Speedy galaxy evolution:
Mature features are detected in an early galaxy

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The processes that transformed small, turbulent, relatively unstructured protogalaxies into rotating spiral or giant elliptical galaxies are not well understood. Most galaxies are expected to go through a spiral-like phase, maturing into an elliptical structure. Many local spiral galaxies have a classic rotating disk of young stars as well as a bulge of older red stars at their centers; these two features are considered to be signatures of galaxies that have evolved from their original primordial forms. Unfortunately, these features are challenging to directly detect, particularly in the very distant (i.e., early) Universe. Now, Lelli et al. [2021] report a galaxy that had evolved features (both a disk and a bulge) when only 1.2 billion years had elapsed since the Big Bang (12.5 billion years ago). This finding suggests that the processes that generate the key features of a mature galaxy arose more rapidly than has been thought.

Theoretical simulations suggest that primordial galaxies started to form shortly after the Big Bang and are expected to merge together through gravity. They form increasingly large but somewhat chaotic structures [Schaye et al., 2015], that may have some rotation but must also eventually form bulges of old stars. The mechanism of bulge formation requires additional observations to constrain the model.

There are two main theories for forming a concentrated population of old stars: galaxy mergers and internal instabilities. Mergers cause huge gravitational disturbances that can compress cold gas (the fuel for new stars), triggering huge but short-lived bursts of star formation. Similarly, the distant Universe was a chaotic place, and it is thought that early galaxies were often gravitationally unstable such that internal stochasticity could have triggered similar dynamical disturbances and compressions of gas leading to an intense starburst. In both scenarios, after the gravitational disturbance, the cold gas fuel for star formation is rapidly exhausted, leading to an aging of the central stellar population along with a relaxation of the dynamics. Because both scenarios lead to similar theoretical outcomes, the question of whether galaxy bulges form from stochastic internal processes or as the result of galaxy mergers re- quires observations to answer the question of how bulges emerge.

Although it is clear that distant galaxies tend to have more irregular and clumpy morphologies than local galaxies, these clumps can be interpreted as evidence for both massive star-forming regions (i.e., secular processes) and mergers, depending on their prevalence and mass [Mandelker et al., 2017, Förster Schreiber and Wuyts, 2020]. Additional data are required to untangle the various processes driving the evolution of distant star-forming galaxies.

Instruments that can map the motion of galaxies' gases and stars in two dimensions have recently gained sensitivity and resolution, enabling astronomers to measure the rotation of galaxies farther into the distant Universe. Multiple tracers now allow researchers to separately pinpoint stars, ionized and molecular gases, and dust in distant galaxies [Chen et al., 2017]. The spatial and dynamical differences between components can point to different formation mechanisms.

Star formation activity in the Universe was at its peak 10 to 11 billion years ago, and large kinematic surveys of massive star-forming galaxies from that time show that most had morphologies consisting of a disk and bulge [Wuyts et al., 2011]. Their internal kinematics were dominated by rotation, as expected for spiral galaxies, albeit with a mass dependence and with the disks typically harbouring more turbulence than their local counterparts [Stott et al., 2016, Wisnioski et al., 2019]. Thus, it seems that systems with similarities to todays spiral galaxy population had already evolved

10 to 11 billion years ago. Thus, to observationally identify even earlier stages in galaxy evolution, the measurement of even more distant systems is required.

For detected light that was emitted when the Universe was less than 2 billion years old, the bright emission lines that are used to trace the dynamics of ionized gas in nearer galaxies are redshifted out of the wavelength range of ground-based near-infrared telescopes. Furthermore, these emissions are blocked from detection by Earth's atmosphere. For these most distant galaxies, another approach is needed, and far-infrared observations of carbon, carbon monoxide, oxygen, or nitrogen are fast becoming the key method for tracing their gas [Hodge and da Cunha, 2020]. Such observations have provided evidence for rotation in massive galaxies at these epochs [Rizzo et al., 2020, Neeleman et al., 2020], suggesting that gas disks formed early in the Universes history.

Ideally, direct observations of gases, stars, and dust would be combined, providing complementary information about a galaxys overall structure. To date, few systems have deep, high-resolution observations in multiple tracers, so observations of tracers in different galaxies are used instead to infer a coherent picture. For example, in the most actively star-forming distant galaxies, star formation tends to be substantially more compact than the existing stars, which could indicate growing bulges [Hodge et al., 2016]. These most active galaxies are thought to represent some of the most massive galaxies at each epoch, and observing them provides an opportunity to explore the limits of galaxy evolution. A handful of these systems now have resolved observations of their cold gas, which typically seems to be more spatially extended than the ongoing star formation. These massive galaxies are also rotating, and substantial fractions of the overall galaxy mass are in the gaseous component [Calistro Rivera et al., 2018, Rizzo et al., 2020].

Lelli et al. [2021] have now brought together many of these different tracers of galaxy evolution for the galaxy ALESS 073.1, which was an extremely active galaxy when the light that we observe was emitted, only 1.2 billion years after the Big Bang. The authors use a far-infrared map of carbon emission to show that the cold gas in ALESS 073.1 is rotating and combines this information with imaging of the compact dust component to measure the distribution of different mass components. The diversity and quality of the data for a galaxy so far away are rare, and the authors show that ALESS 073.1 not only comprises a rotating cold gas disk, a stellar disk, and a dark matter halo, but also must have already established a substantial central bulge as well. Because ALESS 073.1 is seen only 1.2 billion years after the Big Bang, this study shows that the galaxy evolution mechanisms that build bulges must act on relatively short time scales, and that if a major merger was involved in the evolution of ALESS 073.1, it must have taken place less than 1 billion years after the Big Bang. If this merger scenario is the correct mechanism, then Lelli et al.s observations of ALESS 073.1 also require that multiple massive galaxies must have already formed by this epoch. Additionally, ALESS 073.1 contains an active galactic nucleus (AGN), indicative of a growing central supermassive black hole, which may be associated with the rapid growth of its bulge.

The next step in understanding the buildup of galaxies so soon after the Big Bang is to determine whether ALESS 073.1 is a rarity or whether the presence of bulges is common at this epoch. It also remains unknown whether all such galaxies with early formed bulges contain AGN and/or are undergoing rapid bursts of star formation as seen in ALESS 073.1. Such studies should reveal important constraining factors and the time scales of typical galaxy evolution processes and will thus provide clues as to the role of galaxy mergers in the growth of very early galaxies.

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