to fight back against the force of gravity. The outer surface of the star, once held up by the power of fusion, then comes crashing down on the core with tremendous force. The rebound of this collapse triggers a powerful explosion that blasts material into space.

As the final stage in the life of massive stars, scientists have learned that supernovae have far-reaching effects on their home galaxies.

> "*The reason some galaxies have the appearance that they do today is in large part because of the supernovae that have occurred in them*," Indebetouw said. "*Though less than 10% of stars become supernovae, they nonetheless are key to the evolution of galaxies*."

Throughout the observable Universe, supernovae are quite common, but since they appear (on average) about once every 50 years in a galaxy the size of the Milky Way, astronomers have precious few opportunities to study one from its first detonation to the point where it cools enough to form new molecules. Although SN 1987A is not located in our home galaxy, it is still close enough for ALMA and other telescopes to study in great detail.

For decades, radio, optical, and even X-ray observatories have studied SN 1987A, but obscuring dust in the remnant made it difficult to analyse the supernova's inner core. ALMA's ability to observe at millimetre wavelengths—a region of the electromagnetic spectrum between infrared and radio emission—makes it possible to see through the intervening dust.

The researchers were therefore able to study the abundance and location of newly formed molecules, especially of silicon monoxide (SiO) and carbon monoxide (CO), which shine brightly at the short 'submillimetre' wavelengths that ALMA can perceive.

The new ALMA image and animation show vast new stores of SiO and CO in discrete, tangled clumps within the core of SN 1987A. Scientists previously modelled how and where these molecules would appear. With ALMA, the researchers finally were able to capture images with sufficiently high resolution to confirm the structure inside the remnant and test those models.

Aside from obtaining this 3D image of SN 1987A, the ALMA data also reveal compelling details about how its physical conditions have changed and continue to change over time. These observations also provide insights into the physical instabilities inside a supernova.

Earlier observations with ALMA verified that SN 1987A produced an enormous amount of dust. The new observations provide even more details on how the supernova made the dust as well as the type of molecules found in the remnant.

> "*One of our goals was to observe SN 1987A in a blind search for other molecules*," said Indebetouw. "*We expected to find carbon monoxide and silicon monoxide, since we had previously detected these molecules*."

The astronomers, however, were excited to find the previously undetected molecules formyl cation (HCO^+) and sulfur monoxide (SO).

> "*These molecules had never been detected in a young supernova remnant before*," noted Indebetouw. "*HCO^+ is especially interesting, because its formation requires particularly vigorous mixing during the explosion*."

Stars forge elements in discrete, onion-like layers. As a star goes supernova, these once well-defined bands undergo violent mixing, helping to create the environment necessary for molecule and dust formation.

The astronomers estimate that about one in a thousand silicon atoms from the exploded star is now found in free-floating SiO molecules. The overwhelming majority of the silicon has already been incorporated into dust grains. Even the small amount of SiO that is present is one hundred times greater than predicted by dust-formation models.

It was previously thought that the massive explosions of supernovae would completely destroy any molecules and dust that may have been already present. However, the detection of these unexpected molecules suggests that the explosive death of stars could lead to clouds of molecules and dust at extremely cold temperatures, which are similar conditions to those seen in a stellar nursery where stars are born.

These new observations will aid astronomers in refining their models. These observations also find that 10% or more of the carbon inside the remnant is currently in CO molecules. Only a few out of every million carbon atoms are in HCO^+ molecules.

> Dr. Mikako Matsuura (Cardiff University, UK) said, "*This is the first time that we've found these species of molecules within supernovae, which questions our long-held assumptions that these explosions destroy all molecules and dust that are present within a star*."
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> "*Our results have shown that as the leftover gas from a supernova begins to cool down to below 200°C, the many heavy elements that are synthesised can begin to harbour rich molecules, creating a dust factory*."
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> "*What is most surprising is that this factory of rich molecules is usually found in conditions where stars are born. The deaths of massive stars may therefore lead to the birth of a new generation.*"

ALMA is rapidly becoming the observational facility of choice for investigations of both the earliest phases of star formation and the details of stellar death throes. Like stellar death in the form of supernova explosions, star birth can also be a violent and explosive event.

A massive protostar, deeply nestled in its dust-filled stellar nursery, recently roared to life, shining nearly 100 times brighter than before. This outburst, apparently triggered by an avalanche of star-forming gas crashing onto the surface of the star, supports the theory that young stars can undergo intense growth spurts that reshape their surroundings.

Astronomers made this discovery by comparing new ALMA observations with earlier observations from the Submillimeter Array (SMA) in Hawai'i.

> "*We were amazingly fortunate to detect this spectacular transformation of a young, massive star*," said Todd Hunter (NRAO). "*By studying a dense star-forming cloud with both ALMA and the SMA, we could see that something dramatic had taken place, completely changing a stellar nursery over a surprisingly short period of time*."

The initial SMA observations revealed what appeared to be a typical protocluster: a dense cloud of dust and gas harbouring several still-growing stars. Young stars form in these tightly packed regions when pockets of gas become so dense that they begin to collapse under their own gravity. Over time, disks of dust and gas form around these nascent stars and funnel material onto their surfaces, helping them grow.

The new ALMA observations, taken in 2015 and 2016, reveal that dramatic changes occurred toward a portion of the protocluster after the original SMA observations. This region is now about four times brighter at millimetre wavelengths, meaning that the central protostar is nearly 100 times more luminous than before.

The astronomers speculate that leading up to this outburst, an uncommonly large clump of material was drawn into the star's accretion disk, creating a logjam of dust and gas. Once enough material accumulated, the logjam burst, releasing an avalanche of gas onto the growing star. This extreme accretion event greatly increased the star's luminosity, heating the surrounding dust observed with ALMA.

> "*These observations add evidence to the theory that star formation is punctuated by a sequence of dynamic events that build up a star, rather than a smooth continuous growth*," concluded Hunter. "*It also tells us that it is important to monitor young stars at radio and millimetre wavelengths, because these wavelengths allow us to peer into the youngest, most deeply embedded star-forming regions.*"

Another example of the power of ALMA came to light in April of this year. Around 500 years ago, a pair of adolescent protostars had a perilously close encounter that blasted their stellar nursery apart. Earlier this year, astronomers used ALMA to examine the widely scattered debris from this explosive event, gaining new insights into the sometimes-fierce relationship among sibling stars.

Shortly after starting to form some 100,000 years ago, several protostars in the Orion Molecular Cloud 1 (OMC-1), a dense and active star factory about 1,500 light-years from Earth just behind the Orion Nebula, latched onto each other gravitationally and gradually drew closer.

Eventually, two of these stars either grazed each other or collided, triggering a powerful eruption that launched other nearby protostars and hundreds of giant streamers of dust and gas into interstellar space at speeds greater than 150 kilometres per second. This cataclysmic interaction released as much energy as our Sun emits over the course of 10 million years.

Today, the remains of this spectacular explosion are visible from Earth.

> "*What we see in this once calm stellar nursery is a cosmic version of a 4th of July fireworks display, with giant streamers rocketing off in all directions*," said John Bally (University of Colorado, USA), referring to the U.S. independence day celebrations annually held on the 4th of July.

Groups of stars such as those in OMC-1 are born when a cloud of gas hundreds of times more massive than our Sun begins to collapse under its own gravity. In the densest regions, protostars form and begin to drift about randomly. Over time, this random motion can dampen, which allows some of the stars to fall towards a common centre of gravity, usually dominated by a particularly large protostar.

If these stars draw too close to each other before they drift away into the galaxy, violent interactions can occur. According to the researchers in Bally's team, such explosions are expected to be relatively short lived, with the remnants like those seen by ALMA lasting only centuries.

> "*Though fleeting, protostellar explosions may be relatively common*," said Bally. "*By destroying their parent cloud, as we see in OMC-1, such explosions may also help to regulate the pace of star formation in these giant molecular clouds*."

Bally and his team observed this feature previously with the Gemini South telescope in Chile. These earlier images, taken at near-infrared wavelengths, reveal the remarkable structure of the streamers, which extend nearly a light-year from end to end.

Hints of the explosive nature of this outflow were first uncovered in 2009 with the SMA. The new ALMA data, however, provide much greater clarity, unveiling important details about the distribution and high-velocity motion of the CO gas inside the streamers. This helps astronomers understand the underlying force of the blast and the impact such events could have on star formation across the Milky Way galaxy.

> "*People most often associate stellar explosions with ancient stars, like a 'nova' eruption on the surface of a decaying star or the even more spectacular supernova death of an extremely massive star*," Bally said. "*ALMA has given us new insights into explosions on the other end of the stellar life cycle, star birth*."

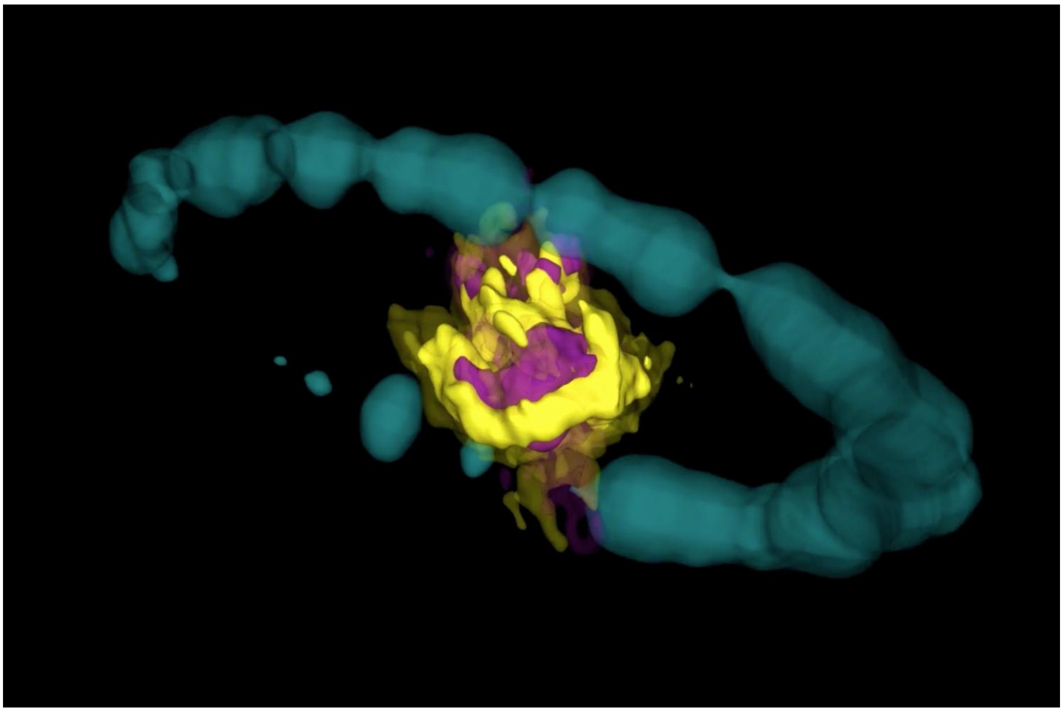

Figure 1: Remnant of Supernova 1987A as seen by ALMA. The purple area indicates emission from SiO molecules; the yellow area is emission from CO molecules. The blue ring is Hubble Space Telescope data that has been artificially expanded into 3D. (*Credit: ALMA (ESO/NAOJ/NRAO); R. Indebetouw; NASA/ESA Hubble Space Telescope*)

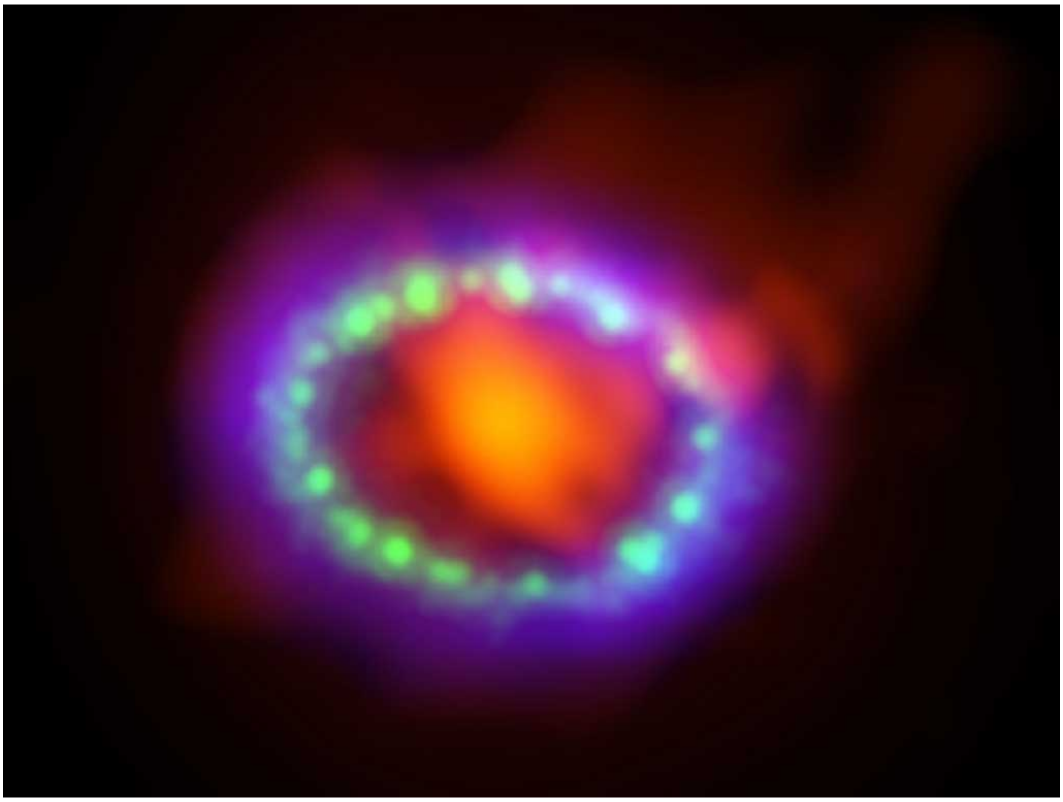

Figure 2: Composite image of supernova 1987A. ALMA data (in red) show newly formed dust in the centre of the remnant. Hubble Space Telescope (green) and Chandra X-ray Observatory (blue) data show the expanding shockwave. (*Credit: Alexandra Angelich (NRAO/AUI/NSF); NASA Hubble; NASA Chandra*)

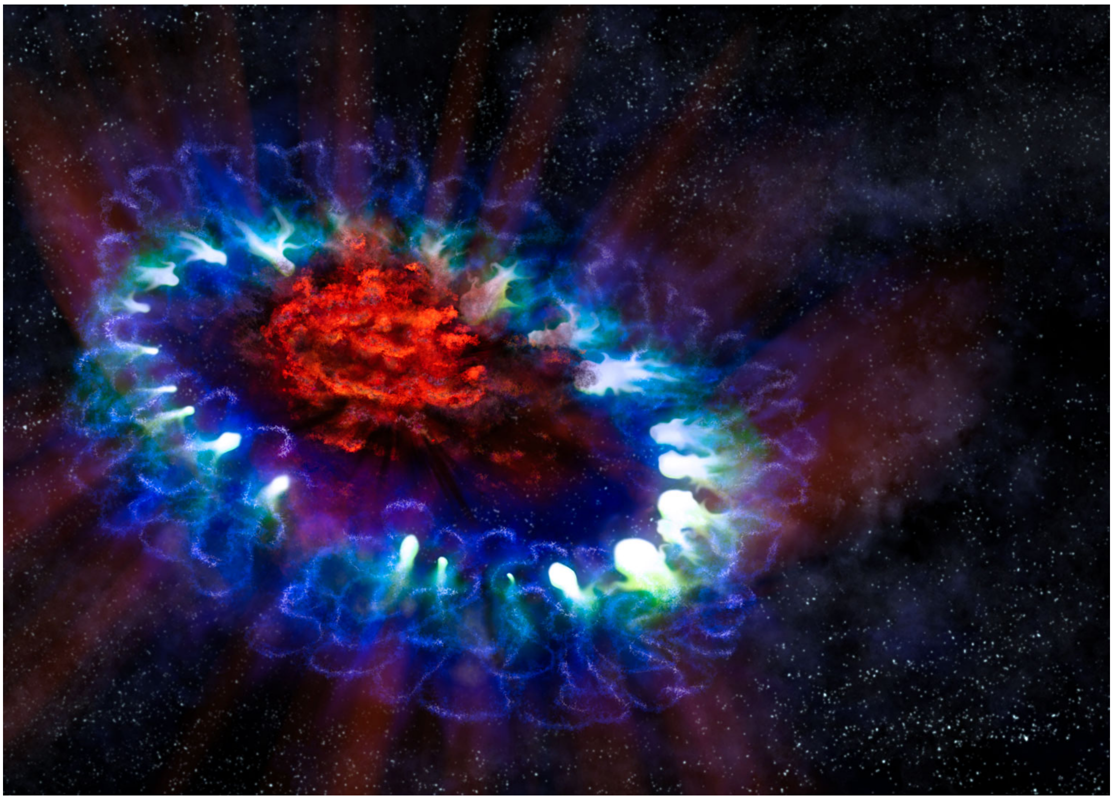

Figure 3: This artist's illustration of supernova 1987A reveals the cold, inner regions of the exploded star's remnants (red) where tremendous amounts of dust were detected and imaged by ALMA. This inner region is contrasted with the outer shell (lacy white and blue circles), where the energy from the supernova is colliding with the envelope of gas ejected from the star prior to its powerful detonation. (*Credit: Alexandra Angelich (NRAO/AUI/NSF)*)

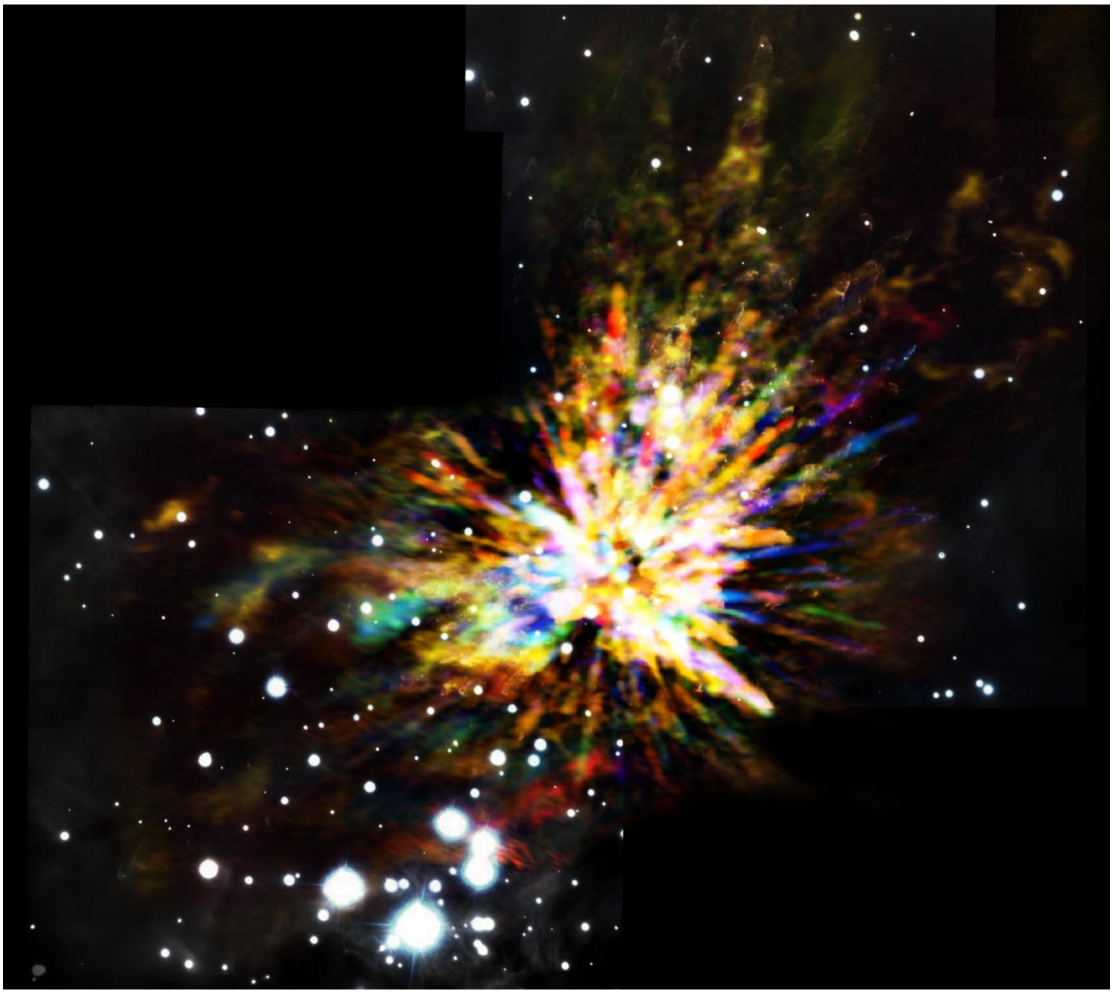

Figure 4: Composite image of the OMC-1 cloud in Orion, showing the sometimes explosive nature of star birth, when several young stars were ejected from the region about 500 years ago. The colours in the ALMA data represent the relative Doppler shifting of the millimetre-wavelength light emitted by CO gas. The ALMA image is combined with a near-infrared image from the Gemini South telescope, showing shock waves produced by the explosion. (*Credit: ALMA (ESO/NAOJ/NRAO), J. Bally; B. Saxton (NRAO/AUI/NSF); Gemini Observatory/AURA*)

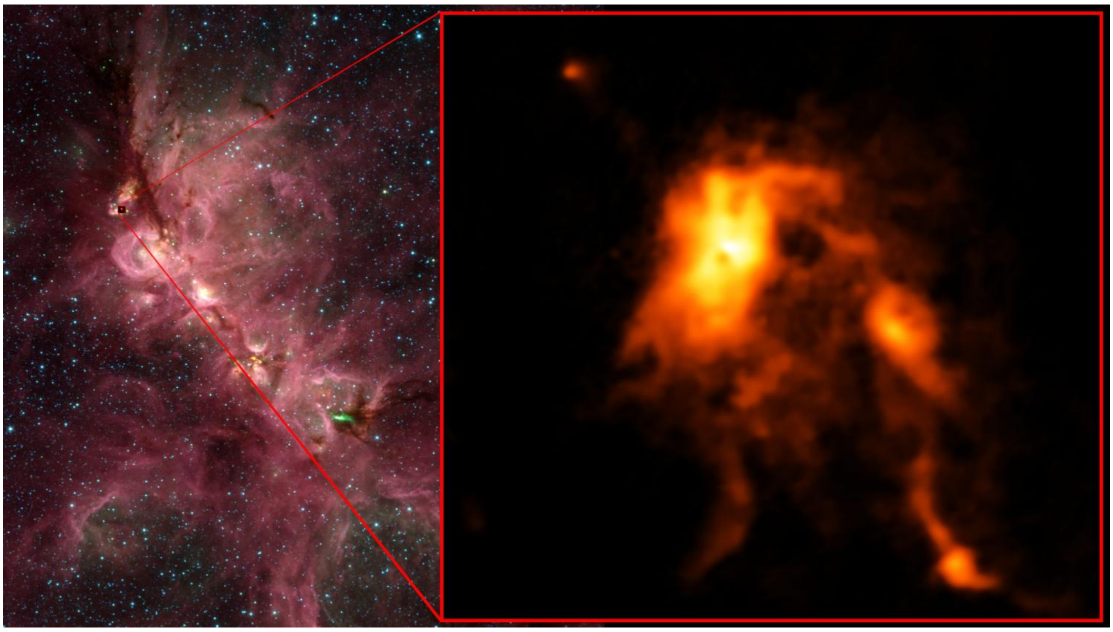

Figure 5: Inside the Cat's Paw Nebula as seen in an infrared image from NASA's Spitzer Space Telescope (left), ALMA discovered that an infant star is undergoing an intense growth spurt, shining nearly 100 brighter than before and reshaping its stellar nursery (right). (*Credit: ALMA (ESO/NAOJ/NRAO), T. Hunter; C. Brogan, B. Saxton (NRAO/AUI/NSF); GLIMPSE, NASA/JPL-Caltech*)

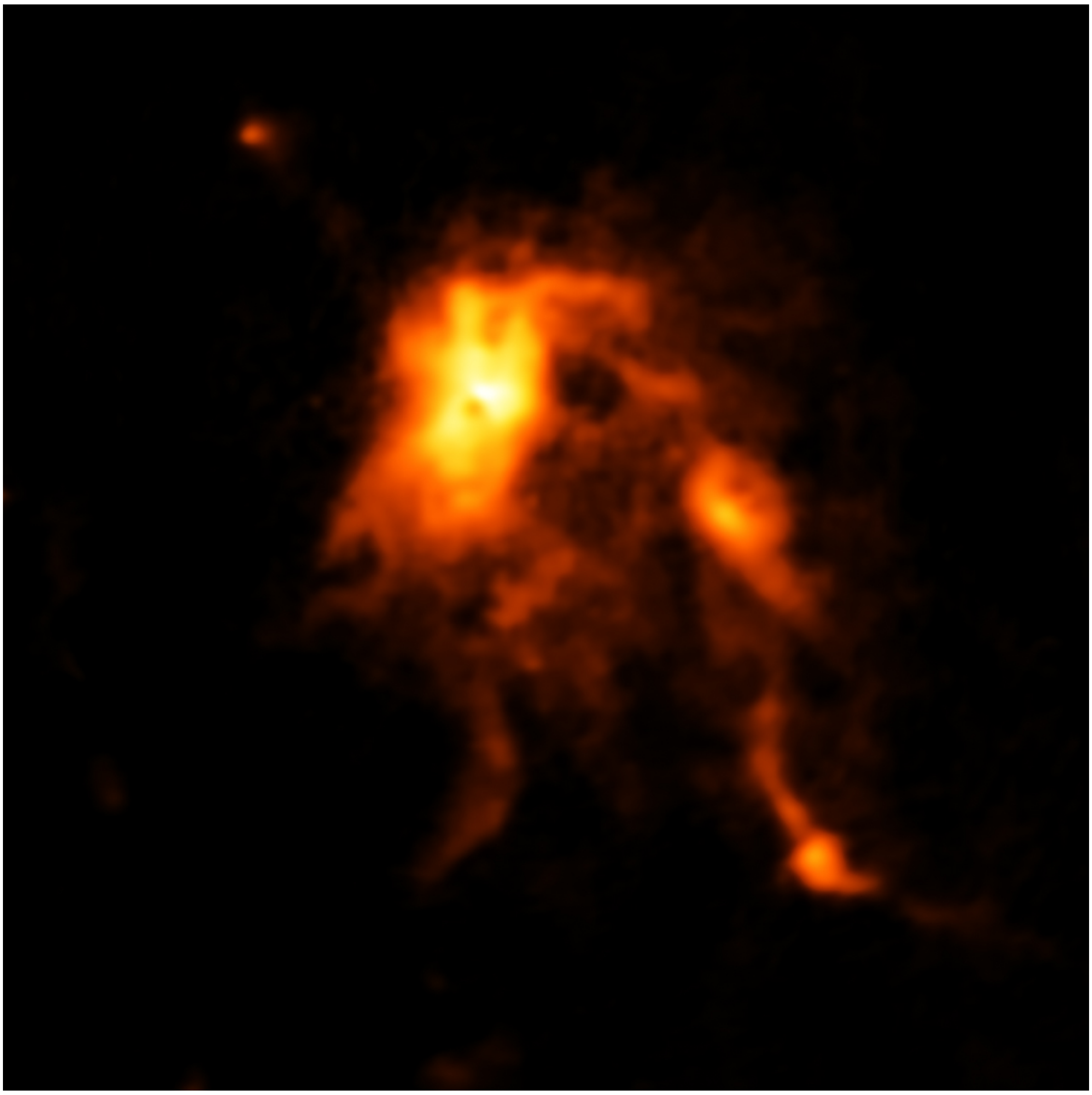

Figure 6: ALMA image of the glowing dust inside NGC 6334I, a protocluster containing an infant star that is undergoing an intense growth spurt, likely triggered by an avalanche of gas falling onto its surface. (*Credit: ALMA (ESO/NAOJ/NRAO); C. Brogan, B. Saxton (NRAO/AUI/NSF)*)

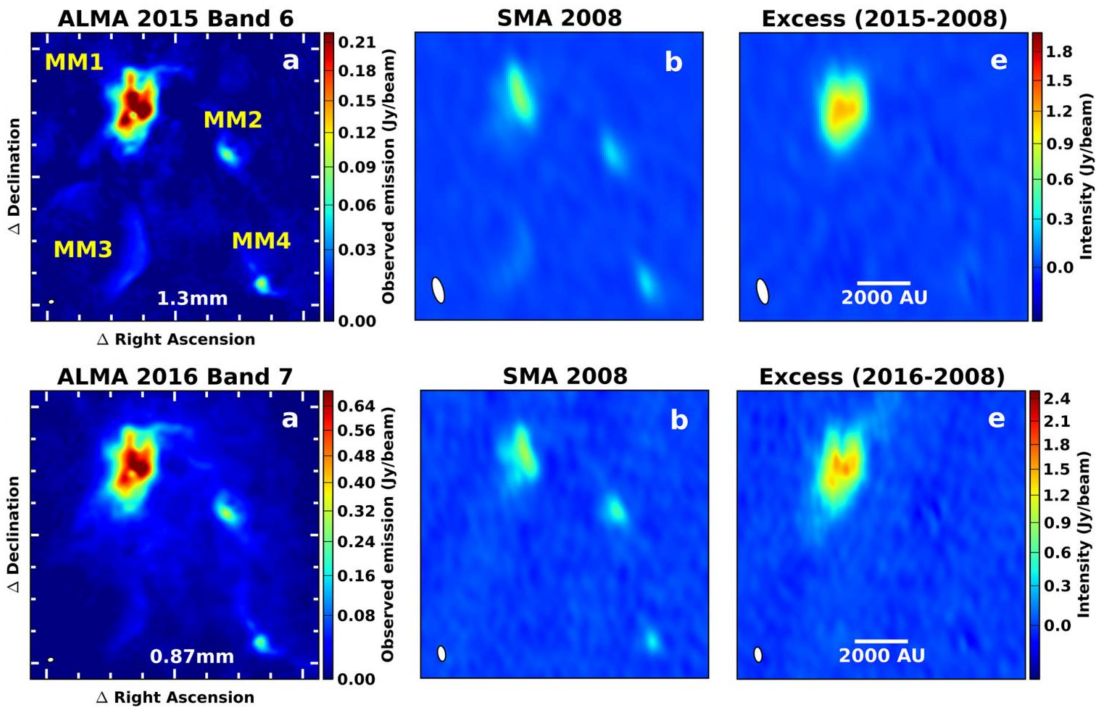

Figure 7: Comparing observations by two different millimetre-wavelength telescopes, ALMA and the SMA, astronomers noted a massive outburst in a star-forming cloud. Because the ALMA images are more sensitive and show finer detail, it was possible to use them to simulate what the SMA could have seen in 2015 and 2016. By subtracting the earlier SMA images from the simulated images, astronomers could see that a significant change had taken place in MM1 while the other three millimetre sources (MM2, MM3, and MM4) are unchanged. (*Credit: ALMA (ESO/NAOJ/NRAO); SMA, Harvard/Smithsonian CfA*)