The window into the past

A little galaxy on the outskirts of our own Milky Way has the power to transform what we know about the origins of galaxies – but as **Jasmin Fox–Skelly** explains, we have to solve its mysteries first.

The Hubble Ultra Deep Field, which is our deepest look into the Universe yet. Some of the smallest, faintest galaxies pictured here existed as long ago as 13.3 billion years and many galaxies like Segue 1 could have existed during this time. Image: NASA/ESA/H Teplitz and M Rafelski (IPAC/ Caltech)/A Koekemoer and Z Levay (STScI)/R Windhorst (Arizona State University).

In the constellation Leo, about 75,000 light years away from Earth, lies a tiny galaxy a billion times dimmer than the Milky Way. Containing just a few hundred ancient stars, Segue 1 is a fossil remnant of the prehistoric Universe, a galaxy whose growth was stunted for an unknown reason, but the existence of which offers a unique window into the conditions of the early cosmos.

Discovered in 2007, astronomers first believed Segue 1 to be a globular cluster of stars orbiting the Milky Way as a satellite (Segue 1's name comes from the Sloan Extension for Galactic Understanding and Exploration survey). Yet further investigations revealed large amounts of dark matter, the hallmark of a galaxy. Astronomers were puzzled though, as most galaxies have billions of stars (our own Milky Way has hundreds of billions) and yet this galaxy has only a few hundred.

Anna Frebel, an assistant professor of physics and astronomy at the Massachusetts Institute of Technology, used the Las Campanas Observatory's Magellan Telescopes in Chile and the W M Keck Observatory in Hawaii to analyse the light from six of Segue 1's brightest red giant stars. By splitting the light up into a rainbow, she could see tell-tale colours missing from the spectrum that corresponded to specific elements. This told her that the stars contained just trace amounts of heavier elements such as iron. This chemical fingerprint tells us a great deal about the age of Segue 1.

Shortly after the big bang, clouds of hydrogen and helium collapsed to form the first stars. In the hot cores of these stars, heavier elements were in time forged by the process of nuclear fusion. When the stars died, they exploded as supernovae, creating even heavier elements and expelling them into space. The next generation of stars were born partly from this material, meaning that each successive generation would contain more and more heavy elements. The fact that Segue 1 contains almost exclusively hydrogen and helium tells us that it must have been one of the very first galaxies to have formed and that its development must have somehow been stunted, as it did not produce later generations of stars with further heavier elements. In short, it seems that Segue 1 went through a single brief bout of star formation about thirteen billion years ago (shortly after the big bang) and then stopped forever. The big question is, why?

"What we see leftover today in Segue 1 are the low mass stars that have long lifetimes," says Frebel. "We think that when these stars formed, larger stars formed at the same time. Because of their extreme mass the larger stars spent up their fuel much quicker and exploded in massive supernovae a long time ago. These first and earliest supernovae in Segue 1 must have evacuated all the gas from the galaxy, preventing additional star formation."

Alternatively, reionisation may explain the stunted growth. When it first came into being the Universe was so hot that all hydrogen was ionised: the constituent protons and electrons were free and could not combine to form atoms. Eventually the Universe cooled enough to allow atomic hydrogen to form, from which the first stars were born. Around 13.2 billion years ago, those hot stars blasted out enough radiation to reionise the hydrogen gas around them, halting the formation of further stars. Could this explain what is being observed in Segue 1?

"As stars formed in the early Universe, they contributed to an increasingly ultra-violent radiation field that ionised the cold gas out of which stars themselves were forming," says Marla Geha, associate professor of Astronomy at Yale University. "Large galaxies have sufficient gas reservoirs to shield themselves from this radiation field and continue forming stars over long timescales. However, the faintest galaxies likely could not protect themselves and their gas reservoir was quickly ionised and evaporated, quenching star formation very early on."

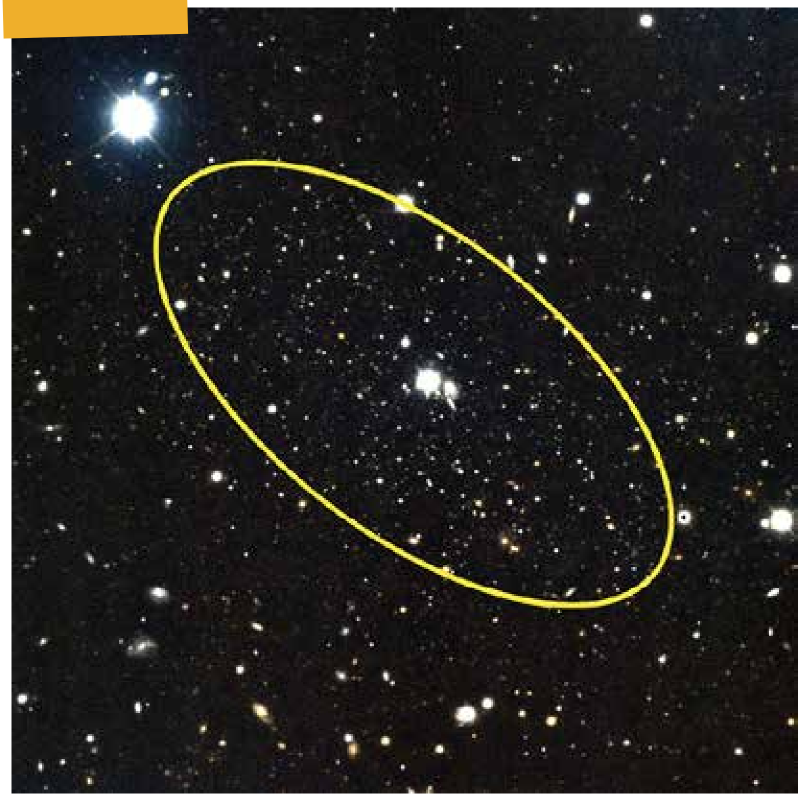
A less likely possibility is that the dwarf galaxy could once have been much larger, but subsequently lost most of its stars to the Milky Way. However, the uniformly low amounts of heavy elements found in the stars make this unlikely, as it would mean that the Milky Way selectively only took the metal-rich stars from the galaxy.

Deep time

Whatever the reason for Segue 1's arrested development, the miniature galaxy offers us a unique insight into the primordial Universe, providing clues to how the first galaxies were formed. Numerous observations have suggested that rather than forming in sudden bursts, the first galaxies may have formed from small 'protogalaxies' with similar masses to Segue 1.

In one key observation astronomers using the Hubble Space Telescope detected light from the deepest reaches of the cosmos. They looked back in time to about 13.3 billion years ago – when the first galaxies were forming – and at a small patch of sky known as the Hubble Ultra Deep Field (HUDF). What they saw hinted at an infant universe populated by countless small galaxies like Segue 1. The astronomers found that the number of galaxies steadily increased as time went on, supporting the idea that the first galaxies did not form in a sudden burst but gradually assembled their stars from the merging of small building blocks.

"The Hubble Ultra Deep Field recently analysed by astronomers found that the Universe was populated at that



Segue 1 is so faint it is hard to distinguish from the stars in the sky around it. Image: Marla Geha/W M Keck Observatory.

time by myriad systems with masses comparable to that of Segue 1," says Richard Ellis, professor of Astronomy at the California Institute of Technology in Pasadena. "Only a small fraction of those systems survived to the present day; many merged with one another to form larger galaxies and some were tidally destroyed as they orbited more massive galaxies."

Computer simulations support this, but they also suggest that a few of the dwarf galaxies avoided this fate. Yet despite Segue 1's stunted growth, its characteristics do not seem to provide any reason as to why it was one of the lucky ones, according to Ellis. "That's why studying it is so important as it gives us a rare glimpse of what was once an abundant population of very early galaxies," he says.

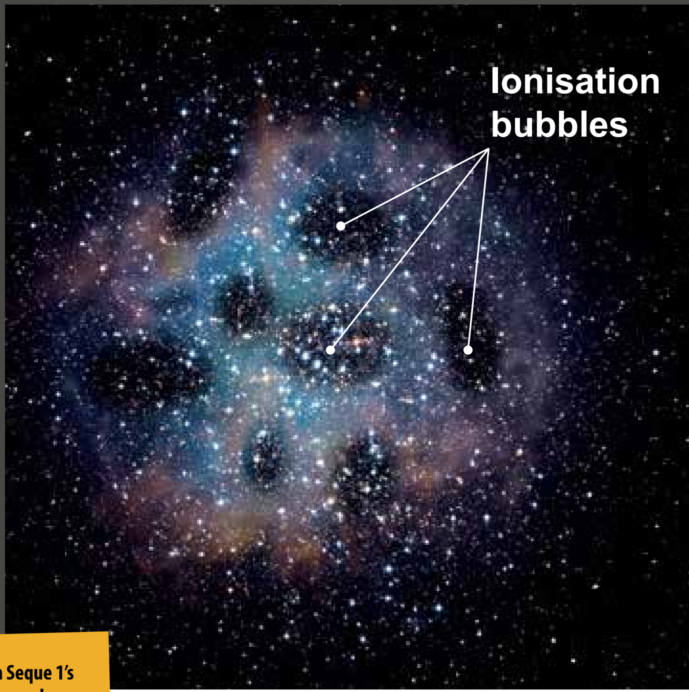
When galaxies stop making stars

So is what happened to Segue 1 unique or are there other galaxies that suffered a similar fate? It turns out that galaxies can stop producing stars for a number of reasons. Many of these reasons have to do with processes that destroy the key ingredient of star formation – cold gas. Without cold gas, no stars can be born. There are two main types of galaxies, namely spiral galaxies and elliptical galaxies. Spiral galaxies are industrious star-making factories, but elliptical galaxies are generally devoid of gas and dust and thus cannot make new stars. Astronomers suspect that many galaxies begin their life as a spiral, fruitfully giving birth to new stars. Over time they slow down their production lines and settle into old age as elliptical galaxies.

What is responsible for this slowing of the production line? Galaxies colliding with one another can prematurely bring star-making to an end. The Large Magellanic Cloud (LMC), for example, which is a nearby dwarf galaxy, has undergone external 'ram pressure stripping' where the gas from the smaller galaxy has been ripped out as the LMC falls through the halo of our bigger galaxy, the Milky Way. As the crucial ingredient for star-making is cold gas, any process that removes this from a galaxy will eventually kill star formation. The Milky Way itself is on a collision course with the neighbouring Andromeda Galaxy. Although the merger will not happen for another three to five billion years, it is possible that mergers between big galaxies plays some part in killing star-formation, turning spiral galaxies into dead elliptical ones. The irony is that during the merger itself star formation can reach its most active levels, before dropping off as all the gas is used up or expelled.

Mergers are not the only possible reason that galaxies stop forming stars. Hiding at the centres of all galaxies are supermassive black holes that exert a huge influence on their galaxies, including possibly suffocating star formation. Usually galaxies stop producing stars when they have run out of cold hydrogen gas, the crucial star-making ingredient. However, scientists found a number of elliptical galaxies that had plentiful stores of the gas remaining. So why were these galaxies not making any more stars? When the astronomers looked closer they found filaments of hot gas — over a million degrees Celsius — that were threading through the pools of cold gas. The hot gas was offloading its energy into the cold gas, stopping it from coalescing and forming stars. The big question is, where was the hot gas coming from? It turns out the hot gas is a product of the supermassive black holes in the galaxies' centres.

As the black holes pull in matter, they propel jets of protons and electrons at nearly the speed of light into intergalactic space. The jets shake up the galaxies' gas, dragging around the hot gas filaments and preventing the cold gas from coalescing into new stars. In the most extreme cases, the black hole jets can heat the gas so much that it too begins to escape the galaxy, expelling it into intergalactic space where it can no longer be used. Black hole jets can become active in spiral galaxies as well as elliptical galaxies.



When Seque 1's stars were born, its more massive stars could have produced enough ultraviolet light to have ionised all the star-forming gas in the little galaxy, preventing any further stars from forming. The massive stars died out, leaving behind just a smattering of fainter, longer-lived stars. AN graphic by Greg Smye–Rumsby.

An empty galaxy

So galaxies can stop producing stars through a combination of mergers, fuel exhaustion and suppression by black holes. However, according to Anna Frebel, the processes are quite different to that of Segue 1. "Gas evacuation does play a role in large galaxies, but usually the galaxies don't get emptied like Segue 1 did," she says.

Timeline of the early Universe

The big bang, 13.8 billion years ago

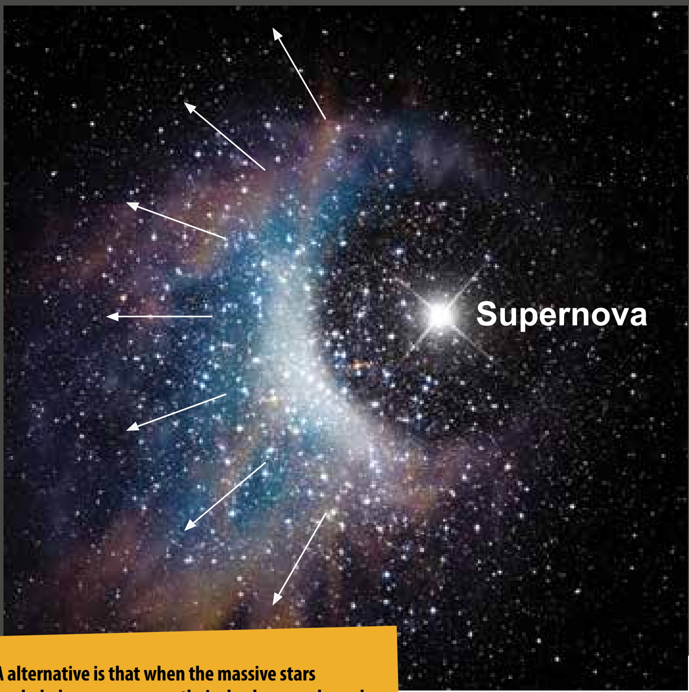
After the big bang the Universe was born, which consisted of a hot, ionised plasma of hydrogen and helium that rapidly cooled as the Universe expanded.

The Dark Ages, 370,000 years after the big bang

Once the Universes' temperature had fallen far enough, protons and electrons combined to make neutral hydrogen and helium atoms, but with nothing to create light the Universe fell dark.

First stars formed, several hundred million years later

Clumps of hydrogen gas drew together under the force of gravity and, after several hundred million years, the densest of the growing clumps began to form the first stars, which ignited by thermonuclear fusion to throw a dim light back into the Universe.



A alternative is that when the massive stars exploded as supernovae, their shockwaves cleared out much of the star-forming material in Segue 1. AN graphic by Greg Smye–Rumsby.

A less likely scenario is that the Milky Way stripped stars and gas from Segue 1, however, this does not explain why the stars of Segue 1 have so few heavy elements. AN graphic by Greg Smye–Rumsby.

What makes Segue 1 different is that, in contrast to all other galaxies, its process of star formation halted at what would normally be an early stage of a galaxy's development. No other dwarf galaxies as depleted as Seque 1 have ever been found, yet mini-galaxies like Segue 1 could be plentiful, but unseen. Only Segue 1's close proximity to the Milky Way makes such a small, dim galaxy detectable.

"Galaxies like Segue 1 should be common," says Geha. "We should see very old galaxies like this throughout the Milky Way and beyond. At the moment, we can only find Segue 1-like galaxies over very limited distances corresponding to roughly a percent of the volume of the Milky Way. However there are deeper imaging surveys currently in progress that could detect many more galaxies like Segue 1."

In the meantime astronomers will have to be content with the window into the early Universe that Segue 1 offers.

"The earliest phase of galaxy formation is very hard to study so having an ancient early galaxy like Segue 1 is like adding another important piece to the puzzle," says Anna Frebel. "It's like finding some baby pictures that suddenly helps to better understand galaxies' infancies and youths."

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The N44 star-forming nebula in the Large Magellanic Cloud sports a 'super-bubble', where radiation from hot stars is ionising the gas. In this case, the super-bubble appears blue, which is X-ray emission from the ionised gas. If enough super-bubbles expanded in Segue 1, they could have ionised all the star-forming hydrogen. Image: NASA/CXC/U Mich/S Oey/JPL/ESO/WFI/2.2m.

Reionisation begins 250 million after the big bang

Stars and active black holes threw out light and ultraviolet radiation that reionised the veil of thick hydrogen and helium gas enveloping them. Observations show that reionisation began roughly 250 million years after the big bang – providing a date for the birth of the first stars.

Creation of the first galaxies, 700–900 million years after the big bang

The prevailing theory of galaxy formation is that luminous galaxies were rare in early times and that they grew from the assembly of smaller building blocks like Segue 1. The number of galaxies seems to have sharply increased between 700 and 900 million years after the big bang.

Reionisation ends a billion years after the big bang

The Universe fully awoke from its slumber, light flooding across space as reionisation was completed, bringing the Dark Ages to a spectacular end.