From Interstellar Clouds to Star-Forming Galaxies:
Universal Processes?
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Molecular gas, stars, and dust in sub-$L^\star$ star-forming galaxies at $z \sim 2$: Evidence for universal star formation and non-universal dust-to-gas ratio

Miroslava Dessauges-Zavadsky[1], **Michel Zamojski**[1], **Daniel Schaerer**[1], **Françoise Combes**[2], **Eiichi Egami**[3], **Panos Sklias**[1], **Mark A. Swinbank**[4], **Johan Richard**[5] **and Tim Rawle**[6]

[1]Observatoire de Genève, Université de Genève,
51 Chemin des Maillettes, 1290 Versoix, Switzerland

[2]Observatoire de Paris, LERMA,
61 Avenue de l'Observatoire, 75014 Paris, France

[3]Steward Observatory, University of Arizona,
933 North Cherry Avenue, Tucson, AZ 85721, United States

[4]Institute for Computational Cosmology, Durham University,
South Road, Durham DH1 3LE, United Kingdom

[5]CRAL, Observatoire de Lyon, Université Lyon 1,
9 Avenue Ch. André, 69561 Saint Genis Laval Cedex, France

[6]ESAC, ESA, PO Box 78, Villanueva de la Canada, 28691 Madrid, Spain

Abstract. Current star-forming galaxies (SFGs) with CO measurements at $z \sim 2$ suffer from a bias toward high star formation rates (SFR) and high stellar masses (M_*). It is yet essential to extend the CO measurements to the more numerous $z \sim 2$ SFGs with $L_{\rm IR} < L^\star = 4 \times 10^{11}$ $L_\odot$ and $M_* < 2.5 \times 10^{10}$ $M_\odot$. We have achieved CO, stars, and dust measurements in 8 such sub-$L^\star$ SFGs with the help of gravitational lensing. Combined with CO-detected galaxies from the literature, we find that the $L_{\rm IR}$, $L'_{\rm CO(1-0)}$ data are best-fitted with a single relation that favours a universal star formation. This picture emerges because of the enlarged star formation efficiency spread of the current $z > 1$ SFGs sample. We show that this spread is mostly triggered by the combination of redshift, specific SFR, and M_*. Finally, we find evidence for a non-universal dust-to-gas ratio (DGR) with a clear trend for a lower DGR mean in $z > 1$ SFGs by a factor of 2 with respect to local galaxies and high-redshift sub-mm galaxies at fixed about solar metallicity.

Keywords. Gravitational lensing, galaxies: evolution, galaxies: high-redshift

1. Introduction

The study of cold gas, the fuel for star formation, across the cosmic time is crucial to understand how galaxies have converted their gas into stars. Thanks to the sensitivity improvement of the IRAM Plateau de Bure interferometer (PdBI) these last years, molecular gas measurements have become accessible in star-forming galaxies at $1 < z < 2.5$ which lie on the "main sequence" (MS). Galaxies following this sequence between stellar mass and star formation rate contribute $\sim 90\%$ to the cosmic SFR density at these redshifts (Daddi *et al.* 2007; Rodighiero *et al.* 2011). Unfortunately, the current sample of $z > 1$ CO-detected SFGs is still biased toward objects distributed at the high SFR and high M_* end. Extending the molecular gas measurements to the more common and

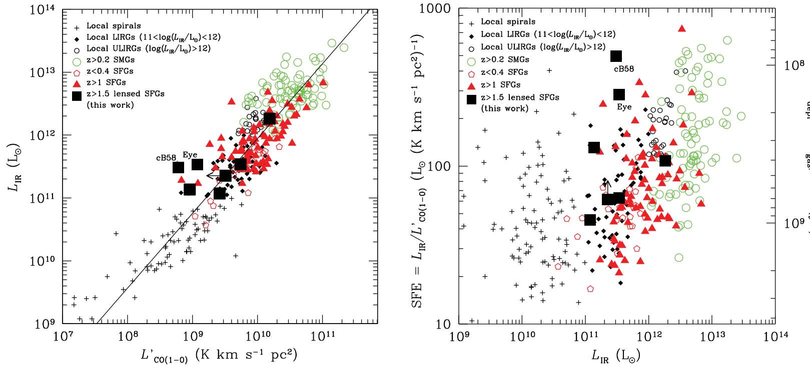

Figure 1. *Left:* IR luminosities as a function of CO(1–0) luminosities of our low-$L_{\rm IR}$-selected SFGs compared to our compilation of galaxies with CO measurements from the literature (see Dessauges-Zavadsky *et al.* 2015). A single linear $\log(L_{\rm IR})$–$\log(L'_{\rm CO(1-0)})$ relation seems to emerge, favouring a universal star formation. *Right:* Star formation efficiencies as a function of IR luminosities for the same galaxies. A large SFE spread is observed for the $z > 1$ SFGs. *Color versions of the figures are available online.*

numerous MS galaxies in the sub-$L^\star$ domain below the knee of the luminosity function is challenging, but feasible with the help of strong gravitational lensing.

2. Target selection

We have selected five targets for new IRAM/PdBI and IRAM/30m CO observations from the *Herschel* Lensing Survey (HLS; Egami *et al.* 2010), designed to observe 54 massive galaxy clusters to discover cluster-lensed, high-redshift background sources. The following selection criteria have been applied: high magnification factors $\mu > 10$; spectroscopic redshifts $z \sim 1.5-3$; lensing-corrected *Herschel* IR luminosities $L_{\rm IR} < 4 \times 10^{11}$ L$_\odot$, or equivalently SFR < 40 M$_\odot$ yr^{-1}, below the characteristic $L^\star$ of the IR luminosity function (Gruppioni *et al.* 2013); and complete photometry from optical, near-IR, IR to far-IR to enable to derive the stellar and dust properties from spectral energy distribution (SED) modeling. To these five targets, we have added the well known strongly-lensed galaxies, MS1512–cB58 and the Cosmic Eye, that also satisfy the above selection criteria.

When comparing our selected cluster-lensed, sub-$L^\star$ SFGs with our compilation of galaxies with CO measurements from the literature (see Dessauges-Zavadsky *et al.* 2015 for the references), we observe that: (1) they populate the domain with the lower $L_{\rm IR}$ at $z > 1.5$ and even fall below the *Herschel* blank field detection limit (Elbaz *et al.* 2011; Sklias *et al.* 2014); and (2) they lie on the MS at their respective redshifts, but probe one order of magnitude smaller M_* with $M_* < 2.5 \times 10^{10}$ M$_\odot$.

3. Evidence for a universal star formation

In Fig. 1 (left panel) we show the IR luminosities as a function of CO(1–0) luminosities of our compilation of CO-detected galaxies from the literature. We observe that the CO measurements achieved in our sample of sub-$L^\star$ SFGs nicely extend the $L_{\rm IR}$–$L'_{\rm CO(1-0)}$ distribution of $z > 1$ SFGs toward lower values. Moreover, evidence for a single linear $\log(L_{\rm IR})$–$\log(L'_{\rm CO(1-0)})$ relation with a slope of ~ 1.2 emerges over 5 orders of magnitude in $L_{\rm IR}$ and for galaxies gathering together spirals, MS SFGs, and starbursts at redshifts from $z = 0$ to 5.3. This strongly favours *a universal star formation*, which was questioned by Daddi *et al.* (2010), Genzel *et al.* (2010), and Sargent *et al.* (2014) who claimed the

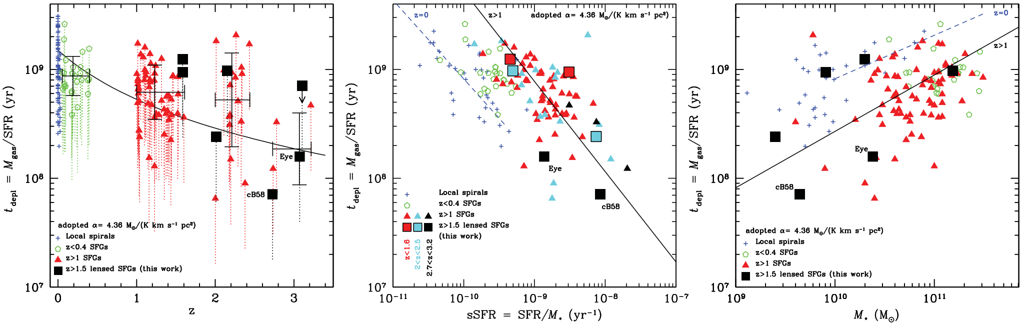

Figure 2. The dependence of the star formation efficiency on mainly three physical parameters: the redshift (*left*), the specific star formation rate (*middle*), and the stellar mass (*right*). All contribute to the large SFE spread observed in SFGs at $z > 1$ (see Fig. 1, right panel).

existence of a bimodal behaviour between the sequences of 'disks' and 'starbursts'. Their reported offset of 0.46−0.5 dex in the normalization between these two galaxy populations is now within the 1.5 σ dispersion of the current sample of $z > 1$ SFGs. Indeed, when looking at the star formation efficiency defined as $\mathrm{SFE} = \mathrm{SFR}/M_{\mathrm{gas}} \equiv L_{\mathrm{IR}}/L'_{\mathrm{CO(1-0)}}$, we clearly see that $z > 1$ SFGs show an enlarged SFE spread and dispersion similar to that of high-redshift starbursts (or sub-mm galaxies) and do not have the SFE confined to the SFE of local spirals any more (Fig. 1, right panel).

The question which follows is: what drives such a large SFE spread in $z > 1$ SFGs? We have investigated the dependence of SFE (or molecular gas depletion timescale, $t_{\mathrm{depl}} = 1/\mathrm{SFE}$) in high-redshift SFGs on several physical parameters: the redshift, the specific star formation rate ($\mathrm{sSFR} = \mathrm{SFR}/M_*$), the M_*, the offset from the main sequence, and the compactness of the starburst. We find that the SFE spread is mostly triggered by the combination of redshift, sSFR, and M_*. The dependence of SFE on the offset from the MS is only valid for starburst galaxies with $\mathrm{sSFR}/\mathrm{sSFR}_{\mathrm{MS}}$ well above the MS limit.

In Fig. 2 we show from left to right the t_{depl}–z, t_{depl}–sSFR, and t_{depl}–M_* relations. While the first two relations have already been reported by Saintonge *et al.* (2011,2013) and Tacconi *et al.* (2013) although in a different context not linked to the SFE spread, for the first time one finds evidence for the last relation between SFE and M_* at high redshift. Both Saintonge *et al.* (2011) and Bothwell *et al.* (2014) reported a t_{depl} increase with M_* initially for massive galaxies with $10^{10} < M_*/\mathrm{M}_\odot < 10^{11.5}$ and then down to $M_* \sim 10^9$ $\mathrm{M}_\odot$. The few data points we have collected at the low-M_* end for the $z > 1$ SFGs seem to trigger the t_{depl}–M_* correlation at high redshift. If correct, it has several important implications: (1) it questions the constant t_{depl} of 0.7 Gyr observed by Tacconi *et al.* (2013); (2) it contradicts the bathtub model that assumes a constant t_{depl}; and (3) it refutes the linearity of the Kennicutt-Schmidt relation ($\Sigma_{\mathrm{SFR}} \propto \Sigma_{\mathrm{H_2}}^N$ with $N \neq 1$).

4. Evidence for a non-universal dust-to-gas ratio

Dust-to-gas ratio measurements from far-IR/sub-mm SED and CO luminosity have several caveats, because of a number of assumptions that have to be done. First, the dust mass estimates from SED are tributary to the adopted dust model, dust emissivity index, and dust mass absorption cross section. Second, a CO–H_2 conversion factor has to be assumed. And third, it is accepted that $M_{\mathrm{gas}} \approx M_{\mathrm{H_2}} \gg M_{\mathrm{HI}}$. To bypass at least the first caveat, Scoville *et al.* (2014) proposed to consider the rest-frame 850 μm continuum as the dust mass tracer. They then derived in a homogeneous way (same Galactic CO–H_2 conversion factor and β-slope = 1.8) the DGR in local galaxies (spirals and

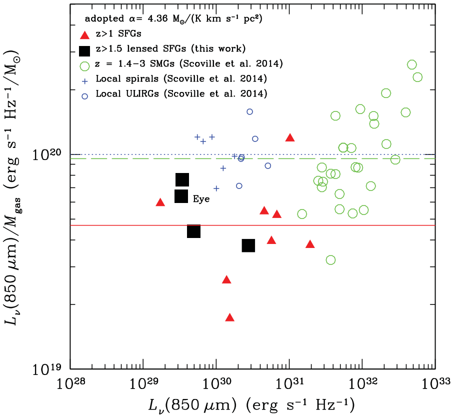

Figure 3. Dust-to-gas ratios as estimated from the 850 μm continuum over the molecular gas mass ratio following the prescriptions from Scoville *et al.* (2014). The DGR non-universality is favoured when comparing at fixed about solar metallicity local spirals, local ultra-luminous IR galaxies, high-redshift sub-mm galaxies, and high-redshift SFGs.

ultra-luminous IR galaxies) and $z > 1.4$ sub-mm galaxies and found the same DGR means. They interpreted the result as a strong evidence for a universal DGR.

We have done the same exercise for our sample of high-redshift, sub-$L^\star$ SFGs plus a few $z > 1$ SFGs from the literature for which the far-IR photometry has been published (Magdis *et al.* 2012; Saintonge *et al.* 2013). But, we have retained for the comparison with the Scoville *et al.* DGR measurements only the $z > 1$ SFGs with about solar metallicities ($Z/Z_\odot > 0.8$), as derived from nebular emission line metallicity estimators or the mass-metallicity relation. We were left with 12 SFGs in total. We find a clear trend for a lower DGR mean in $z > 1$ SFGs by ~ 0.33 dex at fixed about solar metallicity, namely a factor of 2 difference with the DGR measured by Scoville *et al.* in local galaxies and high-redshift sub-mm galaxies (see Fig. 3). This favours *a non-universal dust-to-gas ratio.* As a consequence, the use of the CO as a molecular gas mass estimator still remains highly recommended despite the uncertain CO–H_2 conversion factor, in comparison with the dust mass derived from the 850 μm continuum.

References

Bothwell, M. S., Wagg, J., Cicone, C., *et al.* 2014, *MNRAS*, 445, 2599
Daddi, E., Dickinson, M., Morrison, G., *et al.* 2007, *ApJ*, 670, 156
Daddi, E., Bournaud, F., Walter, F., *et al.* 2010, *ApJ*, 713, 686
Dessauges-Zavadsky, M., Zamojski, M., Schaerer, D., *et al.* 2015, *A&A*, 577, 50
Egami, E., Rex, M., Rawle, T. D., *et al.* 2010, *A&A*, 518, 12
Elbaz, D., Dickinson, M., Hwang, H. S., *et al.* 2011, *A&A*, 533, 119
Genzel, R., Tacconi, L. J., Gracia-Carpio, J., *et al.* 2010, *MNRAS*, 407, 2091
Gruppioni, C., Pozzi, F., Rodighiero, G., *et al.* 2013, *MNRAS*, 432, 23
Magdis, G. E., Daddi, E., Béthermin, M., *et al.* 2012, *ApJ*, 760, 6
Rodighiero, G., Daddi, E., Baronchelli, I., *et al.* 2011, *ApJL*, 739, L40
Saintonge, A., Kauffmann, G., Wang, J., *et al.* 2011, *MNRAS*, 415, 61
Saintonge, A., Lutz, D., Genzel, R., *et al.* 2013, *ApJ*, 778, 2
Sargent, M. T., Daddi, E., Béthermin, M., *et al.* 2014, *ApJ*, 793, 19
Scoville, N., Aussel, H., Sheth, K., *et al.* 2014, *ApJ*, 783, 84
Sklias, P., Zamojski, M., Schaerer, D., *et al.* 2014, *A&A*, 561, 149
Tacconi, L. J., Neri, R., Genzel, R., *et al.* 2013, *ApJ*, 768, 74