Large molecular gas reservoirs in ancestors of Milky Way-mass galaxies nine billion years ago

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The gas accretion and star formation histories of galaxies like the Milky Way remain an outstanding problem in astrophysics1,2. Observations show that 8 billion years ago, the progenitors to Milky Way-mass galaxies were forming stars 30 times faster than today and were predicted to be rich in molecular gas3, in contrast to the low present-day gas fractions (<10%)4–6. Here we show the detection of molecular gas from the CO ($J = 3–2$) emission (rest-frame 345.8 GHz) in galaxies at redshifts $z = 1.2–1.3$, selected to have the stellar mass and star formation rate of the progenitors of today’s Milky Way-mass galaxies. The CO emission reveals large molecular gas masses, comparable to or exceeding the galaxy stellar masses, and implying that most of the baryons are in cold gas, not stars. The total luminosities of the galaxies from star formation and CO luminosities yield long gas consumption timescales. Compared to local spiral galaxies, the star formation efficiency, estimated from the ratio of total infrared luminosity ($L_{IR}$) to CO emission, has remained nearly constant since redshift $z = 1.2$, despite the order of magnitude decrease in gas fraction, consistent with the results for other galaxies at this epoch7–9. Therefore, the physical processes that determine the rate at which gas cools to form stars in distant galaxies appear to be similar to that in local galaxies.

Studies of the distribution of stellar ages and elemental abundances in the Milky Way and M31 have shown that most of their stars formed in the distant past, more than seven billion years ago10–12. This agrees with recent work showing that star formation in present-day galaxies with the mass of the Milky Way peaked more than 8 billion years ago13, at $z > 1$, with star formation rates (SFRs) that exceed $30 M_\odot$ yr$^{-1}$, compared with a present-day SFR of $1.7 \pm 0.2 M_\odot$ yr$^{-1}$ for the Milky Way13.

Theoretical models explain periods with high SFRs as a result of rapid baryonic gas accretion from the intergalactic medium (IGM), which leads to high cold gas concentrations in galaxies at earlier times14. These models predict that the gas settles into rotationally supported, highly turbulent disks, which fragment to form stars15. Observations of star-forming galaxies at $z > 1$ (stellar masses, $M_\star > 2 \times 10^{10} M_\odot$) show evidence for gas-rich rotating disks16–19, supporting these theories. However, the situation is far from settled for more common lower mass ($M_\star \sim 10^{10} M_\odot$) galaxies such as the progenitors to the Milky Way. Some models20 predict that these galaxies should experience early, rapid star formation, leaving low gas fractions (<10%) at redshifts $z \approx 1$. Others predict that the gas flows from the IGM can perturb and disrupt the formation of disk instabilities, thereby suppressing star formation in galaxies and extending star formation histories21,22. The first step to understanding star formation in galaxies like the Milky Way is to measure the amount of the cold gas in their progenitors at $z > 1$. As the gas is the fuel for star formation, the ratio of the SFR to gas mass could be used to test the physical processes in the models23.

With the greatly improved sensitivity offered by the Atacama Large Millimeter Array (ALMA), we are now able to explore the evolution of cold molecular gas in low-mass galaxies at redshifts $z > 1$. With ALMA, we observed the $J = 3–2$ transition of CO in four galaxies with the stellar mass and SFR expected of the main progenitors to present-day Milky Way-mass galaxies at redshifts $z = 1.2–1.3$ selected from deep imaging by the FourStar Galaxy Evolution (ZFOURGE) survey24 (see the discussion in Methods). Figure 1 shows the integrated emission from the CO $J = 3–2$ transition in these galaxies, where the detections range in significance from 4.8$\sigma$ to 13.7$\sigma$ (root mean square). The CO($J = 3–2$) emission coincides with the spatial positions of the galaxies in Hubble Space Telescope (HST) imaging (Fig. 1); the small offsets are consistent with astrometric calibrations and ALMA beam smearing. Table 1 gives the measured properties of these galaxies. The ALMA detections of CO emission probe the molecular mass in galaxies with the stellar mass and SFRs that the main progenitor of the Milky Way was expected to have a few billion years ago. This provides an important extension of previous work, as the galaxies in our sample have lower stellar masses and SFRs than have been generally possible to study at these redshifts25.

CO is the most luminous tracer of molecular hydrogen (H$_2$), the fuel for star formation. The CO specific intensity from the $J$ to $J+1$ transition, $I_{CO(J\rightarrow J+1)}$, is a function of both the gas density and temperature. In high redshift galaxies, studies have shown that the average excitation of CO($J = 3–2$) is similar to that of star-forming regions in the Milky Way26, and we assume an integrated Rayleigh–Jeans brightness temperature line ratio27, $r_{10} = I_{CO(1\rightarrow 0)} / I_{CO(3\rightarrow 2)} \approx 0.66$. The total CO luminosity in the $J = 1$ to 0 transition is then $L_{CO} = 3.25 \times 10^{22} r_{10}^3 I_{CO(3\rightarrow 2)} \nu_d^{1/2} D_L^2 (1+z)^{3}$, where $\nu_d$ is the frequency (in gigahertz) of the CO emission in the observed frame and $D_L$ is the luminosity distance in megaparsecs. Table 1 displays the $L_{CO}$ values. Using lower values of $r_{10} \approx 0.4–0.5$, as indicated in some other studies of star-forming galaxies at $z \approx 1–2$25,27, would increase the $L_{CO}$ values slightly, but would not change our conclusions.

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The combination of the CO luminosity and the luminosity from newly formed stars provides a crucial constraint on the star formation efficiency (SFE). We use the thermal infrared luminosity ($L_{\text{IR}}$, measured over 8–1,000 μm in the rest frame), which originates from dust in dense molecular clouds heated by young stars, and is directly proportional to the total SFR. We measured $L_{\text{IR}}$ for galaxies in our study using model fits to fluxes measured from Spitzer Space Telescope and Herschel Space Observatory imaging covering 24–160 μm (see Methods). Table 1 displays these values. They span $L_{\text{IR}} = (1.5–2.7) \times 10^{11} L_{\odot}$ (corresponding to SFRs of 15–30 $M_\odot$ yr$^{-1}$). Uncertainties are approximately 0.2 dex (60%) and are dominated by systematics from differences in the infrared model (see Methods).

Figure 2 shows the SFE, defined as $L_{\text{IR}} / L_{\text{CO}}$, as a function of $L_{\text{CO}}$ for the $z = 1.2–1.3$ galaxies in our sample compared with control samples. With ALMA we are now able efficiently to probe the CO luminosities of $z > 1$ star-forming galaxies at a factor of two lower than was previously possible. The galaxies in our sample have SFEs typical of the upper range of both local spiral galaxies and more massive, high-redshift star-forming galaxies. In such galaxies, star formation occurs in rotationally supported disks. In at least two of our galaxies, the CO($J = 3–2$) spectra show line profiles with a strong double peak (see Methods). This and the apparent presence of spatial velocity shear (see Methods) observed in our analysis of the CO data suggest that the same may be true for all of the $z = 1.2–1.3$ galaxies in our sample. Therefore, although both the SFRs and gas fractions are substantially higher in these distant galaxies, star formation probably occurs in rotating disks, where the physical processes governing the evolution of the gas appear to be similar to.

**Figure 1** Images of Milky Way progenitors at redshifts $z = 1.2–1.3$. The top four images are ALMA images of the redshifted CO($J = 3–2$) emission for each galaxy. The hashed ellipses show the size of the synthesized ALMA beam of each observation. The contours denote the emission at 2 times the noise. The bottom four images are combined HST images at 0.78, 1.1 and 1.6 μm (approximately the rest-frame U-, V-, and R-band emissions). The contours denote ALMA CO($3–2$) emission with levels at 2, 2$\sqrt{2}$, 4 times the noise.
those of spiral galaxies in the local Universe. In contrast, the SFEs of more luminous, rarer objects, for example ultraluminous infrared galaxies (ULIRGs), quasi-stellar objects (QSOs) and submillimetre galaxies (SMGs), are significantly enhanced in the local and distant Universe. A prevailing theory is that ULIRGs, QSOs and SMGs are galaxies at $z > 1$ star-forming regions because the SFEs are similar (see Methods). Table 1 lists these values. These conditions seem to be inconsistent with the galaxies in our sample, suggesting that major mergers are not common among the main progenitors of Milky Way-mass galaxies at $z = 1.2–1.3$.

The inverse of the SFE is proportional to the gas consumption timescale, which corresponds to a range of 200 to 700 Myr for the galaxies in our sample. In contrast, the consumption timescales for ULIRGs, QSOs and SMGs are less than 10 Myr. Star formation in the average, main progenitor of Milky Way galaxies at $z = 1.2–1.3$ appears to be long-lasting, and comparable to findings for other star-forming disk galaxies at high redshifts.

The CO luminosity is very high, and the molecular gas fractions for the galaxies in our sample at $z = 1.2–1.3$, where we adopt the ratio of CO luminosity to mass in H2, are much greater than that for Galactic star-forming regions because the SFEs are similar (see Methods). Table 1 lists these values. Figure 3 shows the molecular gas fractions, $f_{\text{gas}} = M_{\text{gas}}/(M_{\text{star}} + M_{\text{gas}})$, derived from CO observations as a function of $M_{\text{star}}$. While present day Milky Way-sized galaxies have low gas fractions, $f_{\text{gas}} < 10\%$, the results from our sample imply that the main progenitors to these galaxies at $z = 1.2–1.3$ have much higher values: in three of the galaxies in our sample the molecular gas mass was greater than or equal to the stellar mass ($f_{\text{gas}} \gtrsim 50\%$). This is consistent with the indirect gas fractions of galaxies at these redshifts that were inferred from the thermal dust emission. The higher $f_{\text{gas}}$ values also argue against models with early, rapid gas consumption and favour longer lasting, feedback-regulated star formation.

The high molecular gas fractions and SFRs of the $z = 1.2–1.3$ galaxies in our sample imply that they will double their stellar mass within the gas consumption timescale. Therefore, at $z > 1.2$, these galaxies have most, but not all, of the fuel needed to produce the $M_{\text{star}} \approx 5 \times 10^{10} M_{\odot}$ in stars in Milky Way-mass galaxies at present (Fig. 3). The average baryon accretion rate from the IGM must exceed $6 M_{\odot} \text{yr}^{-1}$ at earlier times ($z > 1.2$) to account for the galaxies’ total stellar and molecular masses. In contrast, the galaxies only need to acquire $\sim 30–50\%$ more baryonic mass from $z = 1$ to the present (even accounting for losses from stellar evolution), which corresponds to an average gas accretion rate of only $\sim 1–2 M_{\odot} \text{yr}^{-1}$. This reflects a dwindling supply of fresh baryonic gas. Therefore, Milky Way-mass galaxies appear to have accreted most of their gas at $z > 1.2$, during the first few billion years of history.
Selection of Milky Way-mass galaxy progenitors. We selected galaxies as targets for ALMA observations of the CO(3–2) transition that have the typical stellar mass and SFR of progenitors to Milky Way-mass galaxies at $z = 1.2–1.3$. We identified progenitors of galaxies with the present-day stellar mass of a Milky Way-mass galaxy ($M_\star = 5 \times 10^{10} \, \text{M}_\odot$) using abundance-matching techniques\(^\text{39}\). The progenitors to such galaxies had a median stellar mass of $\log(M_\star/M_\odot) = 10.21$ at $z = 1.1–1.4$ (ref.\(^\text{1}\)). These abundance matching methods give a stellar mass $-0.2$ dex lower than those selected at a constant co-moving number density at these redshifts\(^\text{38}\). More recent work has shown that progenitors of Milky Way-mass galaxies have a continuous stellar mass distribution between $5 \times 10^9$ and $7 \times 10^{10} \, \text{M}_\odot$ at $z = 2–4$\(^\text{40}\). While observations of CO in $z > 2$ galaxies have probed stellar masses down to $\log(M_\star/M_\odot) > 10.4$ (ref.\(^\text{1}\)), these correspond to the more massive progenitors of present-day Milky Way-mass galaxies. Our sample extends studies of the CO emission to the median stellar mass of progenitors of present-day Milky Way galaxies.

We also selected galaxies with the typical SFRs of the Milky Way-mass progenitors for observations with ALMA. In our previous work we used deep Spitzer and Herschel imaging to measure an average total $L_\text{IR}$, $L_\text{IR} = (2.0 \pm 0.1) \times 10^{11} \, \text{L}_\odot$, for all Milky Way-mass progenitor galaxies in this redshift and stellar mass range in ZFOURGE\(^\text{1}\). This corresponds to a SFR of $21 \pm 2 \, \text{M}_\odot\, \text{yr}^{-1}$.

In summary, we used the following criteria to select targets for ALMA:

1. Photometric redshift, $1.1 < z < 1.4$
2. Stellar mass, $-0.15 \, \text{dex} < \log(M_\star/M_\odot) < 10.2 < +0.15$
3. SFR, $-0.15 < \log(SFR/M_\odot\, \text{yr}^{-1}) < 1.3 < +0.15$
4. Measured spectroscopic redshift

The restrictions on photometric redshift, stellar mass and SFR results in the selection of galaxies with stellar mass and SFR within 0.15 dex (that is, within 40%) of the expected median values of the progenitors to Milky Way-mass galaxies.

The final selection criterion requires that the galaxies have a redshift measured from spectroscopy. This ensures that the redshift accuracy is sufficient for the redshifted CO(3–2) emission line to fall within the frequency range of an ALMA spectral window. While the ZFOURGE photometric redshifts are good ($\sigma/(1+2\times\text{C})<0.1$), they are not sufficient for this purpose.

Of the 24,690 galaxies in the full ZFOURGE catalogue, 39 satisfied the first three criteria at the time of our proposal for ALMA for cycle 2 observations (2013 December), seven galaxies satisfied all of our selection criteria (including having a published spectroscopic redshift in the literature)\(^\text{1}\). From these, we selected four objects that offered some contrast in SFR (spanning nearly 0.3 dex). For the analysis presented here, we re-derived stellar masses and uncertainties using the FAST code\(^\text{41}\) with an extended stellar population library (including a broader metallicity range of 0.2–1.0 Z\(_\odot\)) and a finer grid spacing of stars in the mass range. For this study, we selected targets from the earlier version 2.1 ZFOURGE catalogues. These include Spitzer Infrared Array Camera imaging (spanning 3.6–8.0 μm), ancillary ground-based imaging (spanning 0.3–2.5 μm) and broad-band optical imaging. This ensures that the redshift accuracy is sufficient for the redshifted CO(3–2) transition.

To measure total infrared luminosities, $L_\text{IR}$, we fit models of the infrared spectral energy distribution (SED) to the flux densities shown in Supplementary Table 1. Because the data sample the Wein side of the thermal emission comprehensively, the constraints on $L_\text{IR}$ are quite robust. Supplementary Fig. 2 shows the fits using the published models\(^\text{42}\) which bracket the range of values. The slight differences in the shapes of the infrared spectral energy distributions lead to systematically different values of $L_\text{IR}$, where $L_\text{IR}$ values from the templates of Rieke et al. are higher by $\Delta(\log(L_\text{IR})) = -0.1 \pm 0.2$ dex. We have also calculated $L_\text{IR}$ using data where objects are detected at 24 μm, but this produces changes in $L_\text{IR}$ by $<15\%$ in most cases. We therefore adopt the $L_\text{IR}$ from the fits to the models of Rieke et al. for all the infrared data, which we report in Table 1. If we instead adopt the results from the fits to the models of Chary & Elbaz, the SEDs would decline, and gas consumption timescales would increase for the $z = 1.2–1.3$ galaxies in our sample studied here. This would bring the SFRs further in line with local spiral galaxies, strengthening that conclusion.

The total $L_\text{IR}$ for the $z = 1.2–1.3$ galaxies in our sample span $L_\text{IR} = (1.5–3.2) \times 10^{11} \, \text{L}_\odot$, as listed in Table 1. In these galaxies, most of the bolometric emission from star formation is emitted in the thermal infrared range. In contrast, according to our measurements, the rest-frame ultraviolet emission (uncorrected for dust extinction) contributes only 4–6% to the total $L_\text{IR}$ in these galaxies. This is consistent with mean values measured in local luminous infrared galaxies\(^\text{43}\).

ALMA observations and data reduction. Our cycle 2 ALMA observations were taken between 2015 April 6 and 2015 May 2 in Band 7 with 36 antennas in the CS4-2 configuration, and these observations provided a maximum baseline of 348.5 m. For each source, we configured ALMA to observe in four spectral windows, 1.875 GHz per window, spanning the frequency range 134.48–156.90 GHz (depending on the expected frequency of the CO(3–2) transition for each source). We centred the CO(3–2) line in one of the spectral windows, assigning the other three windows to the other CO transitions in the literature\(^\text{44}\). The ALMA integrations ranged between 37.3 and 41.8 m in time. One source (ZFOURGE CDFS 6497) was erroneously observed twice, and received double the exposure time. The other spectral windows probe the continuum of the line. Flux, phase and band-pass calibrators were also obtained. Supplementary Table 2 provides details about the observations for each source.

We reduced the data with the Common Astronomy Software Applications (CASA) version 4.5.0-REL with the calibration script supplied by the National Radio Astronomy Observatory. We then ran the cleaning algorithm with natural weighting. For the spectral window containing the CO(3–2) transition, we fitted models of the infrared emission to the optical spectroscopic redshift obtained from the Rieke et al. catalogue\(^\text{44}\). The velocity offsets between the CO redshift and the redshift from the optical spectroscopic redshift range from $-30$ to $+100$ km s$^{-1}$, which is consistent with uncertainties in the redshift measurements.

We also attempted to measure the continuum for each galaxy by cleaning and combining the spectral windows excluding channels expected to have CO emission. We failed to detect any signal of the continuum; we also therefore made no correction for the continuum to the CO line (Fig. 3).

Supplementary Fig. 3 shows the spectra of the CO(3–2) emission for the four galaxies. For each galaxy, there is positive emission in the channels at the expected location of the CO(3–2) line. To determine the peak of emission we fitted the spectra to models using single and double gaussian distributions. The velocity offsets between the CO redshift and the redshift from the optical spectroscopic redshift range from $-30$ to $+100$ km s$^{-1}$. This is consistent with uncertainties in the redshift measurements.

We created total intensity maps of the CO(3–2) lines in each galaxy by combining the channels showing positive emission around the expected position of each line. We also created first moment (velocity) and second moment (velocity dispersion) images (Fig. 2) of the galaxy using a standard Gaussian fitting technique. From the total intensity maps corrected for the primary beam, we measured integrated flux densities for the CO(3–2) transition, $I_{300-200}$, for each galaxy in our sample using the first moment images corrected for the primary beam.
the two-dimensional profile fitting tool in CASA. These are presented in Table 1, and are in the range \( I_{\text{CO}(3-2)} \approx 0.11–0.33 \, \text{Jy km s}^{-1} \). However, the SNR of the integrated values in Table 1 are significantly lower in the range 2.3–7.7, the detection significance (measured from the peak of the emission) is much higher, with SNRs in the range 4.8–13.7.

As discussed in the next section, the ALMA spectra in Supplementary Fig. 3 show evidence for complex velocities, except for ZFOURGE CDFS 467, which contains a calibration issue. The factor for converting CO to molecular gas is \( \alpha \), and therefore the molecular gas accounts for the majority of baryons in the gas phase. The constant of proportionality \( \alpha \) is given by

\[
\alpha = \frac{M_{\text{gas}}}{L_{\text{CO}}} \tag{1}
\]

Based on the \( L_{\text{CO}}/L_{\text{H}_{2}} \) ratios, the conditions in the \( z = 1.2–1.3 \) galaxies in our sample appear to be similar to those in normal star-forming regions and star-forming disk galaxies, which show values of \( \alpha \approx 4 \, M_{\odot} \left( \text{K km s}^{-1} \right)^{-1} \). The factor for converting CO to molecular gas is \( \alpha \approx 4.3 \, M_{\odot} \left( \text{K km s}^{-1} \right)^{-1} \) for star-forming regions in the Milky Way galaxy and in normal star-forming galaxies. The gas in our sample have \( L_{\text{CO}}/L_{\text{H}_{2}} \) ratios consistent with those of other normal star-forming galaxies (Fig. 2). We therefore adopt \( \alpha \approx 3.6 \, M_{\odot} \left( \text{K km s}^{-1} \right)^{-1} \) for star-forming galaxies in the young Universe. Nature 463, 781–784 (2010).

Conventions. Throughout, we assume a Chabrier initial mass function at \( z < 2.7 \) and a Salpeter function at \( z > 2.7 \). De Lucia et al. Cold streams in early massive haloes as the main mode of galaxy formation. Nature 457, 451–454 (2009).

\[
\begin{align*}
\text{L}_\text{CO} & = 4 \times 10^{21} \left( \frac{L}{M_{\odot}} \left( \text{K km s}^{-1} \right)^{-1} \right) \\
\text{L}_\text{H_2} & = 4 \times 10^{21} \left( \frac{L}{M_{\odot}} \left( \text{K km s}^{-1} \right)^{-1} \right)
\end{align*}
\]

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Author contributions

C.P. led the ALMA observing programme, handled the data reduction and led the writing of the manuscript. L.E., K.G., R.Q., L.S., C.S. and K.-V.T. contributed to the writing of the manuscript. I.L., K.G., R.Q., L.S., C.S. and K.-V.T. contributed extensively to the ZFOURGE data set, used in much of the analysis. S.L.E., D.F. and R.C.L. contributed to the design of the ALMA observing programme and assisted in the reduction and interpretation of the ALMA data. G.B. and K.G. assisted in the interpretation of the ALMA data. M.D. and H.I. carried out the data analysis of the Spitzer and Herschel imaging. All coauthors contributed to the writing of the manuscript and to the ALMA observing programme.

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Competing interests

The authors declare no competing financial interests.