UNIDAD DE CULTURA CIENTÍFICA

PRESS RELEASE

ALMA Unlocks the Chemical Secrets of a Starburst Galaxy

An international team of astrophysicists, with the participation of researchers of the Centro de Astrobiología (CAB, CSIC-INTA), has observed with unprecedented detail the center of a galaxy known as NGC 253 using the Atacama Large Millimeter/submillimeter Array (ALMA). They detected more than one hundred molecules, far more than previous studies outside the Milky Way have detected. Among them, they have identified, for the first time outside our Galaxy, species containing phosphorus, one of the key chemical elements for life. All these molecules can be used as tracers of different physical processes, and hence are also powerful tools to study various stages of star formation the central region of NGC 253. Therefore, this wealth of data has allowed astronomers to better understand the chemistry and physics of this kind of galaxy, which produces stars at a very high rate.

01-04-2024

In the Universe, some galaxies are forming stars at a much faster rate than the Milky Way. These galaxies are called starburst galaxies. Starburst phenomena do not last forever. It is still a mystery how exactly such extremely prolific formation of stars can take place and how it ends. The chance for stars to form depends on the properties of the raw material from which stars are born, molecular gas — a gaseous material made up of various molecules — is such material. For example, stars form in dense regions within molecular clouds where gravity can act more effectively. Some time after the active formation of stars, existing stars and explosions of dead stars impart energy to the surrounding medium, which could hinder future star formation. These physical processes impact the chemistry of the galaxy and imprint a signature in the strengths of signals from molecules. Because each molecule emits at certain frequencies, observations over a wide frequency range enable us to analyze the physical properties, and give us insights into the mechanism of starbursts.

Astronomers have gained a new understanding of phenomena related to star birth in a starburst galaxy. They detected more than one hundred molecular species in the center of a starburst galaxy known as NGC 253 located about 10 million light-years away. The observations were performed using the Atacama Large Millimeter/submillimeter Array (ALMA), a radio telescope in Chile. This survey was conducted as an ALMA Large Program named the ALMA Comprehensive High-resolution Extragalactic Molecular Inventory (ALCHEMI), with participation of multiple international teams, including researchers of the Centro de Astrobiología (CAB, CSIC-INTA).

“ALMA is the only instrument capable of providing the sensitivity and resolution for this kind of study. Thanks to the possibility of observing large programs (requiring more than 50 hours of observations), we managed to compile a comprehensive study of the chemistry of this extragalactic object that can be directly compared to the one found in the Milky Way and the Solar System” explains Sergio Martín, one of the Principal Investigators of this study, and Head of the Department of Science Operations at ALMA.

Among the chemical feedstock revealed by ALCHEMI, the researchers have identified molecules such as ethanol (C_2H_5OH), and species containing one of the key elements for life, phosphorus. In a work lead by the PhD student at CAB David Haasler, the team discovered that phosphorus nitride (PN) was present in two giant molecular clouds in the center of NGC 253. “This is the first time that we detect a molecule with phosphorus in another Galaxy” explains Haasler, “which confirms that the basic chemical ingredients for the biochemistry we know are also present beyond the Milky Way.”

The ALCHEMI survey found also the high-density molecular gas that is likely promoting active star formation in this galaxy. Each molecule emits at multiple frequencies, and their relative and absolute signal strengths change according to the density and the temperature. By analyzing multiple signals of some molecular species, the amount of dense gas in the center of NGC 253 turned out to be more than 10 times higher than that in the center of the Milky Way, which could explain why NGC 253 is forming stars about 30 times more efficiently even with the same amount of molecular gas.

One of the mechanisms that could aid the compression of molecular clouds into denser ones is a collision between such clouds. At the center of NGC 253, cloud collisions are likely to take place where streams of gas and stars intersect, generating shock waves traveling at supersonic speeds. These shock waves evaporate molecules such as methanol and HNCO frozen onto icy dust particles. When the molecules evaporate as gas, they become observable by radio telescopes such as ALMA.

Certain molecules also trace ongoing star formation. It has been known that complex organic molecules are abundant around young stars. In NGC 253, this study suggests that active star formation creates a hot and dense environment, similar to the ones seen around individual young stars (protostars) in the Milky Way. The amount of complex organic molecules in the center of NGC 253 turns out to be similar to that around protostars in the Galaxy.

In addition to physical conditions that could promote star formation, the survey also revealed the harsh environment left by previous generations of stars, which could slow down future star formation. When massive stars die, they cause massive explosions known as supernovae, which emit energetic particles called cosmic rays. The molecular composition of NGC 253 revealed from the enhancement of species such as H_3O^+ and HOC^+ that molecules in this region have had some of their electrons stripped off by cosmic rays at a rate at least 1000 times higher than that near the Solar System. This suggests a large energy input from supernovae, which makes it difficult for gas to condense to form stars.

Finally, the ALCHEMI survey provided an atlas of 44 molecular species, doubling the number available from previous studies outside the Milky Way. By applying a machine-learning technique to this atlas, the researchers were able to identify which molecules can most effectively trace the story of star formation mentioned above - from the beginning to the end. As described above with some examples, certain molecular species trace phenomena such as shock waves or dense gas, which could aid star formation. Young star-forming regions host rich chemistry including complex organic molecules. Meanwhile, the developed starburst shows an enhancement of the cyano radical that indicates energy output from massive stars in the form of UV photons, which could also hinder future star formation. Finding these tracers may help to plan future observations using the wideband sensitivity upgrade expected in the near future as a part of the ALMA 2030 Development roadmap, with which simultaneous observations of multiple molecular transitions will become much more manageable. "With the new updates being performed during this decade to the observatory, known as the Wideband Sensitivity Upgrade (WSU), we will be able to extend this kind of study to fainter and further objects to understand the evolution of chemistry in the Universe", concluded Sergio Martín.

Publication list:

- Harada et al. (ApJS 2024) "The ALCHEMI atlas: principal component analysis reveals starburst evolution in NGC 253" 10.3847/1538-4365/ad1937 published on Mar 15th, 2024
- Martin et al. (A&A 2021) "ALCHEMI, an ALMA Comprehensive High-resolution Extragalactic Molecular Inventory. Survey presentation and first results from the ACA array" 10.1051/0004-6361/202141567
- Tanaka et al. (ApJ 2024) "Volume Density Structure of the Central Molecular Zone NGC 253 through ALCHEMI Excitation Analysis" 10.3847/1538-4357/ad0e64
- Huang et al. (A&A 2023) "Reconstructing the shock history in the CMZ of NGC 253 with ALCHEMI" 10.1051/0004-6361/202245659
- Behrens et al. (ApJ 2022) "Tracing Interstellar Heating: An ALCHEMI Measurement of the HCN Isomers in NGC 253" 10.3847/1538-4357/ac91ce
- Harada et al. (ApJ 2022) "ALCHEMI Finds a "Shocking" Carbon Footprint in the Starburst Galaxy NGC 253" 10.3847/1538-4357/ac8dfc
- Humire et al. (A&A 2022) "Methanol masers in NGC 253 with ALCHEMI" 10.1051/0004-6361/202243384
- Holdship et al. (A&A 2022) "Energizing Star Formation: The Cosmic-Ray Ionization Rate in NGC 253 Derived from ALCHEMI Measurements of H3O+ and SO" 10.3847/1538-4357/ac6753
- **Haasler et al. (A&A 2022) "First extragalactic detection of a phosphorus-bearing molecule with ALCHEMI: Phosphorus nitride (PN)" 10.1051/0004-6361/202142032**
- Harada et al. (2021 ApJ) "Starburst Energy Feedback Seen through HCO+/HOC+ Emission in NGC 253 from ALCHEMI" 10.3847/1538-4357/ac26b8
- Barrientos et al. (Experimental Astronomy 2021) "Towards the prediction of molecular parameters from astronomical emission lines using Neural Networks" 10.1007/s10686-021-09786-w
- Holdship et al. (A&A 2021) "The distribution and origin of C2H in NGC 253 from ALCHEMI" 10.1051/0004-6361/202141233
- Butterworth et al. (A&A in press) "Molecular isotopologue measurements toward super star clusters and the relation to their ages in NGC253 with ALCHEMI" 10.48550/arXiv.2402.10721

About CAB

Centro de Astrobiología (CAB) is a joint research center of the National Institute of Aerospace Technology (INTA) and the National Research Council (CSIC) of Spain. Created in 1999, it was the world's first center dedicated specifically to astrobiological research and the first non-US associate member of NASA's Astrobiology Institute (now the NASA Astrobiology Program). It is an interdisciplinary research center whose main objective is to study the origin, presence and influence of life in the universe from a transdisciplinary approach. In 2017, CAB was distinguished by the Ministry of Science and Innovation as "María de Maeztu Unit of Excellence".

CAB has led the development of the REMS, TWINS and MEDA instruments, all operational on Mars since August 2012, November 2018 and February 2021, respectively; as well as the science of the RLS and RAX Raman instruments, which will be launched in this decade on board of ExoMars and MMX missions. In addition, CAB develops the SOLID instrument, aimed at the search for life in planetary exploration. Likewise, CAB participates in different missions and instruments of great astrobiological relevance, such as CARMENES, CHEOPS, PLATO, BepiColombo, DART, Hera, the MIRI and NIRSpec instruments at JWST and the HARMONI instrument at ESO's Extremely Large Telescope (ELT).

More information

Figure 1. Artist's impression of the center of the starburst galaxy, NGC 253. Credit: ALMA (ESO/NAOJ/NRAO)

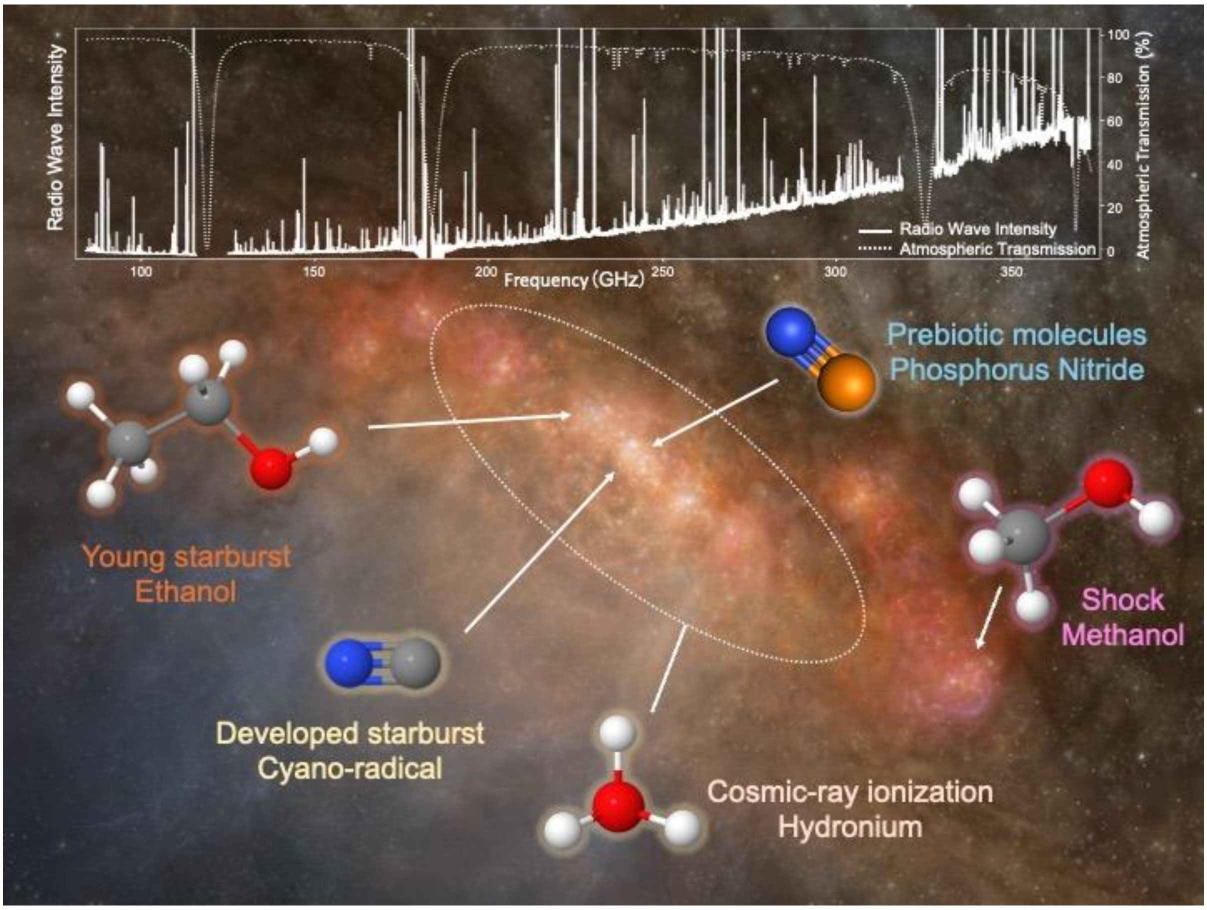

Figure 2*. (Top) Spectra from the ALCHEMI survey. (Bottom) A schematic image of the center of the starburst galaxy, NGC 253, describing locations where various tracer molecular species are enhanced according to the ALCHEMI survey. Credit: ALMA (ESO/NAOJ/NRAO), N. Harada et al.*

Contact

CAB researchers that have participated in the ALCHEMI international collaboration:

- Víctor M. Rivilla: vrivilla@cab.inta-csic.es
- Laura Colzi: lcolzi@cab.inta-csic.es
- David Haasler: dhaasler@cab.inta-csic.es

CAB SCIENTIFIC CULTURE UNIT (UCC)

divulgacion (+@cab.inta-csic.es); (+34) 915202107