Inefficient star formation in extremely metal poor galaxies

Yong Shi1,2, Lee Armus3, George Helou3, Sabrina Stierwalt4, Yu Gao5,6, Junzhi Wang7, Zhi-Yu Zhang8 & Qiusheng Gu1,2

The first galaxies contain stars born out of gas with few or no 'metals' (that is, elements heavier than helium). The lack of metals is expected to inhibit efficient gas cooling and star formation1–2, but this effect has yet to be observed in galaxies with an oxygen abundance (relative to hydrogen) below a tenth of that of the Sun2–4. Extremely metal poor nearby galaxies may be our best local laboratories for studying in detail the conditions that prevailed in low metallicity galaxies at early epochs. Carbon monoxide emission is unreliable as a tracer of gas at high redshift5–7, and while dust has been used to trace gas in low-metallicity galaxies5–8, low spatial resolution in the far-infrared has typically led to large uncertainties8–10. Here we report spatially resolved infrared observations of two galaxies with oxygen abundances below 10% of the solar value, and show that stars formed very inefficiently in seven star-forming clumps in these galaxies. The efficiencies are less than a tenth of those found in normal, metal rich galaxies today, suggesting that star formation may have been very inefficient in the early Universe.

The two galaxies that are the focus of this study are Sextans A, a dwarf irregular at a distance of 1.4 Mpc with an oxygen abundance of 7% of the solar value11,12, and ESO 146-G14, a low-surface-brightness galaxy at 22.5 Mpc with a 9% solar oxygen abundance11,13. Their metallicities may be similar to that of the gas out of which population II stars formed in the early Universe at redshifts around 7 to 12 (ref. 14). An effective way to estimate the total gas content in extremely metal poor galaxies is to employ spatially resolved maps of the far-infrared-emitting dust as tracers of the atomic and molecular gas; this may be done by multiplying the dust mass by an appropriate gas-to-dust ratio (GDR) that is inferred from regions with little or no active star formation, a methodology that has been extensively demonstrated in relatively metal rich galaxies7,15.

The infrared observations described here were carried out at wavelengths of 70, 160, 250, 350 and 500 μm with the Photodetector Array Camera and Spectrometer (PACS)16 and the Spectral and Photometric Imaging REceiver (SPIRE)17 on board the Herschel Space Observatory. We complement our far-infrared data with mid-infrared images from the Spitzer Space Telescope to construct the full infrared spectral energy distributions (SEDs). Far-ultraviolet images from the GALEX Space Telescope archive are used to trace un-obscured star formation. Maps of atomic gas are available in the literature for Sextans A18 and ESO 146-G1419.

Figure 1 shows multi-wavelength images of our sample galaxies. We defined the star-forming disk as an ellipse to closely follow the 10σ (~26 AB mag per arcsec2) contour of the far-ultraviolet emission, as shown in Fig. 1 and listed in Table 1. Individual star-forming clumps within the disk are identified as circled regions with elevated (>3σ) emission relative to local disk backgrounds in both far-ultraviolet and 160 μm bands after smoothing images to 28 arcsec resolution. The diffuse emission is measured by subtracting the total emission of all star-forming clumps in the disk from the integrated disk emission. For Sextans A, we also identified several individual diffuse regions that show extended emission in the 70 and 160 μm bands but with surface brightness below 3σ of local disk backgrounds. In order to derive the dust mass, including both diffuse and clumped components, we fitted the infrared SED with a standard dust model20. The best-fit SEDs are shown in Fig. 2, and derived dust masses are listed in Table 1.

With spatially resolved dust and H I maps, the total gas masses of individual star-forming clumps can be derived by multiplying their dust masses with the appropriate GDR based on regions with little or no star formation. As is usually done for nearby galaxies7–13, the GDR in the star-forming clumps is taken as the ratio of atomic gas to dust in the diffuse star-forming clumps, while small yellow dashed ellipses indicate individual diffuse regions. Figure 1 shows multi-wavelength images of our sample galaxies.

**Figure 1** | False-colour, multi-wavelength images of our sample galaxies. a, Images of Sextans A: red, the sum of Herschel 160 and 250 μm data; green, GALEX far-ultraviolet; blue, radio 21 cm data. The star-forming disk is defined as the large circle. The small white circles indicate individual dusty star-forming clumps, while small yellow dashed ellipses indicate individual diffuse regions. b, Images of ESO 146-G14; colours as a. The disk is indicated as the large ellipse while individual star-forming clumps are shown as small circles.

---

1School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China. 2Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210093, China. 3Infrared Processing and Analysis Center, California Institute of Technology, 1200 East California Boulevard, Pasadena, California 91125, USA. 4Department of Astronomy, University of Virginia, PO Box 400325, Charlottesville, Virginia 22904, USA. 5Purple Mountain Observatory, Chinese Academy of Sciences, 2 West Beijing Road, Nanjing 210008, China. 6Key Laboratory for Radio Astronomy, Chinese Academy of Sciences, 2 West Beijing Road, Nanjing 210008, China. 7Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, China. 8Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK.
region of the disk. This works because (1) the atomic gas dominates the total mass in the diffuse regions, and (2) the GDR is roughly constant in star-forming disks after removing the metallicity gradients\(^1,2\). Dwarf galaxies in general show little or no metallicity gradients across their disks\(^3\), including Sextans A, which has a variation of less than 0.1 dex (ref. 12). Table 1 lists the derived gas masses of individual star-forming clumps corrected for inclination based on the GDR of the integrated diffuse emission (GDR = 1.4 × 10\(^{-3}\)) for Sextans A and 4,400 for ESO 146-G14. For Sextans A, three individual diffuse regions have similar GDRs that are only a factor of 1.5–2 lower than the one derived from the integrated diffuse emission. Adopting a GDR of 140 at the solar metallicity\(^6\), our derived GDR values for the diffuse regions of the two galaxies scale roughly with metallicity \(Z\) as \(1/2^{1.5–1.7}\). For each star-forming clump, the star formation rate (SFR) is estimated by combining the far-ultraviolet-based (unobscured) and 24-\(\mu\)m-based (obscured) SFRs\(^2\). The uncertainties in the derived gas masses and SFRs are estimated to be around 0.3 dex and 0.2 dex, respectively.

Figure 3 shows the distribution of seven dusty star-forming clumps in the plane of SFR surface densities versus total gas mass surface densities, compared to spirals and merging galaxies\(^1,4\). When the dust is used to estimate the total gas (filled symbols), the metal-poor star-forming clumps appear to have significantly lower star formation efficiencies (SFEs) than those found in metal-rich galaxies, or those derived for the clumps using the HI gas alone (open symbols). Four extremely metal poor clumps in Sextans A show almost two orders of magnitude lower SFEs compared to spirals when measured over the similar physical scales. This result still holds if we adopt GDR values of three individual diffuse regions, which causes the gas densities to only drop by 0.2–0.3 dex. For ESO 146-G14, one star-forming clump shows significantly (100) lower SFEs and the remaining two have SFEs about a factor of 10 lower than spirals at sub-kpc scales and similar gas densities. If any dark molecular gas is present in the diffuse region, the derived SFEs would be even lower. For our seven metal poor clumps as a group, the Kolmogorov–Smirnov test indicates a probability of only 10\(^{-4}\) that their SFRs have the same distribution as the SFRs of spiral galaxies at comparable gas densities.

As illustrated in Fig. 3, the gas masses of individual clumps, derived from dust masses, are much higher than the atomic gas masses, indicating high molecular gas fractions. By subtracting the observed atomic gas from the dust-derived gas mass for our seven star-forming clumps, we find that the derived molecular gas mass is on average ~6 times larger than the atomic gas mass. For the star-forming clumps, the median and standard deviation of the molecular SFE (in units of yr\(^{-1}\)) is \(\log(SFE_{\text{H}_2}) = -10.8 \pm 0.6\). The log of the corresponding molecular gas depletion

---

**Table 1 | The properties of the sample**

| Region         | Right ascension (h.m.m.s.; J2000) | Declination (°.´.″; J2000) | \(m_\text{HI} \times m_\text{H}_2\) (arcsec, kpc) | Dust mass (\(M_\odot\)) | \(M_\text{H}_2 / M_\text{gas}\) | \(\log SFR_{\text{H}_2}\) (log \(M_\odot\) pc\(^{-2}\)) | \(\log SFE_{\text{H}_2}\) (log \(M_\odot\) yr\(^{-1}\) kpc\(^{-2}\)) |
|----------------|----------------------------------|-----------------------------|-----------------------------------------------|--------------------------|-------------------------------|-----------------------------------------------|-----------------------------------------------|
| Sextans A/disk | 10:11:01.4                       | -04:41:25                   | 152 × 152; 1.06 × 1.06                         | (9.5 ± 1.1) × 10\(^3\)  | (7.7 ± 0.5) × 10\(^3\)       | 2.26 ± 0.23                                  | -2.66 ± 0.2                                  |
| Sextans A/sf-1 | 10:10:56.9                       | -04:40:27                   | 22 × 22; 0.16 × 0.16                           | (9.9 ± 2.3) × 10\(^2\)  | (1.3 ± 0.5) × 10\(^3\)       | 2.0 ± 0.22                                   | -2.77 ± 0.2                                  |
| Sextans A/sf-2 | 10:11:10.0                       | -04:41:44                   | 22 × 22; 0.16 × 0.16                           | (2.0 ± 0.2) × 10\(^3\)  | (1.3 ± 0.5) × 10\(^3\)       | 2.57 ± 0.22                                   | -3.22 ± 0.2                                  |
| Sextans A/sf-3 | 10:11:06.2                       | -04:42:23                   | 32 × 32; 0.22 × 0.22                           | (1.8 ± 0.4) × 10\(^3\)  | (3.2 ± 0.6) × 10\(^3\)       | 2.21 ± 0.23                                   | -3.22 ± 0.2                                  |
| Sextans A/sf-4 | 10:10:55.5                       | -04:42:59                   | 22 × 22; 0.16 × 0.16                           | (1.6 ± 0.1) × 10\(^3\)  | (4.1 ± 0.8) × 10\(^3\)       | 2.46 ± 0.21                                   | -3.19 ± 0.2                                  |
| Sextans A/diff-1 | 10:10:53.2                      | -04:41:43                   | 38 × 20; 0.26 × 0.14                           | (5.1 ± 0.2) × 10\(^2\)  | (6.9 ± 0.7) × 10\(^3\)       | 2.0 ± 0.22                                   | -3.19 ± 0.2                                  |
| Sextans A/diff-2 | 10:11:09.2                      | -04:41:02                   | 21 × 14; 0.15 × 0.10                           | (1.8 ± 0.3) × 10\(^2\)  | (8.6 ± 0.6) × 10\(^3\)       | 2.46 ± 0.21                                   | -3.19 ± 0.2                                  |
| Sextans A/diff-3 | 10:10:54.0                      | -04:40:44                   | 27 × 18; 0.19 × 0.13                           | (3.2 ± 0.5) × 10\(^2\)  | (6.6 ± 0.7) × 10\(^3\)       | 2.0 ± 0.22                                   | -3.19 ± 0.2                                  |
| Sextans A/diffuse | 10:10:53.2                      | -04:41:43                   | 38 × 20; 0.26 × 0.14                           | (5.1 ± 0.2) × 10\(^2\)  | (6.9 ± 0.7) × 10\(^3\)       | 2.0 ± 0.22                                   | -3.19 ± 0.2                                  |
| ESO146-G14/disk | 22:13:01.3                       | -62:04:00                   | 90 × 15; 9.34 × 1.56                           | (5.9 ± 0.5) × 10\(^3\)  | (2.5 ± 0.5) × 10\(^3\)       | 1.21 ± 0.24                                   | -3.46 ± 0.2                                  |
| ESO146-G14/sf-1 | 22:13:06.0                       | -62:03:33                   | 10 × 10; 1.04 × 1.04                           | (7.5 ± 2.1) × 10\(^4\)  | (1.6 ± 0.2) × 10\(^3\)       | 1.21 ± 0.24                                   | -3.46 ± 0.2                                  |
| ESO146-G14/sf-2 | 22:13:02.5                       | -62:03:52                   | 10 × 10; 1.04 × 1.04                           | (6.2 ± 0.3) × 10\(^4\)  | (2.7 ± 0.5) × 10\(^3\)       | 1.12 ± 0.22                                   | -3.26 ± 0.2                                  |
| ESO146-G14/sf-3 | 22:12:59.0                       | -62:04:14                   | 10 × 10; 1.04 × 1.04                           | (2.7 ± 0.2) × 10\(^5\)  | (5.0 ± 0.7) × 10\(^3\)       | 1.77 ± 0.21                                   | -3.65 ± 0.2                                  |
| ESO146-G14/diffuse | 22:13:01.3                      | -62:04:00                   | 90 × 15; 9.34 × 1.56                           | (5.9 ± 0.5) × 10\(^3\)  | (2.5 ± 0.5) × 10\(^3\)       | 1.21 ± 0.24                                   | -3.46 ± 0.2                                  |

* Major and minor axis lengths are given in arcsec and kpc.
† The atomic gas to dust mass ratio. The atomic gas includes helium by multiplying HI gas by a factor of 1.36.
‡ Surface densities of total gas masses for star-forming clumps are derived from their dust masses multiplied by gas-to-dust ratio of the integrated diffuse emission, with inclination correction based on the defined disk ellipse.
§ Surface densities of SFRs are derived from the combination of infrared and far-ultraviolet tracers\(^7\), with inclination corrected based on the defined disk ellipse.

---

**Figure 2 | Infrared SEDs of individual regions were fitted to derive dust masses.** Red symbols are the Spitzer and Herschel photometric points with 1σ error bars. The blue solid line indicates the best-fit by the dust model\(^30\).
gas from forming new stars. It is possible that the molecular gas does not effectively cool due to intense radiation fields, slowing the SFRs in these environments. Warm H$_2$ gas with surface densities as high as $50 \, M_\odot \, pc^{-2}$ is seen in some blue compact dwarfs\textsuperscript{27}. Although our two galaxies are not blue compact dwarfs, the SFR surface densities of the star-forming regions in our galaxies are comparable to those found in such dwarfs. This similarity suggests the possible presence of abundant warm H$_2$ in our two extremely metal poor galaxies. Extended Data Table 6 also lists the predicted H$_2$ S(1) $17.03 \, \mu m$ line flux based on the example of Mrk 996\textsuperscript{27}. There are archived Spitzer spectroscopic observations of the region ‘sf-3’ of Sextans A. Based on the archived reduced data, after accounting for the difference between the Spitzer aperture and the size of our ‘sf-3’, the observed H$_2$ $17.03 \, \mu m$ flux is about $4 \times 10^{-16} \, W \, m^{-2}$, a factor of two lower than our predicted value.

The extremely metal poor galaxies may provide a close-up view of the highly inefficient star formation occurring in galaxies in the early Universe where population II stars formed out of gas whose metallicity was 1/10 solar or less\textsuperscript{14}. The suppressed SFEs in extremely low metallicity galaxies at early epochs may be able to reconcile some tensions between observations and theoretical models for early galaxy evolution\textsuperscript{28}.

Online Content Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper, references unique to these sections appear only in the online paper.

Received 14 April; accepted 29 August 2014.

1. Ostriker, E. C., McKee, C. F. & Leroy, A. K. Regulation of star formation rates in multiphase galactic disks: a thermal/dynamical equilibrium model. Astrophys. J. 721, 975–994 (2010).
2. Krumholz, M. R. The star formation law in molecule-poor galaxies. Mon. Not. R. Astron. Soc. 436, 2747–2762 (2013).
3. Begel, F. et al. The star formation law in nearby galaxies on sub-kpc scales. Astron. J. 136, 2846–2871 (2008).
4. Bolatto, A. D. et al. The state of the gas and the relation between gas and star formation at low metallicity: the small Magellanic cloud. Astrophys. J. 741, 12–30 (2011).
5. Elmegreen, B. G. et al. Carbon monoxide in clouds at low metallicity in the dwarf irregular galaxy WLM. Nature 495, 487–489 (2013).
6. Bolatto, A. D. et al. The Co-to-H$_2$ conversion factor. Ann. Rev. Astron. Astrophys. 51, 207–268 (2013).
7. Leroy, A. K. et al. The Co-to-H$_2$ conversion factor from infrared dust emission across the Local Group. Astrophys. J. 737, 12–24 (2011).
8. Fisher, D. et al. The rarity of dust in metal-poor galaxies. Nature 505, 186–189 (2014).
9. Hunt, L. K. et al. ALMA observations of cool dust in a low-metallicity starburst, SBS 0335–052. Astron. Astrophys. 561, A49 (2014).
10. Remy-Ruyer, A. et al. Gas-to-dust mass ratios in local galaxies over a 2 dex metallicity range. Astron. Astrophys. 563, A31 (2014).
11. Pettini, M. & Pagel, B. [OIII]/[NII] as an abundance indicator at high redshift. Mon. Not. R. Astron. Soc. 348, L59–L63 (2004).
12. Klaizae, A. Y. et al. Spectrophotometry of Sextans A and B: chemical abundances of H II regions and planetary nebulae. Astron. J. 130, 1558–1573 (2005).
13. Bergvall, N. & Ronnback, J. ESO 146–G14, a retarded disc galaxy. Astron. J. 273, 603–614 (1995).
14. Wise, J. et al. The birth of a galaxy: primordial metal enrichment and stellar populations. Astrophys. J. 745, 50–59 (2012).
15. Sandstrom, K. M. et al. The Co-to-H$_2$ conversion factor and dust-to-gas ratio on kiloparsec scales in nearby galaxies. Astrophys. J. 777, 5–37 (2013).
16. Petitpas, A. et al. The Photodetector Array Camera and Spectrometer (PACS) on the Herschel Space Observatory. Astron. Astrophys. 518, L2 (2010).
17. Griffin, M. J. et al. The Herschel-SPIRE instrument and its in-flight performance. Astron. Astrophys. 518, L13 (2010).
18. Ott, J. et al. VLA-ANGST, a high-resolution HI survey of nearby dwarf galaxies. Astron. J. 144, 123–195 (2012).
19. Peters, S. P. C. et al. The shape of dark matter halos in edge-on galaxies: I. Overview of HI observations. Preprint at http://arxiv.org/abs/1303.2463 (2013).
20. Draine, B. T. & Li, A. Infrared emission from interstellar dust. IV. The silicate-graphite-PAH model in the post-Spitzer era. Astrophys. J. 657, 810–837 (2007).
21. Draine, B. T. et al. Andromeda’s dust. Astrophys. J. 780, 172–189 (2014).
22. Westmoquette, M. S. et al. Piecing together the puzzle of NGC 5253: abundances, kinematics and WR stars. Astron. Astrophys. 550, A88 (2013).
23. Leroy, A. et al. The star formation efficiency in nearby galaxies: measuring where gas forms stars effectively. Astron. J. 136, 2782–2845 (2008).
24. Daddi, E. et al. Different star formation laws for disks versus starbursts at low and high redshifts. Astrophys. J. 714, L118 (2010).
25. Cormier, D. et al. The molecular gas reservoir of 6 low-metallicity galaxies from the Herschel Dwarf Galaxy Survey. A ground-based follow-up survey of CO(1–0), CO(2–1), and CO(3–2). Astron. Astrophys. 564, A121 (2014).

©2014 Macmillan Publishers Limited. All rights reserved
Acknowledgements Y.S. acknowledges support for this work from the Natural Science Foundation of China (NSFC), grant 11373021, the Strategic Priority Research Program 'The Emergence of Cosmological Structures' of the Chinese Academy of Sciences (CAS), grant XDB09000000, and Nanjing University grant 983. Y.G. acknowledges support from the NSFC (grants 11173059 and 11390373) and from the CAS Program (grant XDB09000000). J.W. was supported by the National 973 programme (grant 2012CB821805) and by the NSFC (grant 11173013). Z.-Y.Z. acknowledges support from the European Research Council (ERC) in the form of advanced grant COSMICISM. Q.G. was supported by the NSFC (11273015 and 11133001) and by the National 973 programme (grant 2013CB834905). We thank F. Bigiel for making his data points available to plot contours in Fig. 3, S. P. C. Peters for making available his HI gas map of ESO 146-G14 to us, and L. Piazzo for help in Herschel data reduction. Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA. This work was supported in part by the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA. It was also supported in part by a NASA Herschel grant (OT2_yshi_3) issued by JPL/Caltech.

Author Contributions Y.S. led the Herschel proposal, Herschel data reduction and the writing of the manuscript. L.A. helped develop Herschel observations and helped in the writing of the manuscript. G.H. and S.S. assisted in the Herschel proposal. All authors discussed and commented on the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to Y.S. (yshipku@gmail.com).
**Infrared flux uncertainty estimates.** The Herschel flux uncertainties are given by the following formula:

\[
\sigma = \sigma_{\text{phot, confusion}} \times A_{\text{sky}} + \frac{\sigma_{\text{phot, confusion}}}{A_{\text{sky}}} + \sigma_{\text{PSF, offset}} + \sigma_{\text{sky}} \text{ -- calibration (1)}
\]

where \(A_{\text{sky}}\) and \(A_{\text{sky}}\) are the area of target regions and sky annuli, respectively. \(\sigma_{\text{phot, confusion}}\) is the scatter of the pixel brightness distribution. Extended Data Table 3 compares our measured \(\sigma_{\text{phot, confusion}}\) to the predicted photon and confusion noises estimated using the Herschel Observing Tool (HSPOT) for our targets. The noise in our images is consistent with the quadratic sum of the HSPOT photon and confusion noise to within a factor of two. The second term in the above equation gives the scatter of the derived sky brightness. \(\sigma_{\text{PSF, offset}}\) is the flux uncertainty caused by the accuracy in positioning an aperture onto a given star-forming clump. For each star-forming region, we estimated this by randomly offsetting the peak of a modelled point spread function to 1/2 the Nyquist sampled beam and measuring the flux variation within the given source aperture. The final term is the absolute flux calibration error taken to be 20% across all wavelengths based on the PACS and SPIRE instrument handbooks as well as systematic comparisons to PACS and MIPS measurements. Extended Data Table 1 lists the quadratic sum of the first three errors. The final error term is added in quadrature when doing the SED fitting but is not used in Extended Data Table 1 as it is a systematic error of the Herschel Space Observatory. Our estimated errors are quite reasonable compared to the expected point source flux errors from HSPOT (also listed in Extended Data Table 3). Note that although in the SPIRE bands the confusion noise is 2–3 times higher than the photon noise, this can be mitigated by using a PACS 160 \(\mu\)m prior on the position. We can further compare our noise estimates to those from other Herschel observations of similar depth. For example, the Herschel lensing survey\(^{46}\) reported a 1\(\sigma\) point-source depth of 2.4 mJy at 250 \(\mu\)m and 3.4 mJy at 350 \(\mu\)m for on-source exposure per sky position of 36 min with position priors from short wavelengths, compared to our 2–4 mJy at 250 \(\mu\)m and 3–5 mJy at 250 \(\mu\)m for our 6–10 min on source exposures.

We further carried out additional checks on the measured flux by comparing Spitzer and Herschel photometry. For Sextans A, we found that individual star-forming clumps as well as the diffuse region have 70 \(\mu\)m Herschel fluxes consistent with Spitzer measurements within 30%. And the integrated light of Sextans A and ESO146-G14 at both 70 and 160 \(\mu\)m are also consistent within 30% between the Spitzer and Herschel data sets.

To check the possibility that the diffuse emission is due to the background fluctuations, we randomly position the source aperture over the observed field of view, and then compared the measured fluxes to the quoted error of the target diffuse emission. For ESO 146-G14, we can randomly position about 30 apertures and found that none of them have S/N larger than 3 at bands where the diffuse emission is detected. For Sextans A, the observed field of view is not large enough for us to perform similar exercises.

**Infrared SED fitting and dust mass measurements.** We fit the infrared data with the dust model\(^{27}\) in order to estimate the dust mass of each region. As shown above, we have three types of flux measurements, and fit all three with the dust model. We choose a Milky Way grain size distribution\(^{35}\) and fix the PAH fraction to the minimum (the total dust mass that is in PAHs, \(q_{\text{PAH}} = 0.47\)) given the low metallicity (the result does not change if this parameter is set free). To further check the effect of different dust grains, for the first type of flux measurements (m1), SMC and LMC dust grains that have different grain compositions and size distributions are also explored. Overall we thus have five dust mass measurements for each region; three of them are for different types of flux measurements with Milky Way grains (referred as m1-MW, m2-MW, m3-MW), and two are for different grain size distributions fitted to the first type of flux measurements (m1-SMC and m1-LMC).

In the following we take the m1-MW as an example to illustrate the fitting procedure. The results are plotted in Fig. 2 and listed in Extended Data Table 4. To do the fit, a 4,000 K black-body spectrum was first added to represent the emission from stellar photospheres which dominates \(<10\) \(\mu\)m. The model was then left with four free parameters, including the dust mass, the minimum (\(U_{\text{min}}\) and maximum intensity (\(U_{\text{max}}\) of the stellar radiation field that is responsible for heating the dust, and the fraction (\(1 - \gamma\)) of dust exposed to the minimum starlight intensity (that is, \(U_{\text{min}}\)). Similar to studies of dust emission in spirals\(^{5,17}\), \(U_{\text{max}}\) was further fixed to a maximum of 10\(^{6}\). We then performed SED fitting with three free parameters for Sextans A and ESO 146-G14. As listed in Extended Data Table 4, the reduced \(\chi^2\) for the majority of the fits have values of around unity, while sf-1, sf-2 and diff-3 of Sextans A have a reduced \(\chi^2\) of around 10. As shown in Fig. 2, the 160 \(\mu\)m photometry of sf-1 and diff-3 shows large deviations from the best fit, while 24 and 70 \(\mu\)m photometry of sf-2 deviates substantially from the best fit. Uncertainties in the derived dust mass were estimated by performing 100 fits to each source after adding in Gaussian noise.
We also carried out simple modified black-body fitting to infrared SEDs of Sextans A and ESO 146-G14 that have enough far-infrared photometric data points. As listed in Extended Data Table 4, the dust temperature of star-forming clumps is between 30 and 50 K while the dust in the diffuse region is about 30–40 K.

Measurements of SFR and gas mass surface densities. The SFRs of star-forming clumps were measured by combining the far-ultraviolet and 24-μm data, which represent the unobscured and obscured star-formation, respectively. The derived SFRs are uniformly assigned a 0.2 dex error to account for the systematic errors in deriving SFRs from ultraviolet and infrared photometry (the photon noise is comparatively small). The SFR surface density is further corrected for inclination based on the major to minor axis ratio of the defined disk. The final result is listed in Table 1.

With derived dust masses, we estimated the GDR of the diffuse region as the ratio of atomic to dust mass. The GDR of the integrated diffuse region is then applied to individual star-forming clumps to derive the total gas mass and thus the gas mass surface density (Σgas). Extended Data Table 5 lists the result for five fits—m1-MW, m2-MW, m3-MW, m1-SMC and m1-LMC. The associated uncertainties of Σgas are the quadratic sum of errors of dust mass measurements, errors of GDRs of diffuse regions contributed by uncertainties on Hα and dust mass estimates of diffuse regions. 0.2 dex for the GDR variation across the disk based on studies of spiral galaxies.

The result of the m1-MW fit is used as a fiducial, as listed in Table 1 and shown in Fig. 3. Our conclusions of significantly reduced SFEs in seven metal poor star-forming clumps change little if adopting other fitting results in Extended Data Table 5.

In addition, there are some concerns that the PACS may miss some extended emission of star-forming clumps change little if adopting other fitting results in Extended Data Table 5. In addition, there are some concerns that the PACS may miss some extended emission ofstar-forming clumps change little if adopting other fitting results in Extended Data Table 5.

We investigate if the derived Σgas can be significantly lowered by forcing changes in dust model parameters, specifically raising Umin, which can result in lower dust masses and hence lower gas surface densities and higher SFEs. In the following discussion, we take the m1-MW fit as the case study. For both targets, the best-fit Umin of all regions are relatively small. We thus keep the best-fit Umin for the diffuse region but gradually increase Umin of star-forming clumps to decrease their Σgas. We find that the star-forming clumps in Sextans A can move into the spiral galaxy regime of Fig. 3 if the Umin rises above 20. However, in this case the corresponding χ^2 rises to 40–60. For star-forming clumps in ESO 146-G14, the Umin needs to be larger than 15 to move into the spiral regime; however, these fits are again poor, with χ^2 values of 10–30. Therefore the significantly reduced SFEs of star-forming clumps in Sextans A and ESO 146-G14 should be robust to the change in their Umin.
Extended Data Figure 1 | Multi-wavelength images of the two galaxies.

a, Images of Sextans A in (left to right) the far-ultraviolet, H i gas, 70 μm, 160 μm and 250 μm dust emission. The large circle is the star-forming disk, small circles are star-forming clumps, and ellipses are diffuse regions. b, Images of ESO 146-G14: wavebands and disks/ellipses as in a.
### Extended Data Table 1 | PACS and SPIRE photometry for the selected regions

| Region         | Right ascension (J2000) | Declination (J2000) | sizes (arcsec) | f(70μm) (mJy) | f(160μm) (mJy) | f(250μm) (mJy) | f(350μm) (mJy) | f(500μm) (mJy) |
|----------------|-------------------------|---------------------|---------------|---------------|---------------|---------------|---------------|---------------|
| Sextans A/disk | 10 11 01.4              | -04 41 25           | 152.0 x 152.0 | 636 ± 16      | 1024 ± 18     | 644 ± 30      | 308 ± 23      | 124 ± 18      |
|                |                         |                     |               | 658 ± 16      | 1098 ± 18     | 722 ± 30      | 356 ± 23      | 155 ± 18      |
|                |                         |                     |               | 605 ± 16      | 979 ± 18      | 557 ± 30      | 236 ± 23      | 78 ± 18       |
| Sextans A/sf-1 | 10 10 56.9              | -04 40 27           | 22.5 x 22.5   | 40 ± 2        | 56 ± 7        | 55 ± 3        | 32 ± 3        | 16 ± 3        |
|                |                         |                     |               | 40 ± 2        | 56 ± 7        | 55 ± 3        | 32 ± 3        | 16 ± 3        |
|                |                         |                     |               | 39 ± 2        | 55 ± 7        | 53 ± 3        | 30 ± 3        | 14 ± 3        |
| Sextans A/sf-2 | 10 11 10.0              | -04 41 44           | 22.5 x 22.5   | 72 ± 3        | 147 ± 18      | 111 ± 4       | 52 ± 4        | 24 ± 3        |
|                |                         |                     |               | 72 ± 3        | 147 ± 18      | 111 ± 4       | 52 ± 4        | 24 ± 3        |
|                |                         |                     |               | 71 ± 3        | 146 ± 18      | 109 ± 4       | 50 ± 4        | 22 ± 3        |
| Sextans A/sf-3 | 10 11 06.2              | -04 42 23           | 32.3 x 32.0   | 265 ± 4       | 296 ± 24      | 164 ± 5       | 89 ± 4        | 33 ± 4        |
|                |                         |                     |               | 265 ± 4       | 296 ± 24      | 164 ± 5       | 89 ± 4        | 33 ± 4        |
|                |                         |                     |               | 264 ± 4       | 294 ± 24      | 160 ± 5       | 85 ± 4        | 30 ± 4        |
| Sextans A/sf-4 | 10 10 55.5              | -04 42 59           | 22.5 x 22.5   | 20 ± 2        | 69 ± 8        | 62 ± 3        | 34 ± 3        | 18 ± 3        |
|                |                         |                     |               | 20 ± 2        | 69 ± 8        | 62 ± 3        | 34 ± 3        | 18 ± 3        |
|                |                         |                     |               | 20 ± 2        | 68 ± 8        | 60 ± 3        | 31 ± 3        | 16 ± 3        |
| Sextans A/diff-1| 10 10 53.2             | -04 41 43           | 38.0 x 20.0   | 75 ± 3        | 85 ± 5        | 47 ± 4        | 27 ± 3        | <13          |
|                |                         |                     |               | 75 ± 3        | 85 ± 5        | 47 ± 4        | 27 ± 3        | <13          |
|                |                         |                     |               | 74 ± 3        | 83 ± 5        | 43 ± 4        | 23 ± 3        | <13          |
| Sextans A/diff-2| 10 11 09.2             | -04 41 02           | 21.4 x 14.6   | 30 ± 2        | 45 ± 6        | 18 ± 3        | <10          | <12          |
|                |                         |                     |               | 30 ± 2        | 45 ± 6        | 18 ± 3        | <10          | <12          |
|                |                         |                     |               | 30 ± 2        | 44 ± 5        | 16 ± 3        | <10          | <12          |
| Sextans A/diff-3| 10 10 54.0             | -04 40 44           | 27.5 x 18.5   | 44 ± 2        | 52 ± 5        | 36 ± 4        | 14 ± 3        | <13          |
|                |                         |                     |               | 44 ± 2        | 52 ± 5        | 36 ± 4        | 14 ± 3        | <13          |
|                |                         |                     |               | 44 ± 2        | 51 ± 5        | 33 ± 4        | 11 ± 3        | <13          |
| Sextans A/diffuse |                   |                      |                | 237 ± 18      | 453 ± 39      | 248 ± 33      | 99 ± 26       | <69          |
|                |                         |                     |               | 258 ± 18      | 527 ± 39      | 326 ± 33      | 147 ± 26      | <69          |
|                |                         |                     |               | 210 ± 18      | 414 ± 39      | 173 ± 33      | <78          | <69          |
| ESO 146 G14/disk| 22 13 01.3             | -62 04 00           | 90.0 x 15.0   | 110 ± 3       | 241 ± 5       | 148 ± 7       | 81 ± 7        | <78          |
|                |                         |                     |               | 110 ± 3       | 241 ± 5       | 148 ± 7       | 81 ± 7        | <78          |
|                |                         |                     |               | 110 ± 3       | 238 ± 5       | 142 ± 7       | 81 ± 7        | <78          |
| ESO 146 G14/sf-1| 22 13 06.0             | -62 03 33           | 10.0 x 10.0   | 28 ± 4        | 38 ± 6        | 29 ± 4        | 17 ± 3        | <13          |
|                |                         |                     |               | 28 ± 4        | 38 ± 6        | 29 ± 4        | 17 ± 3        | <13          |
|                |                         |                     |               | 28 ± 4        | 37 ± 6        | 28 ± 3        | 16 ± 3        | <13          |
| ESO 146 G14/sf-2| 22 13 02.5             | -62 03 52           | 10.0 x 10.0   | 36 ± 5        | 52 ± 8        | 28 ± 3        | 12 ± 3        | <13          |
|                |                         |                     |               | 36 ± 5        | 52 ± 8        | 28 ± 3        | 12 ± 3        | <13          |
|                |                         |                     |               | 36 ± 5        | 51 ± 8        | 27 ± 3        | 12 ± 3        | <13          |
| ESO 146 G14/sf-3| 22 12 59.0             | -62 04 14           | 10.0 x 10.0   | 15 ± 2        | 57 ± 9        | 49 ± 6        | 31 ± 5        | <31          |
|                |                         |                     |               | 15 ± 2        | 57 ± 9        | 49 ± 6        | 31 ± 5        | <31          |
|                |                         |                     |               | 15 ± 2        | 57 ± 8        | 49 ± 6        | 31 ± 5        | <31          |

For each region, at each wavelength, we give three types of flux measurements (top to bottom; m1, m2 and m3, see text and Methods). The 1σ flux errors are the quadratic sum of photon and confusion noise, scatter of the sky brightness, and uncertainties in the flux due to mis-centring of extraction apertures. The 3σ upper limits are given where appropriate. The uncertainties in the absolute flux calibration are not included here, but are added in quadrature before performing the SED fitting as described in the text.
Extended Data Table 2 | Spitzer photometry

| region         | f(3.6μm) (mJy) | f(4.5μm) (mJy) | f(5.8μm) (mJy) | f(8.0μm) (mJy) | f(24μm) (mJy) |
|----------------|----------------|----------------|----------------|----------------|---------------|
| SextansA/disk  | 255.33±0.06    | 157.29±0.05    | 108.28±0.26    | 59.46±0.23     | 28.98±3.00    |
| SextansA/sf-1  | 1.67±0.01      | 1.05±0.01      | <0.12          | 0.62±0.04      | 1.09±0.14     |
| SextansA/sf-2  | 1.68±0.01      | 1.36±0.01      | 0.70±0.04      | 0.48±0.04      | 3.25±0.34     |
| SextansA/sf-3  | 2.85±0.01      | 2.20±0.01      | 1.14±0.06      | 0.60±0.05      | 6.36±0.65     |
| SextansA/sf-4  | 1.17±0.01      | 0.69±0.01      | 0.34±0.04      | 0.28±0.04      | 0.97±0.13     |
| SextansA/diff-1| 1.60±0.01      | 1.01±0.01      | <0.15          | 0.81±0.04      | 2.27±0.25     |
| SextansA/diff-2| 11.96±0.01     | 7.43±0.01      | 5.83±0.03      | 2.81±0.03      | 1.11±0.13     |
| SextansA/diff-3| 0.98±0.01      | 0.78±0.01      | <0.12          | 0.93±0.04      | 1.33±0.16     |
| SextansA/diffuse | 247.96±0.06   | 151.99±0.05    | 106.00±0.29    | 57.47±0.26     | 17.31±3.11    |
| ESO146-G14/disk | 4.67±0.01     | 3.05±0.02      | 3.00±0.08      | 3.00±0.08      | 3.87±0.66     |
| ESO146-G14/sf-1 | 0.33±0.00     | 0.24±0.00      | 0.25±0.02      | 0.29±0.02      | 1.03±0.16     |
| ESO146-G14/sf-2 | 0.38±0.00     | 0.28±0.00      | 0.35±0.02      | 0.29±0.02      | 1.23±0.18     |
| ESO146-G14/sf-3 | 0.74±0.00     | 0.50±0.00      | 0.44±0.02      | 0.49±0.02      | 0.92±0.16     |
| ESO146-G14/diffuse | 3.22±0.01   | 2.03±0.02      | 1.96±0.08      | 1.92±0.08      | <2.17         |

Spitzer photometric measurements were performed in a similar way to the Herschel m1 method.
Extended Data Table 3 | Measured sky noises of our observations compared to predictions by HSPOT

| galaxy/band      | Extended Source     | Point Sources     |
|------------------|---------------------|-------------------|
|                  | $\sigma_{\text{measured-sky}}$ | $\sigma_{\text{HSPOT, photon}}$ | $\sigma_{\text{HSPOT, confusion}}$ | $\sigma_{\text{HSPOT, photon}}$ | $\sigma_{\text{HSPOT, confusion}}$ |
| SextansA/70$\mu$m | 2.86                | 2.03              | 0.22              | 0.52                | 0.08            |
| SextansA/160$\mu$m| 1.20                | 0.92              | 0.74              | 0.83                | 1.34            |
| SextansA/250$\mu$m| 0.93                | 0.24              | 1.19              | 2.86                | 7.0             |
| SextansA/350$\mu$m| 0.49                | 0.11              | 0.67              | 2.38                | 8.2             |
| ESO146-G14/70$\mu$m| 1.82                | 1.53              | 0.20              | 0.60                | 0.08            |
| ESO146-G14/160$\mu$m| 1.10                | 0.99              | 0.74              | 1.33                | 1.33            |
| ESO146-G14/250$\mu$m| 0.75                | 0.24              | 1.18              | 2.86                | 7.0             |
| ESO146-G14/350$\mu$m| 0.46                | 0.11              | 0.67              | 2.38                | 8.1             |

HSPOT, Herschel observation planning tool. See Methods for details of parameters given here.
## Extended Data Table 4 | Fitting results

| region            | $U_{\text{min}}$ | $U_{\text{max}}$ (fixed) | $\gamma$ | $\chi^2$/dof | $M_{\text{dust}}$ (M$_{\odot}$) | $M_{\text{HI}}/M_{\text{dust}}$ | $T_{\text{dust}}$ (K) |
|-------------------|------------------|------------------------|----------|--------------|-------------------------------|-----------------------------|-------------------|
| SextansA/disk     | 2.0              | $10^6$                 | 0.01     | 1.31         | $(9.5^{+1.0}_{-0.9})\times10^3$ | $(5.7^{+0.5}_{-0.4})\times10^3$ | 33±1             |
| SextansA/sf-1     | 1.2              | $10^6$                 | 0.00     | 9.00         | $(9.9^{+0.3}_{-0.3})\times10^2$ | $(1.3^{+0.3}_{-0.3})\times10^3$ | 45±7             |
| SextansA/sf-2     | 1.2              | $10^6$                 | 0.00     | 14.41        | $(2.0^{+0.2}_{-0.2})\times10^3$ | $(1.3^{+0.3}_{-0.3})\times10^3$ | 28±2             |
| SextansA/sf-3     | 4.0              | $10^6$                 | 0.00     | 2.87         | $(1.8^{+0.5}_{-0.3})\times10^3$ | $(3.2^{+0.3}_{-0.3})\times10^3$ | 38±3             |
| SextansA/sf-4     | 0.7              | $10^6$                 | 0.00     | 2.21         | $(1.6^{+0.1}_{-0.1})\times10^3$ | $(4.1^{+0.1}_{-0.1})\times10^2$ | 27±2             |
| SextansA/diff-1   | 4.0              | $10^6$                 | 0.01     | 2.07         | $(5.1^{+0.5}_{-0.5})\times10^2$ | $(6.9^{+0.2}_{-0.2})\times10^3$ | 40±4             |
| SextansA/diff-2   | 5.0              | $10^6$                 | 0.00     | 0.14         | $(1.8^{+0.1}_{-0.1})\times10^2$ | $(8.6^{+0.1}_{-0.1})\times10^3$ | 30±8             |
| SextansA/diff-3   | 4.0              | $10^6$                 | 0.01     | 7.20         | $(3.2^{+0.3}_{-0.3})\times10^2$ | $(6.6^{+0.2}_{-0.2})\times10^3$ | 37±6             |
| SextansA/diffuse  | 2.5              | $10^6$                 | 0.01     | 0.05         | $(3.1^{+0.3}_{-0.3})\times10^3$ | $(1.4^{+0.1}_{-0.1})\times10^4$ | 29±3             |
| ESO146-G14/disk   | 1.5              | $10^6$                 | 0.01     | 4.13         | $(5.9^{+0.9}_{-0.9})\times10^5$ | $(2.5^{+0.2}_{-0.2})\times10^3$ | 30±1             |
| ESO146-G14/sf-1   | 2.5              | $10^6$                 | 0.01     | 3.45         | $(7.5^{+1.1}_{-1.0})\times10^4$ | $(1.6^{+0.2}_{-0.2})\times10^3$ | 44±12            |
| ESO146-G14/sf-2   | 4.0              | $10^6$                 | 0.01     | 0.19         | $(6.2^{+0.9}_{-0.9})\times10^4$ | $(2.7^{+0.2}_{-0.2})\times10^3$ | 31±5             |
| ESO146-G14/sf-3   | 0.7              | $10^6$                 | 0.01     | 3.65         | $(2.7^{+0.2}_{-0.2})\times10^5$ | $(5.3^{+0.2}_{-0.2})\times10^2$ | 28±4             |
| ESO146-G14/diffuse| 0.7              | $10^6$                 | 0.12     | 1.77         | $(2.5^{+0.3}_{-0.3})\times10^5$ | $(4.4^{+0.2}_{-0.2})\times10^2$ | 25±7             |

Key derived parameters from fitting the dust model to the m1 flux measurements of Extended Data Table 1 and 2. In addition to the flux errors reported in Extended Data Table 1, the uncertainties in the absolute flux calibration were added before performing the fits, as described in the text. The last column is the dust temperature as given by modified black-body fitting.
Extended Data Table 5 | Gas mass surface densities given by models of different dust types

| region        | $\log \Sigma_{1-MW}$ (log$M_\odot$/pc$^2$) | $\log \Sigma_{2-MW}$ (log$M_\odot$/pc$^2$) | $\log \Sigma_{3-MW}$ (log$M_\odot$/pc$^2$) | $\log \Sigma_{1-SCMC}$ (log$M_\odot$/pc$^2$) | $\log \Sigma_{1-LMC2}$ (log$M_\odot$/pc$^2$) |
|---------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|------------------------------------------|
| SextansA/sf-1 | 2.26$^{+0.23}_{-0.22}$                  | 2.10$^{+0.23}_{-0.22}$                  | 2.39$^{+0.24}_{-0.22}$                  | 2.24$^{+0.24}_{-0.22}$                  | 2.19$^{+0.24}_{-0.22}$                  |
| SextansA/sf-2 | 2.57$^{+0.21}_{-0.21}$                  | 2.40$^{+0.21}_{-0.21}$                  | 2.71$^{+0.21}_{-0.21}$                  | 2.62$^{+0.21}_{-0.21}$                  | 2.65$^{+0.21}_{-0.21}$                  |
| SextansA/sf-3 | 2.21$^{+0.23}_{-0.23}$                  | 2.05$^{+0.23}_{-0.23}$                  | 2.35$^{+0.22}_{-0.22}$                  | 2.25$^{+0.22}_{-0.22}$                  | 2.31$^{+0.22}_{-0.22}$                  |
| SextansA/sf-4 | 2.46$^{+0.21}_{-0.21}$                  | 2.30$^{+0.21}_{-0.21}$                  | 2.59$^{+0.21}_{-0.21}$                  | 2.52$^{+0.21}_{-0.21}$                  | 2.55$^{+0.21}_{-0.21}$                  |
| ESO146-G14/sf-1 | 1.21$^{+0.22}_{-0.22}$                | 1.21$^{+0.22}_{-0.22}$                | 1.25$^{+0.24}_{-0.24}$                | 1.14$^{+0.22}_{-0.22}$                | 1.15$^{+0.24}_{-0.24}$                |
| ESO146-G14/sf-2 | 1.12$^{+0.22}_{-0.22}$                | 1.12$^{+0.22}_{-0.22}$                | 1.16$^{+0.22}_{-0.22}$                | 1.09$^{+0.22}_{-0.22}$                | 1.16$^{+0.22}_{-0.22}$                |
| ESO146-G14/sf-3 | 1.77$^{+0.21}_{-0.21}$                | 1.77$^{+0.21}_{-0.21}$                | 1.80$^{+0.21}_{-0.21}$                | 1.82$^{+0.22}_{-0.22}$                | 1.80$^{+0.21}_{-0.21}$                |

Gas surface densities $\Sigma_{\text{gas}}$ were derived from dust masses based on infrared SED fitting by dust models of Milky Way (MW), Small Magellanic Cloud (SMC) and Large Magellanic Cloud (LMC) grains.
## Extended Data Table 6 | Predicted CO and warm H$_2$ line fluxes

| region           | $I_{CO}$ (K km/s) | $f_{H_2}(S(1)-17.035\mu m)$ (W m$^{-2}$) |
|------------------|-------------------|--------------------------------------------|
| SextansA/sf-1    | 0.33              | 2.0E-17                                    |
| SextansA/sf-2    | 0.67              | 1.5E-16                                    |
| SextansA/sf-3    | 0.25              | 6.1E-16                                    |
| SextansA/sf-4    | 0.56              | 1.1E-16                                    |
| ESO146-G14/sf-1  | 0.02              | 4.2E-18                                    |
| ESO146-G14/sf-2  | 0.01              | 1.1E-17                                    |
| ESO146-G14/sf-3  | 0.10              | 5.4E-18                                    |