

A miniature milky way: approximately 40 million light-years away, UGC 5340 is classified as a dwarf galaxy. Dwarf galaxies exist in a variety of forms – elliptical, spheroidal, spiral, or irregular – and originate in small halos of dark matter. Dwarf galaxies contain the oldest known stars.

MIDWIFE OF THE GALACTIC ZOO

TEXT: THOMAS BÜHRKE

IMAGE: NASA, ESA & LEGUS TEAM



Stars cluster in galaxies of dramatically different shapes and sizes: elliptical galaxies, spheroidal galaxies, lenticular galaxies, spiral galaxies, and occasionally even irregular galaxies. Nadine Neumayer at the Max Planck Institute for Astronomy in Heidelberg and Ralf Bender at the Max Planck Institute for Extraterrestrial Physics in Garching investigate the reasons for this diversity. They have already identified one crucial factor: dark matter.

Nature has bestowed an overwhelming diversity upon our planet. The sheer resourcefulness of the plant and animal world is seemingly inexhaustible. When scientists first started to explore this diversity, their first step was always to systematize it. Hence, the Swedish naturalist Carl von Linné established the principles of modern botany and zoology in the 18th century by classifying organisms.

In the last century, astronomers have likewise discovered that galaxies can come in an array of shapes and sizes. In this case, it was Edwin Hubble in the mid-1920s who systematized them. The “Hubble tuning fork diagram” classified elliptical galaxies according to their ellipticity. The series of elliptical galaxies along the diagram branches off into two arms: spiral galaxies with a compact bulge along the upper branch and galaxies with a central bar on the lower branch. From left to right, Hubble classified the galaxies as early and late types, although he didn’t necessarily regard this as a chronological evolution.

32 The idea of an evolutionary relationship between the two basic forms emerged later: “When I first started my research in the mid-1980s, many people were convinced that giant elliptical galaxies form when two spirals collide and merge,” says Ralf Bender, who has been Director at the Max Planck Institute for Extraterrestrial Physics in Garching since 2002. Present-day astronomers do indeed observe such collisions in the universe, and computer simulations confirm the theory proposed at the time.

Collision with the Andromeda Galaxy

In several billion years, our Milky Way will likewise collide with the Andromeda Galaxy, currently about 2.5 million light years away, and swirl into an elliptical galaxy. “However, this process can only have created the small and medium-sized ellipticals, not the very large ones,” says Bender. Bender and his team have long been especially focused on determining the age of galaxies, and their work has cast doubt on the existing model. Just how do you go about determining the age of a galaxy? The current theory is that the Big Bang only produced light elements, almost exclusively hydrogen and helium. The heavier elements first had to bake in the hot interior of stars in fusion reactions known as “stellar nucleosynthesis” and they were then released in stellar explosions. They dispersed in space and formed the raw material for the next generation of



PHOTO: PETER FRIEDRICH

Pursuing the evolution of galaxies: Ralf Bender studies the formation and evolution of galaxies. Bender is a Director of the Max Planck Institute for Extraterrestrial Physics and observes ancient, luminous star clusters, which are thought to be the forerunners of today’s giant ellipticals.

“The size and density of the halos were key.”

RALF BENDER

stars. This development progressed from generation to generation. The more heavy elements a star contains, the later it was born in the course of cosmic evolution and, from our perspective, the younger it is.

With this in mind, Ralf Bender observed luminous elliptical galaxies whose light had taken nine billion years to reach us. In other words, the scientists were looking far back into the past, when the universe was just under five billion years old. One theoretical analysis suggests that these galaxies are the forerunners of today's giant ellipticals, which contain up to a trillion stars. Bender and his colleagues measured the abundance of the various elements in the galaxies from then and now and discovered that these giant galaxies formed about two billion years after the Big Bang, the majority of their stars having been born within a period of just one billion years. After this early vigorous baby boom, star births declined and soon ceased altogether. The elliptical galaxies we see today, therefore, contain primarily

older stars. They could be regarded as retirement homes for stars.

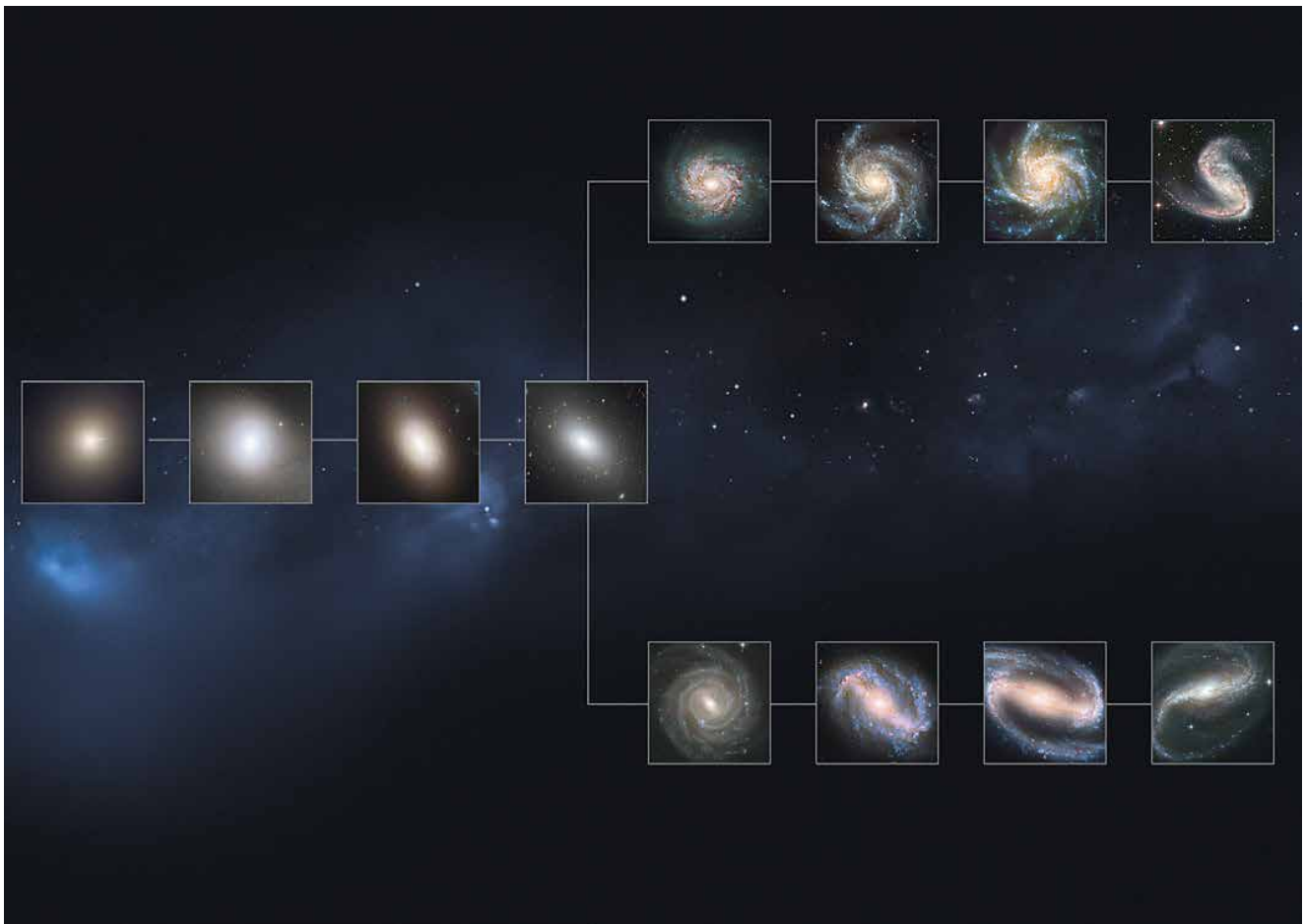
Spiral galaxies like our Milky Way have developed quite differently. They have developed over a longer period of time, and new stars continue to form within them. Furthermore, even the largest known spiral galaxies are not massive enough to merge and form a giant elliptical. "In much the same way that humans didn't evolve from today's apes, but from more evolved hominids, elliptical galaxies didn't evolve from the predecessors of the spirals we see today," explains Ralf Bender. "It is, however, conceivable that they were created by the merging of very large and dense star clusters."

Scientists had long doubted whether such huge accumulations of stars could have formed in the early universe, but recent discoveries confirm this. Scientists at the Max Planck Institute for Astronomy in Heidelberg, Germany, have discovered a disk-shaped galaxy that

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Surprising kinship: spiral galaxies (left) have long been recognized by astronomers as a conventional galaxy shape; viewed from outside, our Milky Way is similar in appearance. What is new, however, is the realization that globular clusters (right) also belong to this family – as the core regions of former dwarf galaxies.





GRAPHIC: NASA, ESA, M. KORNMESSE

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Cosmic tuning fork: the astronomer Edwin Hubble was the first to classify galaxies based on their form – from spheroidal to elliptical (top), spiral (top right), and barred spirals (bottom right). However, this scheme does not represent an evolutionary sequence for galaxies.

had already reached the impressive mass of 70 billion solar masses a mere 1.5 billion years after the Big Bang. This puts it in the size range of our Milky Way. And an international team recently used the Atacama Large Millimeter/submillimeter Array (ALMA) operated by the European Southern Observatory (ESO) to discover approximately one hundred large, highly evolved galaxies dating from one to one-and-a-half billion years after the Big Bang. All these observations are forcing cosmologists to reconsider their models. The standard theory is that initially the universe was solely composed of a large number of small star accumulations, which then collided, merged, and slowly grew. This “hierarchical” scenario would mean that large galaxies could only exist in a later phase of the universe. But this has been definitively disproved. What then determines which galaxy types arise? Dark matter is the answer.

“We’ve identified three populations of different ages.”

NADINE NEUMAYER

Dark matter is matter that only interacts with “ordinary” matter through gravitation

After the Big Bang 13.8 billion years ago, the primordial gas consisting mainly of hydrogen and helium on the one hand, and dark matter on the other, formed a fairly evenly distributed nebula. Researchers still don't know exactly what dark matter is, but at present everything points to the existence of an unknown form of elementary particle that makes itself felt solely through its gravitational effects. Most notably, its particles exert no repulsive electrical forces on each other. This was crucial at the beginning of the universe; gravity tended to condense this mixture of matter into large clumps. However, the hydrogen and helium atomic nuclei were electrically charged and repelled each other. This prevented the hot gas from compressing. Dark matter particles, on the other hand, exert no electrical forces and clumped together to form huge clouds and long filaments. Termed “dark matter halos” by astronomers, these acted like gravity traps, sucking in the normal gas particles. The particles accumulated like marbles in a trough and condensed into the first stars and galaxies.

“The size and density of these halos, as well as their distribution, were critical in determining the diversity of galaxy types,” says Ralf Bender. The denser a halo was, the faster it collapsed, and the faster it dragged the gas with it. If, in this turbulent initial phase, several halos merged together, huge galaxies could form, rapidly leading to the generation of a huge number of stars. This was how elliptical galaxies formed soon after the Big Bang. Today, we see the stars in these galaxies orbiting around the center on all possible trajectories. Spiral galaxies, on the other hand, take many billions of years to form and maintain their uniform structure. “Spiral galaxies need time in isolation without suffering major collisions,” says Bender.

Hence, spiral galaxies were formed in halos that were so widely dispersed that they didn't impinge on each other. “You can still see this in our Milky Way today,” says the Max Planck researcher. “Together with the

Andromeda Galaxy and a few other stellar systems, it forms the Local Group, whose collective average density is very low.” Large, dense halos, on the other hand, formed regions like the Coma cluster, with its two giant elliptical galaxies.

While Ralf Bender focuses on the most massive galaxies, Nadine Neumayer, who heads a Lise Meitner group at the Max Planck Institute for Astronomy, is investigating smaller “dwarf” galaxies. For a long time, these were regarded as the “gray mice” of the universe. They can also be ellipsoidal, spheroidal, spiral, and irregular in form, but because of their dimness, only the closest ones can be observed. At present, researchers know of 24 dwarf galaxies orbiting our Milky Way.

SUMMARY

Recent observations and computer simulations increasingly support the scenario that large clouds (halos) of dark matter existed after the Big Bang that acted as gravity traps, within which galaxies of all sizes formed.

Huge elliptical galaxies also formed relatively soon after the Big Bang.

Dwarf galaxies can plunge through large galaxies, stripping the dwarfs of their outer, lightly bound stars. What remains is a compact globular cluster, similar to that at the center of our Milky Way.

Their formation is consistent with the dark matter scenario: large galaxies were formed in the large halos, while in contrast only small amounts of matter flowed into the small ones, subsequently condensing to form stars. Depending on the density of the halos, small ones collided into large ones and dispersed or remained as satellites. “Because the flow of matter into these small halos dwindled very quickly, the supply for new stars likewise diminished,” Neumayer says. “That's why we tend to find the oldest stars in dwarf galaxies, as evidenced by their elemental abundance.”

The connection between dwarf galaxies and globular clusters is a new discovery. The latter also orbit large galaxies; some 150 of these clusters are currently known to orbit the Milky Way. However, they are not

considered to be galaxies. They were once believed to be the oldest objects in the universe, in which no stars have formed for a long time. But this picture is changing. One case in point is a dwarf galaxy in the constellation Sagittarius.

Discovered only in the 1990s, this dwarf galaxy in Sagittarius is located outside the plane of the disk of our Milky Way. Astronomers at the Max Planck Institute in Heidelberg have recently discovered that it possesses a long tail of stars. This developed because the dwarf galaxy's orbit around the Milky Way is nearly perpendicular to the plane of the disk. Over the past billions of years, it has crossed the disk several times, “stripping” stars from its outer region and leaving only



those bound more tightly within its central region. Especially significant is the fact that the core of the Sagittarius dwarf galaxy is a globular cluster. The cluster's former designation, Messier 54, is indicative that it was discovered more than 200 years ago, but the dwarf galaxy surrounding it remained unidentified.

In a departure from the previous standard explanation for globular clusters, a recent analysis of the elemental abundances within Messier 54 revealed its eventful history. "We have identified three stellar populations of different ages, approximately 2.2, 4.3, and 12.2 billion years old," says Nadine Neumayer. These ages, in combination with the calculated stellar orbits, have yielded the following explanation. The oldest of these stars formed less than two billion years after the Big Bang. The younger stars may have formed when the dwarf galaxy crossed the plane of the Milky Way, during which it accumulated gas from which the new stars formed. After further passages through the Milky Way, the dwarf galaxy will eventually shed its entire mantle, leaving only the globular cluster. "We suspect this is very similar to what happened to the globular cluster Omega Centauri," Neumayer says. Our galaxy's largest globular cluster, Omega Centauri has a mass of 3.5 million suns and can also look back on a complex evolutionary history, and also recently revealed a tail of barely visible stripped-off stars.

Invisible giant in the center of a dense star cluster

The question whether all globular clusters are in fact cores of former dwarf galaxies is at present impossible to answer. But they are definitely a source of surprises, as was demonstrated just a few years ago. An international team that included Nadine Neumayer observed a dwarf galaxy located near the center of the large elliptical galaxy Messier 60. This ultra-compact system contains more than a hundred million stars, all within a relatively small volume measuring 160 light-years in diameter. At its center, however, the researchers discovered a black hole of 21 million solar masses. No other galaxy contains a central object that accounts for such a large fraction of its total mass. "Interestingly, we find a similar mass ratio at the center of the Milky Way," says the Max Planck astronomer.

At the center of our galaxy resides a black hole of around four million solar masses. Reinhard Genzel of the Max Planck Institute for Extraterrestrial Physics and Andrea Ghez from the U.S. were awarded this year's Nobel Prize in Physics for their detailed analysis of this black hole. This dark giant resides in the middle of an ultra-compact star cluster of 25 million stars. Nadine

Neumayer has measured the elemental abundance of the stars in this cluster and has deduced that most were formed more than eight billion years ago. However, it also contains a young generation, which was formed approximately one billion years ago within a comparatively short period of time.

Nadine Neumayer is investigating whether this cluster represents a merger of high-mass globular clusters that have gravitated towards the center and subsequently formed additional stars. This research also sheds light on how supermassive black holes formed. The latest research undertaken by the Heidelberg astronomers reveals that black holes containing up to ten billion solar masses existed as early as one to two billion years after the Big Bang. One of the most interesting questions in cosmology today is how these giants were able to grow so rapidly to this gigantic size and what influence they had on the evolution of galaxies. One hypothesis is that, early on, intermediate-mass black

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Research in the library: Nadine Neumayer (right) heads a Lise Meitner Group at the Max Planck Institute for Astronomy. Together with her team, she studies dwarf galaxies and star clusters.

holes existed, comprising perhaps tens of thousands of solar masses, and that they grew by merging with other black holes and by sucking up gas. So far, however, no galaxies of this kind have been definitively identified. “Intermediate-mass black holes of this type should exist at the center of globular clusters,” says Nadine Neumayer, “but our current telescopes are unable to detect them.”

Neumayer is pinning her hopes on an instrument called MICADO, which will yield hyper-accurate images and will be Earth’s largest telescope – the ESO’s Extremely Large Telescope. It is being developed in an international consortium led by the Max Planck Institute for Extraterrestrial Physics with major contributions from the Max Planck Institute for Astronomy. This mega-telescope will usher in a new era for science, as well as for Ralf Bender and Nadine Neumayer.

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GLOSSARY

DARK MATTER

About 27 percent of the universe is made up of invisible matter that only interacts through gravitation. Researchers are still unable to determine the nature of this matter. Candidates include axions, WIMPs (weakly interacting massive particles), and sterile neutrinos.

HALO

A roughly spherical region in which a galaxy is embedded. Halos are composed of various types of matter, such as hot gas (X-ray halos) or dark matter.

