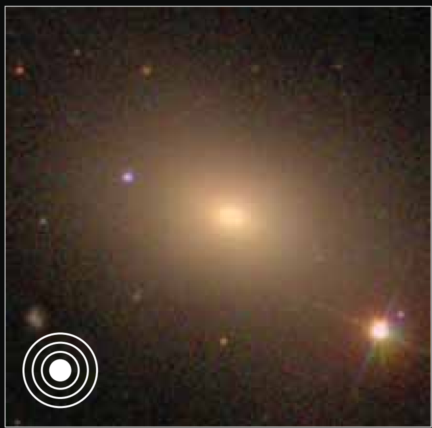
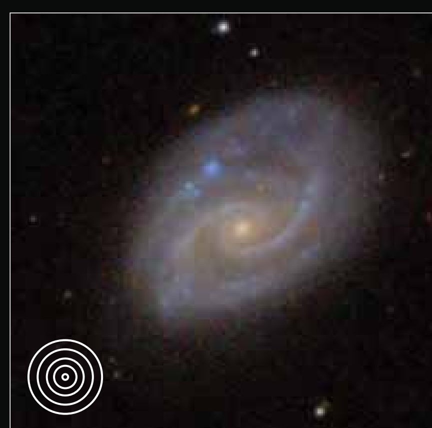
PATTERNS OF STAR FORMATION



HIGH MASS Galaxies with masses of more than 70 billion suns, such as NGC 6411, form most of their stars in five billion years, from the inside out

CRITICAL MASS Galaxies with masses of approximately 70 billion suns, such as NGC 4047, form their stars in less than three billion years, from the inside out



LOW MASS Galaxies with masses of fewer than a few dozen billion suns, such as UGC 9476, continue to form stars in all their regions

IMAGES ENRIQUE PÉREZ AND ANDRE LUIZ DE AMORIM **INFOGRAPHICS** ANA PAULA CAMPOS

Star archeology

Survey identifies three patterns of galaxy evolution

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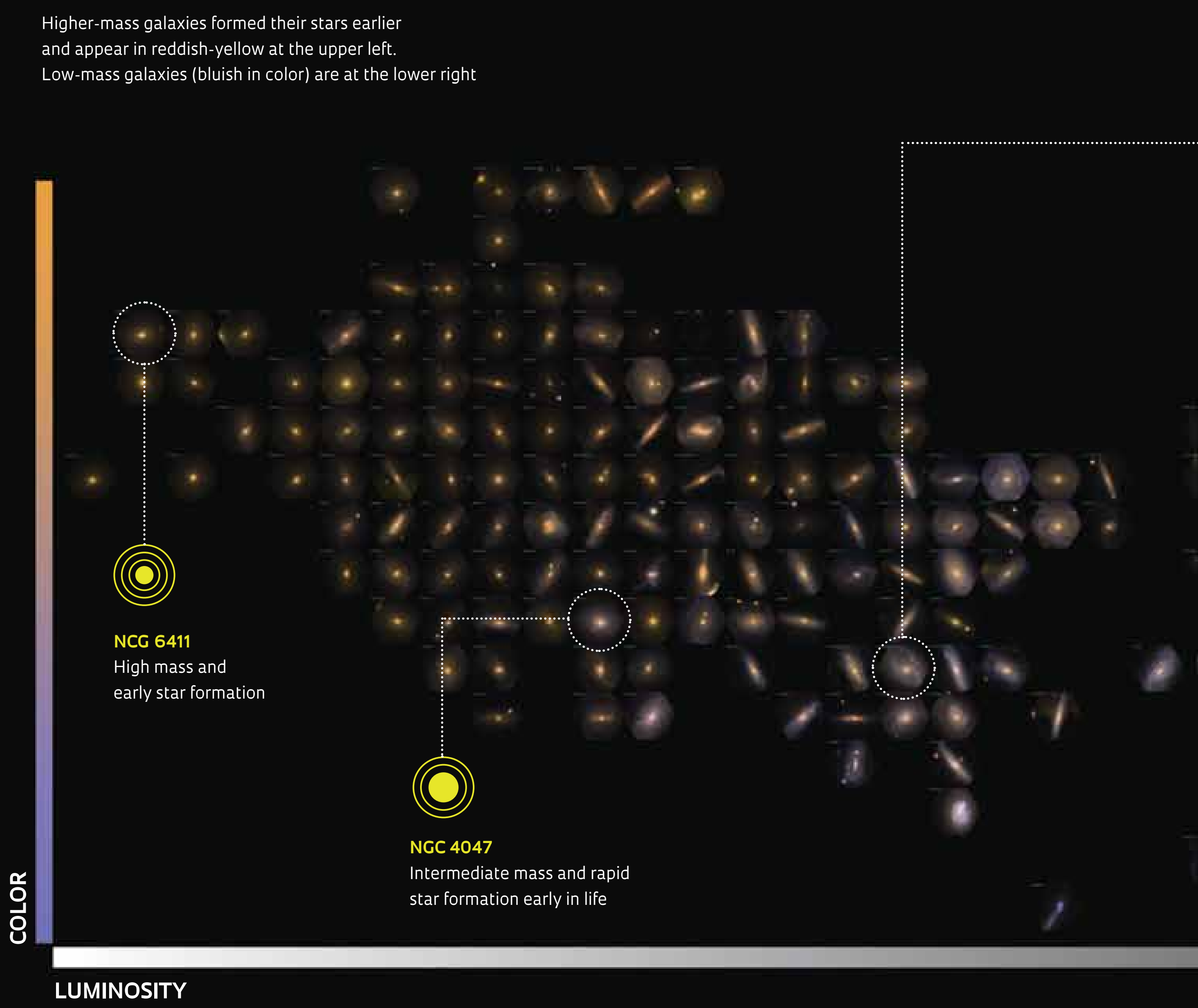
A pioneering study has begun to trace the evolutionary history of galaxies. Under the leadership of Spaniard Enrique Pérez of the Institute of Astrophysics of Andalucía, the study has identified where and when the stars were formed in approximately one hundred galaxies that have emerged in the last 10 billion years and are relatively close to the Milky Way, which is home to our Sun and the Earth. The study, published in the journal Astrophysical Journal Letters in January of this year, compared different types of galaxies and enabled scientists to understand how their stellar masses affect the rate of star formation within them. The research team included Brazilian astrophysicists Roberto Cid Fernandes of the Federal University of Santa Catarina—who, in 2005, developed Starlight, a software code that analyzes light emitted by galaxies to reconstruct the history of their stellar populations and conduct a kind of star archeology—and his doctoral student, André Luiz de Amorim.

The research confirmed that galaxies with hundreds of billions of stars and very high masses formed most of their stars more than five billion years ago from the inside out, and today, these galaxies are true star sanctuaries. Smaller galaxies with only a few billion stars are old, but they continue to form stars in all their regions.

The study was based on data from the CALIFA survey (Calar Alto Legacy Integral Field Area Survey), a collaboration of 80 researchers from 13 countries whose mission is to observe details of star formation in approximately 600 galaxies. The project, begun in 2010, uses a telescope at the Calar Alto Observatory in Andalucía, Spain.

Evolutionary profile

Galaxy mass influences the rate of star formation



The sample of 105 galaxies, as described in Astrophysical Journal Letters, is insignificant when compared with the billions of galaxies in the visible Universe. It is small, too, when compared with the total number of galaxies—approximately one million—already observed by the largest astronomical survey ever conducted, the Sloan Digital Sky Survey (SDSS), which was accomplished through the efforts of another international consortium using a telescope in the United States. However, while the SDSS analyzed light from galaxies as if each one were a point in the sky, the CALIFA survey uses a more costly and complex technique that divides each galaxy into a thousand pieces and analyzes the light from each piece separately. The result is a map that reveals the differences in the physical and chemical properties of the various parts of the galaxy.

The CALIFA survey observes galaxies that are at relatively close distances—70

105
galaxies between 70 million and 400 million light-years from the Sun have been analyzed in the project

IMAGES CALIFA AND SDSS

"The lower-mass galaxies continue to form stars, while for the higher-mass galaxies, the party's over," Fernandes says

UGC 9476
Low mass and continuing star formation

million to 400 million light-years away—in the Milky Way. These galaxies are neither distant enough to observe what they were like in the remote history of the Universe nor close enough to identify their stars individually.

CRITICAL MASS

The most important selection criterion was to observe galaxies with the greatest variety of colors and luminosities. When seen from more or less the same distance, young galaxies are bluish, while older ones are reddish. Luminosity serves as an indicator of a galaxy's mass: the brighter it is, the more stars it contains. "The idea was to ensure a diversity of galaxies in order to have an overall view," Fernandes says.

By analyzing the CALIFA data using Starlight, the researchers determined what combination of young and old stars contributed to the light from each piece of the galaxies. Following this method, the astrophysicists identified when and with what frequency the stars formed in various galactic regions.

The first difference confirmed by the study concerns the rate of star formation. Galaxies with a mass of more than 70 billion suns condensed all their gas into stars rapidly when they were young and formed most of their stars five billion years ago. Galaxies of the same age but less than 10 billion solar masses expel their gas sparingly. "The lower-mass galaxies continue to form stars at a respectable rate, while for the higher-mass galaxies, the party's over," Fernandes says.

Another difference lies in the order of star formation. The low-mass galaxies formed their stars more or less at the same time throughout, starting slightly earlier in their outer regions. In the high-mass galaxies, however, the opposite occurred: star formation began earlier in the center and moved outward. This pattern, in fact, appears to have occurred in the Milky Way itself, a galaxy of approximately 60 billion solar masses. "The regions farther from the center of the Milky Way have fewer heavy chemical elements than the inner regions," explains astrophysicist Hélio J. Rocha-Pinto of the Federal University of Rio de Janeiro, who studies remnants of collisions between the Milky Way and dwarf galaxies. "This is indirect evidence that the stars in the inner region formed first and chemically enriched that part of the galaxy more rapidly."

This difference between the center and the periphery, however, does not increase with galaxy mass. It reaches its maximum in galaxies of approximately 70 billion solar masses, in which the stars in the center were formed twice as quickly as those on the periphery.

"There is something special about that critical mass," Fernandes says. However, no one knows exactly what that something special is. Rocha-Pinto suggests that the critical mass is the mass beyond which galaxies do not grow in isolation. Scientists believe that the larger galaxies were formed out of mergers of smaller galaxies—events in which star formation increases in the centers of the recently formed galaxies.

Fernandes, however, calls attention to another possibility. Large galaxies have black holes at their centers that are so large that they would interfere with star formation. In small galaxies, fewer stars are formed because some of the gas is expelled from the galaxy during supernova explosions. Both of these effects could be less operant in galaxies of critical mass and could increase star formation. "The question," according to Rocha-Pinto, "is whether we can prove the effects we are proposing are of the magnitude to explain what we are observing."

Next year, the astronomers working on the SDSS hope to begin a similar study, called MaNGA, that will map 10,000 galaxies. "Increasing the sample by a factor of 100 will be transformational," says astrophysicist Kevin Bundy of the University of Tokyo, Japan, who is coordinating the MaNGA study. "We're going to test the CALIFA conclusions and much more." ■

Scientific article

PÉREZ, E. *et al.* The evolution of galaxies resolved in space and time: an inside-out growth view. **The Astrophysical Journal Letters**. v. 763. Jan. 2013.