James Webb Space Telescope and ALMA capture the core of the most distant galaxy protocluster

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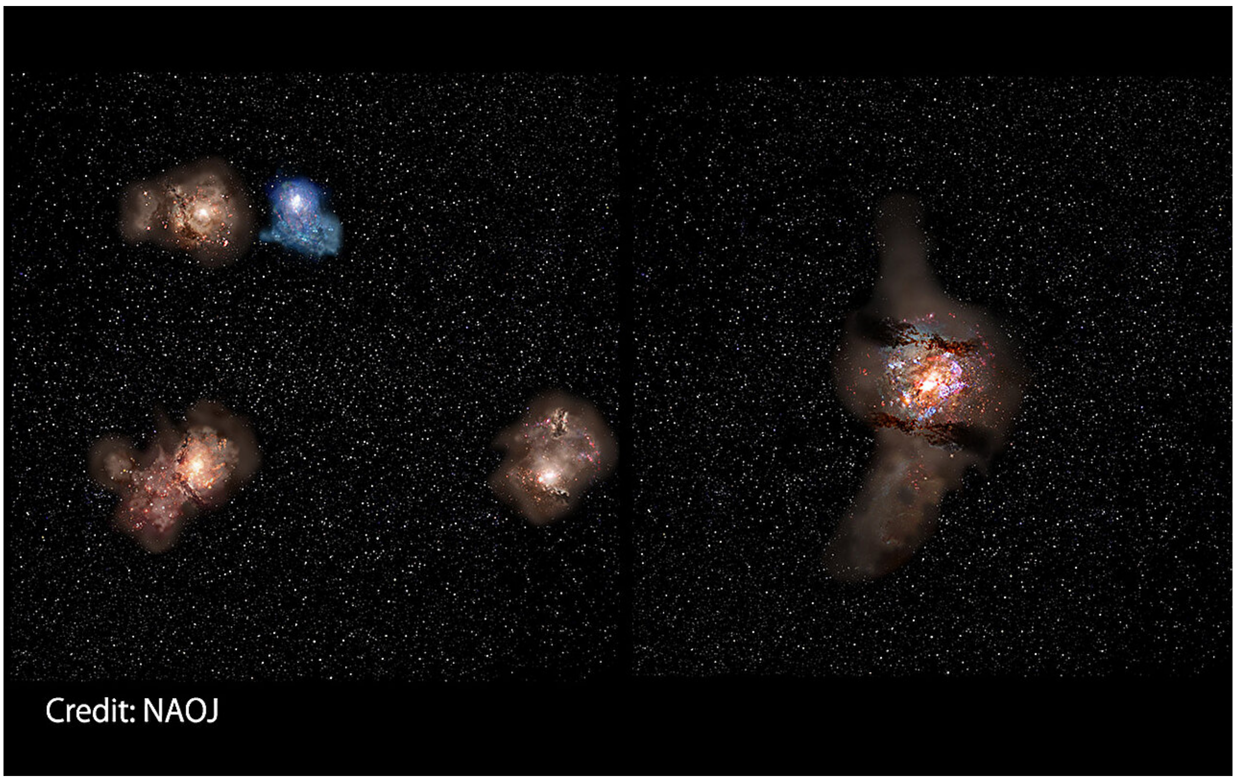


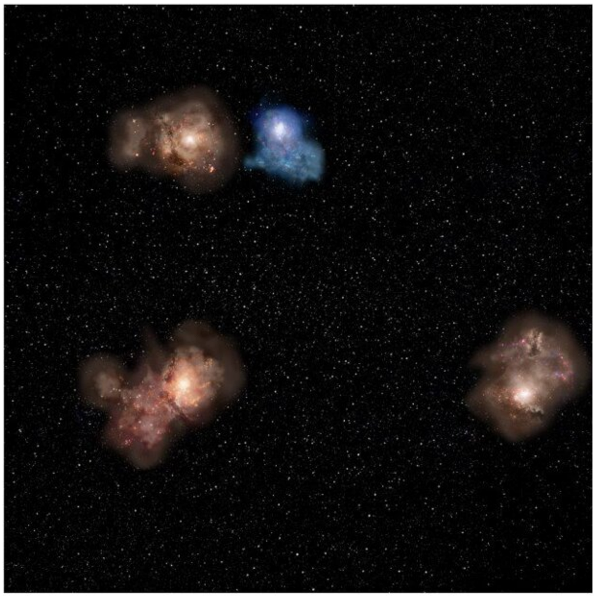
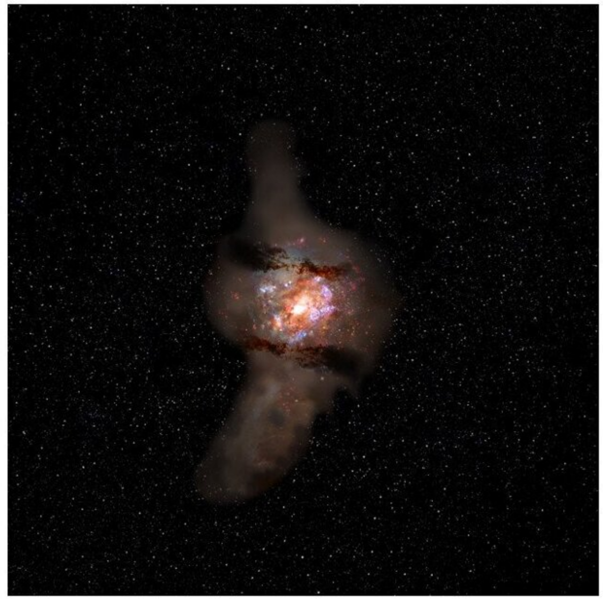
Artist's impression. Credit: University of Tsukuba

The study of how individual stars are born and die in galaxies, how new stars are born from remnants of old stars, and how galaxies themselves grow are important themes in astronomy, as they provide insight into our roots in the universe. Galaxy clusters, one of the largest structures in the universe, are the assembly of more than 100 galaxies which are bound together through mutual gravitational force.

Observations of nearby galaxies have shown that the growth of a galaxy depends on its environment in the sense that mature stellar populations are commonly seen in regions where galaxies are densely collected. This is referred to as the "environment effect." Although the environment effect has been considered an important piece to understand galaxy formation and evolution, it is not well known when the effect initiated in the history of the universe.

One of the keys to understanding this is to observe the ancestors of galaxy clusters shortly after the birth of the universe; known as galaxy protoclusters (hereafter protoclusters), these are assemblies of about 10 distant galaxies. Fortunately, astronomy allows us to observe the distant universe as it was in the past. For example, light from a galaxy 13 billion light-years away takes 13 billion years to reach Earth, so what we observe now is what that galaxy looked like 13 billion years ago.

However, light that travels 13 billion light-years becomes fainter, so the telescopes that observe it must have high sensitivity and spatial resolution.

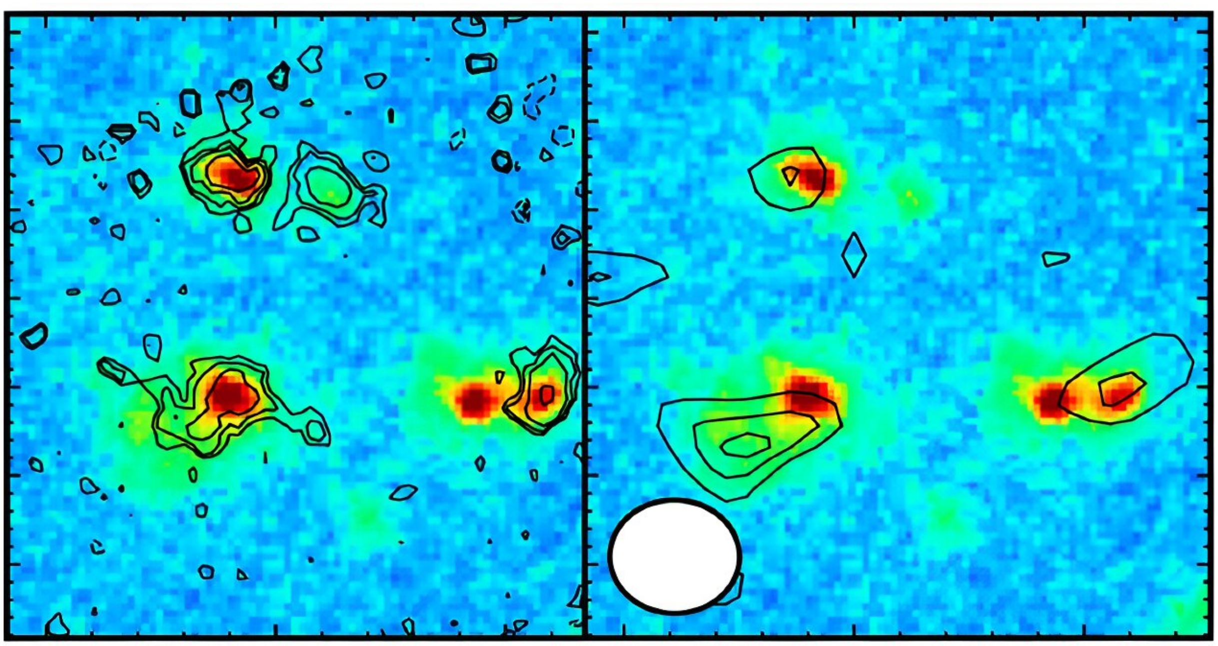
(Left) Artist's impression of the "metropolitan area" of the protocluster A2744ODz7p9 revealed by the James Webb Space Telescope and ALMA. (Right) Artist's impression of what the "metropolitan area" will become tens of millions of years after the observed time. Credit: NAOJ

An international research team led by Assistant Professor Takuya Hashimoto (University of Tsukuba, Japan) and researcher Javier Álvarez-Márquez (Spanish Center for Astrobiology) has used the James Webb Space Telescope (JWST, observing visible and infrared light) and the Atacama Large Millimeter/submillimeter Array (ALMA, observing radio waves) to study the "core region" of the protocluster A2744z7p9OD.

The protocluster A2744z7p9OD had been announced as the most distant proto-cluster at 13.14 billion light-years away based on observations with JWST by another research group. "However, we have not been able to observe the entire core region, the metropolitan area, with the largest number of galaxy candidates in this protocluster. It was unclear whether the environmental effects of galaxies had begun in this protocluster. So we decided to focus our research on the core region," says Hashimoto.

The research team first observed the core region of this protocluster using JWST. Using NIRSpec, an instrument that observes spectra at wavelengths ranging from visible to near-infrared, the team made integral field spectroscopy observations that can simultaneously acquire spectra from all locations within the field of view.

The team has successfully detected ionized oxygen-ion light ([OIII] 5008 Å) from four galaxies in a quadrangle region measuring 36,000 light-years along a side, which is equivalent to half the radius of the Milky Way galaxy. Based on the redshift of this light (the elongation of the wavelength due to the cosmic expansion), the distance of the four galaxies from the Earth was identified as 13.14 billion light years.



The background color image shows a map of the light intensity (redder color shows stronger emission) in the core region of the protogalactic cluster

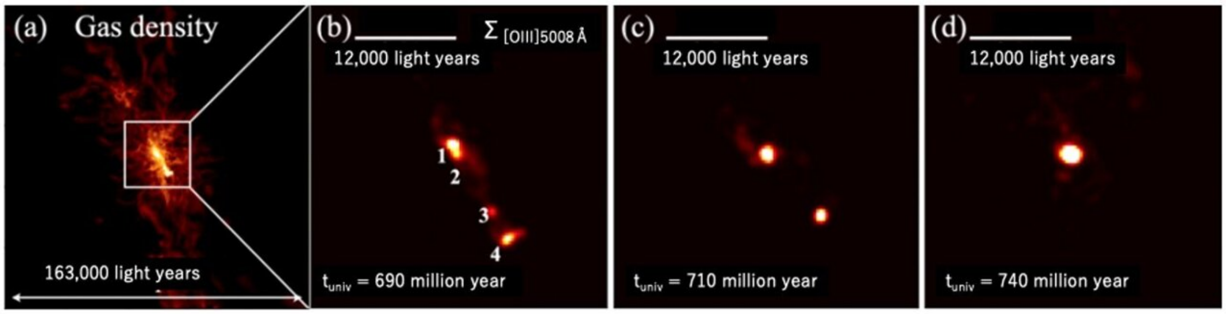
A2744ODz7p9, acquired with the NIRCam onboard JWST. The size of the image corresponds to about half of the radius of the Milky Way Galaxy. (Left) Contours show the distribution of light emitted by ionized oxygen, obtained with the NIRSpec instrument onboard JWST. 4 galaxies were identified at 13.14 billion light-years away. (Right) Contours show the distribution of dust emission from three of the four galaxies. The white circle in the lower left of the figure indicates the beam size of the ALMA data.Credit: JWST (NASA, ESA, CSA), ALMA (ESO/NOAJ/NRAO), T. Hashimoto et al.

"I was surprised when we identified four galaxies by detecting oxygen-ion emission at almost the same distance. The 'candidate galaxies' in the core region were indeed members of the most distant protocluster," says Yuma Sugahara (Waseda/NAOJ), who led the JWST data analysis.

In addition, the research team paid attention to the archival ALMA data, which had already been acquired for this region. The data captures radio emission from cosmic dust in these distant galaxies. As a result of analyses, they detected dust emissions from three of the four galaxies.

This is the first detection of dust emission in member galaxies of a protocluster this far back in time. Cosmic dust in galaxies is thought to be supplied by supernova explosions at the end of the evolution of massive stars in the galaxies, which provide the material for new stars.

Therefore, the presence of large amounts of dust in a galaxy indicates that many of the first-generation stars in the galaxy have already completed their lives and that the galaxy is growing. Professor Luis Colina (El Centro de Astrobiología (CAB, CSIC-INTA)) describes the significance of the results: "Emission from cosmic dust was not detected in member galaxies of the protocluster outside the core region. The results indicate that many galaxies are clustered in a small region and that galaxy growth is accelerated, suggesting that environmental effects existed only ~700 million years after the Big Bang."



Galaxy formation simulations of the future of the core of A2744z7p9OD. (a) Gas density in a region similar to the proto-cluster A2744z7p9OD at a cosmological age of 689 million years. (b) A zoomed-in view of the core region in (a), corresponding to the region observed by JWST. The color map indicates the light distribution of oxygen ions. (b) to (d) show the evolution of the simulated object: the four galaxies gradually merge and evolve into a larger object. Credit: T. Hashimoto et al.

Furthermore, the research team conducted a galaxy formation simulation to theoretically test how the four galaxies in the core region formed and evolved. The results showed that a region of dense gas particles existed around 680 million years after the Big Bang. In the middle four galaxies are formed, similar to the observed core region. To follow the evolution of these four galaxies, the simulation calculated physical processes such as the kinematics of stars and gas, chemical reactions, star formation, and supernovae.

The simulations showed that the four galaxies merge and evolve into a single larger galaxy within a few tens of millions of years, which is a short time scale in the evolution of the universe.

"We successfully reproduced the properties of the galaxies in the core region owing to the high spatial resolution of our simulations and the large number of galaxy samples we have. In the future, we would like to explore the formation mechanism of the core region and its dynamical properties in more detail," says Yurina Nakazato, a graduate student at the University of Tokyo, who analyzed the simulation data.

Javier Álvarez-Márquez (Spanish Center for Astrobiology) says, "We will conduct more sensitive observations of the proto-cluster A2744z7p9OD with ALMA to see if there are any galaxies that were not visible with the previous sensitivity. We will also apply the JWST and ALMA observations, which have proven to be very powerful, to more protoclusters to elucidate the growth mechanism of galaxies, and to explore our roots in the universe."

The work is published in *The Astrophysical Journal Letters*.

More information: T. Hashimoto et al, Reionization and the ISM/Stellar Origins with JWST and ALMA (RIOJA): The Core of the Highest-redshift Galaxy Overdensity at z = 7.88 Confirmed by NIRSpec/JWST, *The Astrophysical Journal Letters* (2023). DOI: 10.3847/2041-8213/acf57c

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