Ten billion years ago, galaxies were already running out of gas

A look into the distant reaches of the universe offers clues about when, why, and how star formation shuts off.

Our sun, at roughly 4.5 billion years old, is a relative latecomer to the universe. Star formation had its heyday more than 10 billion years ago, 3.5 billion years after the Big Bang. It's been declining exponentially since then. (See the article by Jeremiah Ostriker and Thorsten Naab, PHYSICS TODAY, August 2012, page 43.)

But not all galaxies were invited to the party. Even when the rate of star formation was at its peak, half of the most massive galaxies were creating almost no new stars. Quiescent galaxies have only increased in number since then, because once a galaxy's star formation shuts off, it rarely turns back on.

Astronomers don't know why some galaxies stop forming new stars, why the shutdown seems to be so sudden and permanent, or why it happens for some galaxies so early. Galaxies distant enough to provide a window into what was happening in the universe so long ago are often too faint to study in the requisite detail.

Now the REQUIEM collaboration (short for "Resolving Quiescent Magnified Galaxies"), co-led by Katherine Whitaker of the University of Massachusetts Amherst and Sune Toft of the Niels Bohr Institute in Copenhagen, has identified a new piece of the puzzle.[1] In a study of half a dozen quiescent galaxies, chosen because their Earthbound light is boosted by gravitational lensing, Whitaker and colleagues found that the galaxies had literally run out of gas: They stopped forming stars because they lacked the necessary cold hydrogen gas to make them.

The result is far from the final word on the matter. It doesn't explain where the gas went—was it simply used up and never replenished, expelled from the galaxy somehow, or heated up into a form that's incapable of condensing into stars? Nor does it prove that all quiescent galaxies are quiescent for the same reason.

But the result does suggest that at least one mechanism is capable of depleting a galaxy's star-forming gas extremely early in the universe's history—at a time when most other galaxies had plenty.

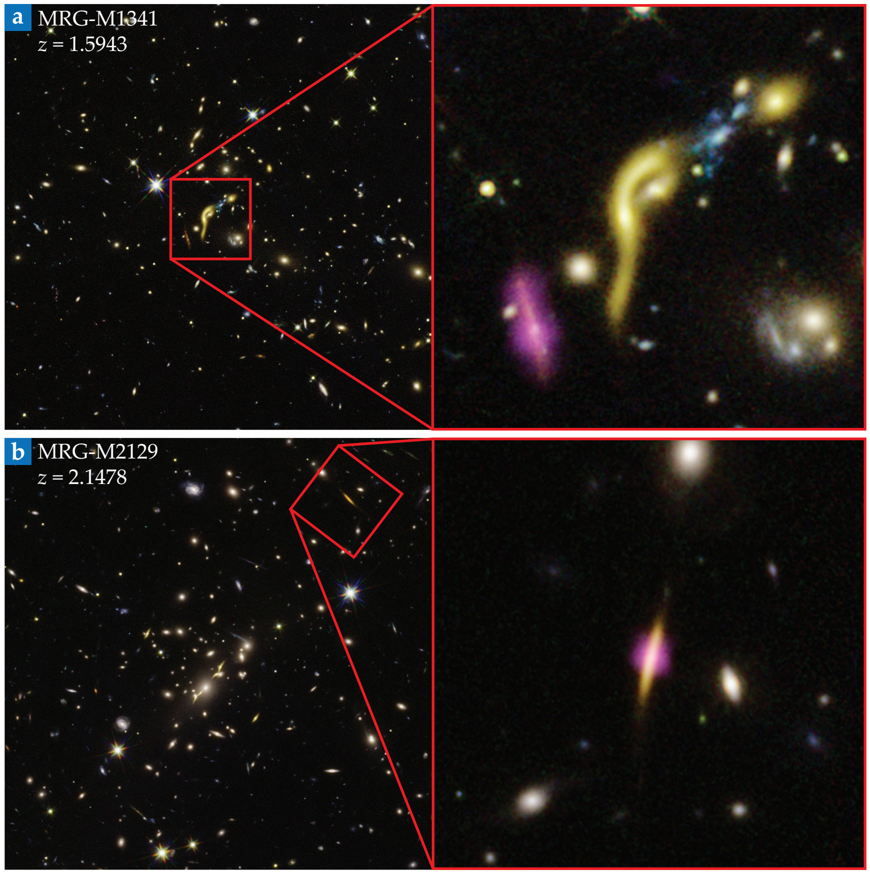

FIGURE 1. GRAVITATIONAL LENSING allows researchers to hunt for dust—a proxy for cold hydrogen gas, the stuff of star formation—in distant galaxies at high redshift z. Here, the dust signal (purple) is superposed on images from the *Hubble Space Telescope*. **(a)** Several highly lensed galaxies, including the one at the center of the right panel, produce no detectable dust signal at all. **(b)** Others show a weak dust signal that, mysteriously, appears to emanate from only part of the galaxy. (Images courtesy of NASA, the European Space Agency, Katherine Whitaker, and Joseph DePasquale.)

Counting dead galaxies

Stars in galaxies other than our own are too distant for telescopes to distinguish, let alone to observe their creation. So how do astronomers know which galaxies are forming new stars and which aren't?

The key is that not all stars are created equal. The heaviest main-sequence stars, with masses more than 10 times that of the Sun, are bright, hot, and blue, and they burn themselves out in as little as 3 million years. At the other end of the continuum, stars less than a tenth of a solar mass are cooler and redder, with expected lifetimes of hundreds of billions of years.

A galaxy's color is thus a record of the kinds of stars it contains. If it emits a lot of blue light, it must be actively making new stars to replenish the short-lived blue stars that are burning themselves out. If blue light is absent, on the other hand, the galaxy is no longer making blue stars, or indeed any stars: It's quiescent—or more colloquially, "red and dead."

For extremely distant galaxies, the measurement is a bit more complicated, because a galaxy's light can be reddened either by the cessation of star formation or by the redshift caused by the expansion of the universe. Those two phenomena have different effects on the shape of

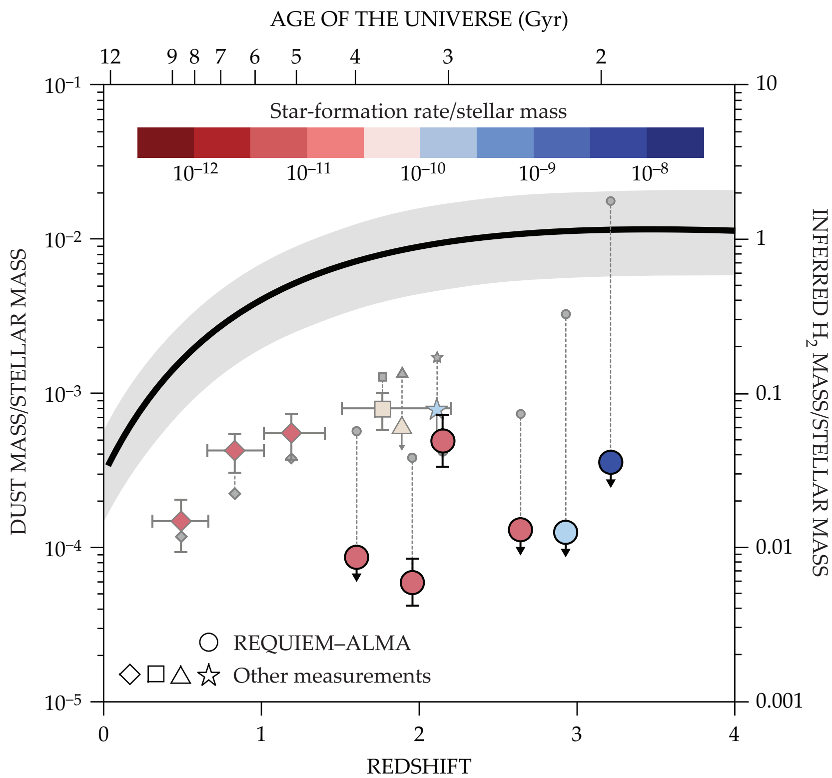

FIGURE 2. SURPRISINGLY LITTLE dust and hydrogen gas is observed in six quiescent REQUIEM target galaxies (colored circles). The amount is low compared with prior measurements[3] of other quiescent galaxies, the expected average for massive galaxies (solid line), and even the expectation based on the galaxies' own star-formation rates (gray symbols). The colors represent the fraction of each galaxy's mass forged into new stars per year. The most strongly redshifted galaxy (dark blue) has a high star-formation rate as averaged over the past 100 million years; it's included in the sample because its star formation has rapidly shut down since then. (Adapted from ref. 1.)

the spectrum, and astronomers are adept at disentangling them to separately measure a galaxy's redshift z and star-formation rate.

To study a distant galaxy in detail, however, the faint, redshifted light often doesn't suffice. That's where REQUIEM comes in, with the idea to exploit gravitational lensing. If a distant galaxy lies directly behind a massive foreground object, the object's gravitational heft can exert such a pull on the galaxy's light that more of the light is bent toward Earth.

That configuration is rare in absolute terms, but out of the billions of galaxies in the universe, some are aligned just right. From a decade of combing through galaxy survey data, the REQUIEM researchers identified 10 suitable target galaxies.[2] All are magnified by lensing by up to a factor of 30. All are distant, with redshifts between 1.6 and 3.2, meaning that their light dates from between 9.5 billion and 11.5 billion years ago. And they're all quiescent: While most are fully red and dead, a few contain some stars blue enough to be less than 100 million years old but have rapidly stopped forming new stars since then.

Gas and dust

The present work uses the Atacama Large Millimeter/Submillimeter Array (ALMA) in Chile to study six of the REQUIEM target galaxies—all that the facility's time would accommodate so far. The ALMA signal, at a wavelength of 1.3 mm, comes not from the galaxies' stars but from their interstellar dust, a proxy for H_2 gas.

Measuring the galaxies' H_2 content directly isn't an option because H_2 molecules themselves are essentially invisible. They're symmetric and lack electric dipole moments, so they don't absorb or emit radiation when they rotate and vibrate. They're visible to telescopes only when they're hot enough to excite into higher electronic states, not when they're cold enough to condense into regions dense enough to become stars.

To observe cold H_2 gas, astronomers need to look for some other substance that's found with it. One option is carbon monoxide, an asymmetric molecule that does have a dipole moment and thus a cold spectral signature. But observing CO is expensive, because it requires greater spectral resolution than most telescope images provide.

The other option is to look for dust. Dust grains grow when gas molecules stick together, explains Whitaker, and "in the local universe, we observe that where you have gas, you have dust." Typical local galaxies contain 100 times as much H_2 as they do dust, and the REQUIEM researchers assumed that their target galaxies do as well. But they don't know for sure—precisely because the dust content has never been measured before in galaxies at such high redshifts. "That's a big assumption that goes into this work," says Whitaker.

The data were collected during 2018 and 2019. (ALMA suspended its operations in March 2020 due to the COVID-19 pandemic.) As each new batch of data arrived, the researchers grew more surprised: The dust signal was almost entirely absent. Four of the six galaxies, including the one shown in figure 1a, showed no observable dust at all; the ALMA signal, shown in purple in the figure, emanated only from other objects in the field of view. The best the researchers could obtain was an upper bound on the dust content.

The other two galaxies, including the one in figure 1b, exhibited weak dust signals. But they presented another mystery: The dust wasn't shaped like the rest of the galaxy. Gravitational lensing caused each galaxy to appear elongated, and the dust signal is confined to only part of it. "What's going on there?" asks Whitaker. "We still don't understand what that means."

A mysterious absence

Overall, as shown in figure 2, the six REQUIEM galaxies (colored circles) had a median dust mass fraction of less than 0.01%, from which the researchers inferred a median H_2 mass fraction of less than 1%. That's a surprisingly small number by several standards. It's less than what was observed in other studies (the other colored symbols in figure 2) that focused on a slightly lower redshift range.[3] It's less than the average amount of gas that must have been present in massive galaxies to power their star formation (the solid line). It's even, in most cases, less than the amount of gas that would be expected based on the galaxies' own rates of star formation (the small gray circles).

"But I think the most important thing," says Whitaker, "is that these are null detections. We're still not going deep enough to really constrain how little cold gas and dust are there." Among the team's next steps is to keep collecting more data with ALMA—now back up and running after its pandemic shutdown—to tighten their upper bounds on the galaxies' dust content.

Because the REQUIEM study included just six galaxies, the researchers can't tell whether the lack of dust and gas is common to quiescent galaxies in general or an unusual feature of the few they happened to sample. Small statistics are an inherent limitation of REQUIEM's approach because strong gravitational lensing of galaxies is rare. "We may eventually find a few more galaxies we can study this way," says Whitaker, "but I doubt we'll ever get to order 100."

Even so, the complete absence of cold H_2 gas in even a few galaxies so early in the universe's history is difficult to reconcile with current understanding of cosmology and galaxy evolution. Ten billion years ago, the universe was much smaller than it is now, and the concentration of intergalactic gas was much higher. Furthermore, intergalactic space was (and still is) permeated by a web of dark-matter filaments that gravitationally attract gas and channel it toward galaxies.

Theorists do have some ideas for how gas could be depleted, expelled, or overheated in early galaxies. Many of the proposed mechanisms involve active galactic nuclei (AGNs): supermassive black holes at galactic centers whose rapid accretion of matter may power the heating or expulsion of a galaxy's gas. As the REQUIEM researchers continue to gather data on their galaxies with more instruments and in more wavelength ranges, much of their effort will focus on looking for the observational signatures of AGNs.

The soon-to-be-launched *James Webb Space Telescope*—already scheduled to gather data on the galaxy in figure 1a—could help considerably. The telescope is optimized to observe in the near-IR, a frequency range where spectral features from redshifted galaxies lie but that's difficult to observe with other existing telescopes. Furthermore, it can image in the near-IR with simultaneously high spatial and spectral resolution. So, for example, it would be able to detect gas flowing outward from an AGN at the center of a galaxy. Says Whitaker, "It really is the perfect telescope for understanding the chemical history of these galaxies."

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References

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