Researchers depict the formation of galaxies

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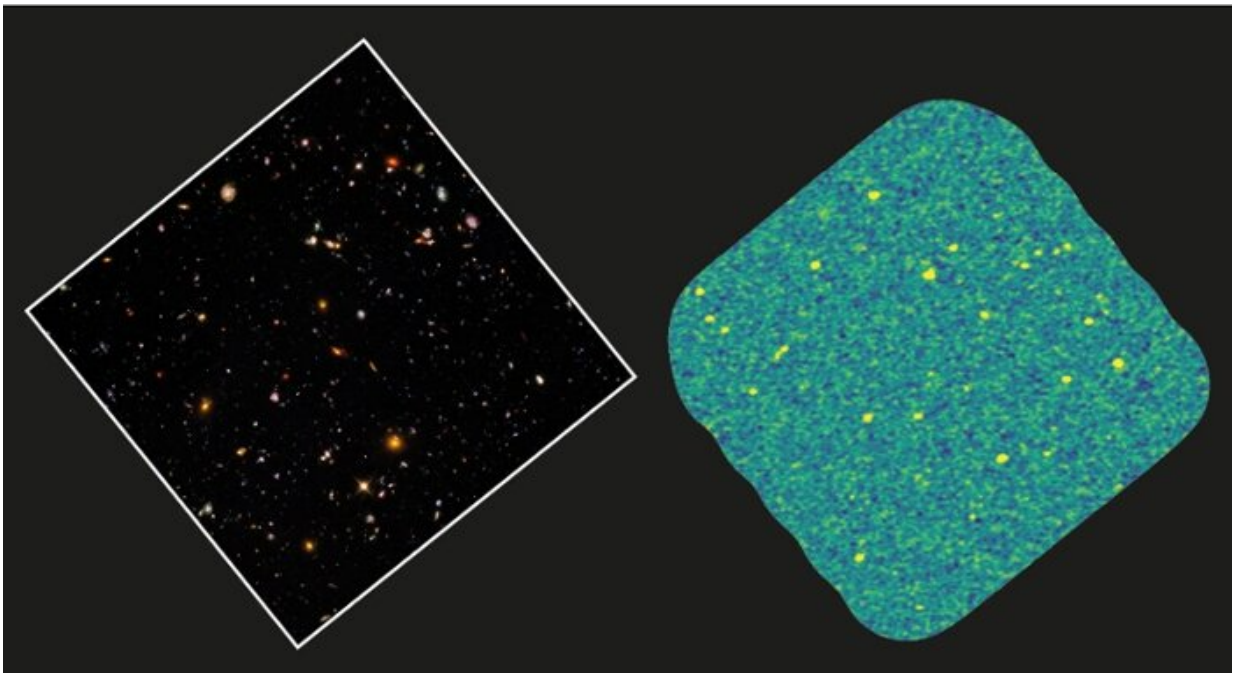

On the left, an image taken with the Hubble Space Telescope in visible light and infrared light, based on the deepest Hubble observations ever obtained. It shows hundreds of galaxies at different distances, and which emitted their light further and further back in time. On the right the same image by the ALMA telescope showing the dust in the galaxies of the Hubble Ultra Deep Field. These ALMA observations constitute the deepest image ever made of dust emission from distant galaxies. Credit: STScI & ASPECS

An international team of astronomers, with researchers at Leiden Observatory playing a leading role, has mapped the fuel for galaxy

formation in the iconic Hubble Ultra Deep Field. The results of the research have been accepted for publication in *The Astrophysical Journal*.

The research shows how galaxies have formed and how they grow. It also shows why the period between 10 and 13 billion years ago represented the golden age for the formation of galaxies.

The astronomers worked together as part of the ASPECS program. ASPECS is one of the first major international projects carried out with the ALMA telescope. Four researchers from Leiden played an important role in the project. The researchers combined 200 hours of observations from the ALMA telescope in Chile with spectroscopy from the MUSE instrument on the Very Large Telescope of the European Southern Observatory, ESO (also in Chile).

Earlier studies have shown that the formation of stars and galaxies peaked some 10 billion years ago. But the cause and size of that birth wave have remained a mystery until now. This was because the telescopes that were used were not capable of seeing through the dust and to directly detect the fuel for star formation. But the ALMA telescope is able to do just that.

Raw material for stars

The astronomers looked for the carbon monoxide emission line in the Hubble Ultra Deep Field. From this, they were able to deduce the amount of molecular hydrogen, the raw material for star formation. To make their inferences as accurate as possible, they needed to know the number of heavy elements in the gas, the density and temperature, and the strength of the radiation field shining on the carbon monoxide. The Leiden Ph.D. candidate Leindert Boogaard performed this task using the MUSE instrument.

Boogaard says, "By combining observations of the cold gas with those of warm gas and starlight, we gain a unique view of the distant galaxies. By combining these many puzzle pieces, we are able to understand the entire process of galaxy growth and formation."

The galaxies in the Hubble Ultra Deep Field with the most fuel were mostly discovered to be mainly normal galaxies, with average star masses and star formation rates. Other galaxies are so-called starburst galaxies, with unusually high star-forming activity, or quiescent galaxies, with unusually low activity.

Golden age

The research shows that the amount of molecular hydrogen in the universe rose steadily until approximately 10 billion years ago, versus 13.8 billion years ago which was the time of the Big Bang. Astronomer Rychard Bouwens says, "So that was the golden age of star formation, with a lot of raw material needed to form new stars and galaxies. Half of the stars that still exist today were born during that brief period of cosmic history."

In the future, astronomers want to look at the individual galaxies in more detail. Such a detailed view will be possible using the high-resolution mode of the ALMA telescopes in combination with observations from the future James Webb Space Telescope.

The results are described in several articles that have been accepted for publication in the *Astrophysical Journal*.

More information: The ALMA Spectroscopic Survey in the HUDF: CO Excitation and Atomic Carbon in Star-Forming Galaxies at z=1–3. By Boogaard et al. *The Astrophysical Journal*. arxiv.org/abs/2009.04348

The Alma Spectroscopic Survey Large Program: the Infrared Excess of Z = 1.5–10 UV-Selected Galaxies and the Implied High-Redshift Star Formation History. By Bouwens et al. *The Astrophysical Journal*. arxiv.org/abs/2009.10727

Leindert A. Boogaard et al. The ALMA Spectroscopic Survey in the HUDF: Nature and Physical Properties of Gas-mass Selected Galaxies Using MUSE Spectroscopy, *The Astrophysical Journal* (2019). DOI: 10.3847/1538-4357/ab3102

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