Astronomy

Key ingredient of galaxy formation measured

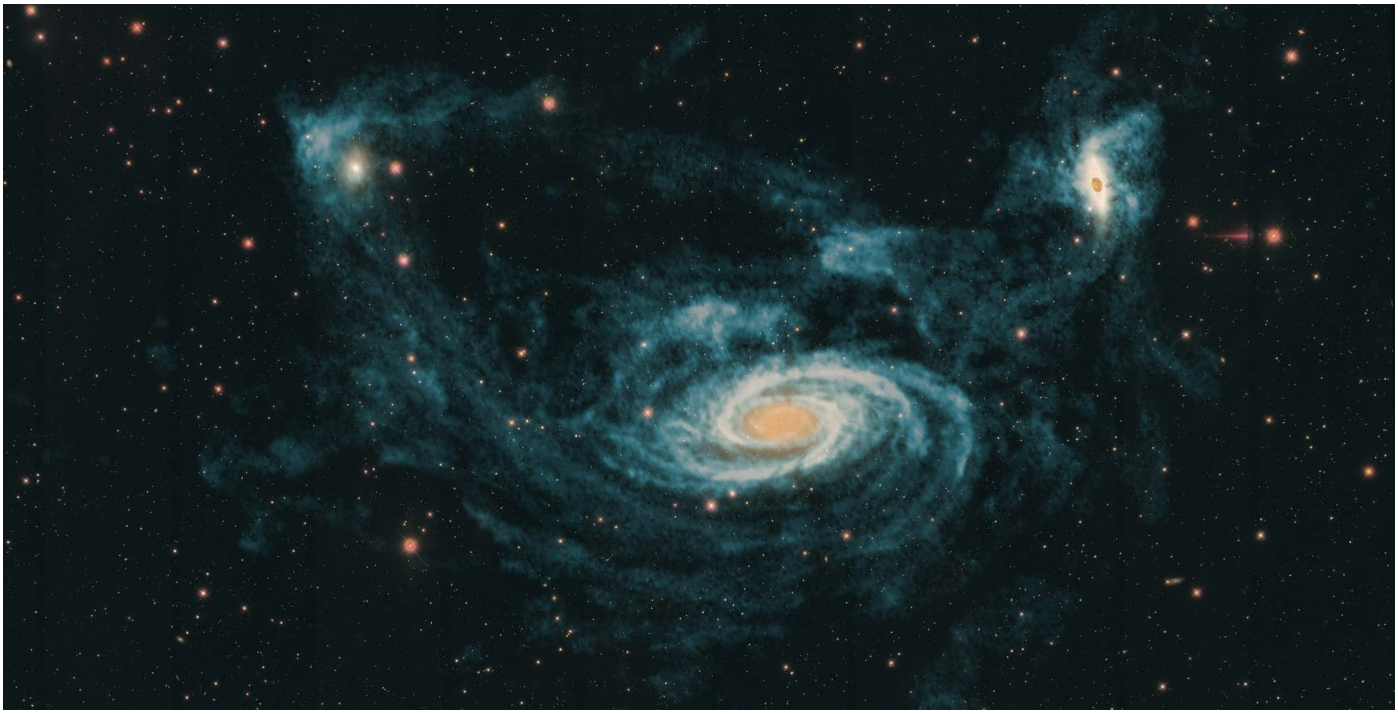
Chris L. Carilli

Measurements of faint radio emission from distant galaxies have revealed the nature of the gases that drove the epoch of peak galaxy formation — and also suggest why star-formation rates have since declined. **See p.369**

On my first day of graduate school, almost 40 years ago, my adviser asked me: "What is galaxy formation?" A stock answer for many cosmologists might be "the gravity-driven clustering of dark matter through cosmic time", where dark matter is the mysterious invisible matter that is thought to make up most of the mass in the Universe. Normal 'baryonic' matter — hydrogen, helium and minor amounts of heavier elements — is just a trace mass component that goes along for the gravitational ride as galaxies coalesce. The answer my adviser gave to his trembling graduate student was "the gravitational accretion of gas onto haloes of dark matter, and its conversion into stars". That's because, to observational astronomers such as him (and now myself), the fun begins only when baryonic matter plays its part. On page 369, Chowdhury *et al.*[1] report findings that fill a crucial gap in our knowledge of the fun part of galaxy formation.

Over the past few decades, starting from studies carried out by the Hubble Space Telescope[2], very deep observations of select fields in the sky have revolutionized our understanding of galaxy formation. These observations have provided quantitative measures of the stars and star formation in galaxies from the present day right back to the first galaxies in the Universe, just a few hundred million years after the Big Bang. The results show that the cosmic star-formation-rate density — the rate of star formation per unit volume of the Universe — peaked between 2.5 and 4.5 gigayears after the Big Bang[3] (1 Gyr is 10^9 years). Roughly half of the stars in the Universe formed during this peak epoch of galaxy assembly. The star-formation-rate density has decreased tenfold over the 10 Gyr that have passed since then.

The determination of the star-formation history of the Universe is one of the great successes of modern observational astronomy — but stars reveal only half of the story



ERWIN DE BLOK

Figure 1 | The M81 triplet of galaxies[10]. The stars in these modern galaxies are shown in red-white; these are true-colour images, obtained as a composite of multicolour optical images from the Sloan Digital Sky Survey in New Mexico. Gas clouds of neutral atomic hydrogen are shown in blue-white, and were imaged by the Very Large Array radio observatory in New Mexico by measuring the 21-centimetre hyperfine structure emission (a characteristic line in the emission spectrum of neutral hydrogen known as the H I 21-cm emission, for short). The ratio of the total mass of neutral hydrogen to the stellar mass in this system is less than 10% (refs 11, 12). Chowdhury *et al.*[1] report measurements of H I 21-cm emission from galaxies during the peak epoch of cosmic star formation, about 8.5 gigayears ago (1 Gyr is 10^9 years), and find that this ratio was about 2.5 times higher, on average, than that in present-day galaxies, such as M81.

of galaxy formation. The other half is what happens to the gas that fuels star formation. Hot gas is thought to settle from the intergalactic medium (the material found in the space between galaxies) into regions of densely concentrated dark matter, as a result of the dark matter's gravitational pull. The gas is then thought to cool to form diffuse clouds of neutral hydrogen atoms, which further cool and condense into dense clouds of hydrogen molecules (H_2), from which stars form. These concentrations of stars and gas are what we call galaxies. Unfortunately, details of the neutral atomic hydrogen that contributes to galaxy formation remain sketchy, beyond what has been observed in galaxies in our local neighborhood of the Universe.

Chowdhury *et al.* now present a direct measurement of the emission from neutral atomic hydrogen in galaxies at a period close to the peak epoch of galaxy assembly. The authors used the Giant Metrewave Radio Telescope near Pune, India, to observe a characteristic feature of the emission spectrum of neutral hydrogen, called the 21-centimetre hyperfine structure line (or the H I 21-cm emission, for short). This feature is often used as a tracer of the neutral-hydrogen content of galaxies (Fig. 1), but is very weak. Detecting the H I 21-cm emission in the spectra of individual galaxies at large distances, such as those involved in Chowdhury and colleagues' study, is problematic, even with the biggest radio telescopes in the world.

To overcome the sensitivity problem, the authors used a method known as a stacking analysis. They selected 7,653 galaxies whose distances from Earth are known from measurements of their redshifts made using optical telescopes. Redshift is a measure of the change in wavelength of a known line in the spectrum of an astronomical object, and occurs as a result of the expansion of the Universe. Redshift increases with distance from Earth and provides a measure not only of that distance, but also of the look-back time – the time elapsed between the emission of light from the source and its detection on Earth.

The light from the galaxies selected by Chowdhury and co-workers was emitted between 4.4 Gyr and 7.1 Gyr after the Big Bang, during the tail end of the peak epoch of galaxy assembly. The authors stacked the individual radio spectra from all the galaxies, lining up the sources in three dimensions (two dimensions corresponded to sky position, the third to redshift), to obtain the mean spectrum of neutral hydrogen for this set of galaxies. In so doing, they achieve a sensitivity that is roughly 90 times better than could be obtained for an individual galaxy.

Chowdhury and colleagues were thus able to determine the average mass of neutral hydrogen in galaxies towards the end of the peak epoch of star formation, about 8 billion years ago. They find that galaxies at that time contained about 2.5 times more of this gas relative to their stellar masses than do galaxies today. Given that atomic hydrogen is a key ingredient in the recipe for star formation, the discovery of an excess of this gas in distant galaxies helps explain the high star-formation rate at those early times.

Moreover, the authors find that the neutral hydrogen would have been consumed by star formation in a relatively short period of time (1–2 Gyr) – continuous gas accretion from the intergalactic medium would have been required to maintain the high rate of star formation. In other words, the slowdown of star formation observed after the peak epoch probably occurred, in part, because the supply of neutral hydrogen from the intergalactic medium was insufficient to fuel a high formation rate.

The gas content of galaxies in the distant Universe was not completely unknown before Chowdhury and co-workers' study. Previous investigations[4–7] of distant galaxies using the latest generation of radio telescopes provided the first observations of how the amount of H_2 in galaxies has evolved through cosmic time. Likewise, studies[8] of a line in the ultraviolet emission spectrum of atomic hydrogen (the Lyman-α line) have been used to determine the neutral-hydrogen content of galaxies at even greater distances than those in Chowdhury and colleagues' work. However, the Lyman-α line emitted from galaxies during the epochs studied by Chowdhury *et al.* cannot be observed from the ground, because redshifting moves it to a part of the electromagnetic spectrum to which Earth's atmosphere is opaque. Using the H I 21-cm line, the authors have therefore finally filled a gap in our knowledge of galaxy formation close to the crucial peak epoch.

> **"The authors have finally filled a gap in our knowledge of galaxy formation."**

The authors' stacking analysis has some limitations, because it provides no information about the gas 'demographics'. For example, the results cannot tell us whether the neutral hydrogen was found mostly in massive galaxies, or was distributed equally among high- and low-mass galaxies. Nor can it tell us whether the gas extends much beyond the stars in each galaxy, or whether the gas rotates in the gravitational field of each galaxy, rather than streaming into the galaxy centres.

A radio telescope called the Square Kilometre Array is currently being designed, and will be the world's largest. Its defining goal is to detect the H I 21-cm emission from individual galaxies at large cosmological distances[9]. Only instruments with this capability will be able to address the detailed questions about gas demographics and morphology on a case-by-case basis. Chowdhury and colleagues' results suggest that studies of the H I 21-cm emission hold great promise.

The authors' detection – even as a statistical mean – of H I 21-cm emission from galaxies during a crucial period of star formation is a watershed moment in our understanding of how baryonic matter is taken up and used by galaxies. It also indicates a clear pathway of research that will guide future studies with the Square Kilometre Array.

Chris L. Carilli is at the National Radio Astronomy Observatory, Socorro, New Mexico 87801, USA.
e-mail: ccarilli@nrao.edu

1. Chowdhury, A., Kanekar, N., Chengalur, J. N., Sethi, S. & Dwarakanath, K. S. *Nature* **586**, 369–372 (2020).
2. Williams, R. E. *et al. Astron. J.* **112**, 1335 (1996).
3. Madau, P. & Dickinson, M. *Annu. Rev. Astron. Astrophys.* **52**, 415–486 (2014).
4. Decarli, R. *et al. Astrophys. J.* **882**, 138 (2019).
5. Riechers, D. *et al. Astrophys. J.* **872**, 7 (2019).
6. Tacconi, L. J., Genzel, R. & Sternberg, A. *Annu. Rev. Astron. Astrophys.* https://doi.org/10.1146/annurev-astro-082812-141034 (2020).
7. Walter, F. *et al. Astrophys. J.* (in the press).
8. Wolfe, A. M., Gawiser, E. & Prochaska, J. X. *Annu. Rev. Astron. Astrophys.* **43**, 861–918 (2005).
9. Staveley-Smith, L. & Oosterloo, T. *Proc. Advancing Astrophysics with the Square Kilometre Array (AASKA14)* https://doi.org/10.22323/1.215.0167 (2014).
10. de Blok, W. J. G. *et al. Astrophys. J.* **865**, 26 (2018).
11. Sheth, K. *et al. Publ. Astron. Soc. Pac.* **122**, 1397–1414 (2010).
12. Walter, F. *et al. Astron. J.* **136**, 2563–2647 (2008).