Gas accretion in distant galaxies as the origin of chemical abundance gradients

G. Cresci[1,2], F. Mannucci[1], R. Maiolino[3], A. Marconi[4], A. Gnerucci[4] & L. Magrini[1]

July 29, 2010

[1] *INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, 50125, Firenze, Italy*

[2] *Max-Planck-Institut für extraterrestrische Physik (MPE), Giessenbachstr. 1, 85748, Garching, Germany*

[3] *INAF - Osservatorio Astronomico di Roma, via di Frascati 33, 00040, Monte Porzio Catone, Italy*

[4] *Dipartimento di Fisica e Astronomia, Universitá di Firenze, Largo E. Fermi 2, 50125, Firenze, Italy*

It has recently been suggested [1] [2] that galaxies in the early Universe can grow through the accretion of cold gas, and that this may be the main driver of star formation and stellar mass growth [3] [4] [5]. Because the cold gas is essentially primordial, it has a very low abundance of elements heavier than helium (metallicity). As it is funneled to the centre of a

1

galaxy, it will lead the central gas having an overall lower metallicity than gas further from the centre, because the gas further out has been enriched by supernovae and stellar winds, and not diluted by the primordial gas. Here we report chemical abundances across three rotationally-supported star-forming galaxies at z∼3, only 2 Gyr after the Big Bang. We find an 'inverse' gradient, with the central, star forming regions having a lower metallicity than less active ones, opposite to what is seen in local galaxies [6] [7]. We conclude that the central gas has been diluted by the accretion of primordial gas, as predicted by 'cold flow' models.

We selected three Lyman-break galaxies [8] among the AMAZE [9] and LSD [10] sample, SSA22a-C16 ($z = 3.065$), CDFa-C9 ($z = 3.219$) and SSA22a-M38 ($z = 3.288$), to test the presence of metallicity gradients in galaxies beyond $z = 3$, when the Universe had only 14-16% of its actual age. This epoch is particularly interesting, as it precedes the peak of the cosmic star formation density [11], when only a small fraction ($\sim$5-10% [12]) of the total stellar mass had already been assembled. We selected these three galaxies because they show a remarkably symmetric velocity field in the [OIII] emission line, which traces the ionized gas kinematics (see Fig. 1). Such kinematics indicates that these are rotationally supported disks (Gnerucci et al., in preparation), with no evidence for more complex merger-induced dynamics. Assuming an exponential disk mass model to reproduce the dynamical properties of the three sources, we derive dynamical masses in the range $\sim 10^{10} - 2\,10^{11}\,M_\odot$. By using the H$\beta$ line flux [13], we infer star formation rates as high as $\sim 120\,M_\odot/yr$ after correcting for dust extinction [9]. We carefully checked for the presence of Active Galactic Nuclei (AGN) in our galaxies, as they would invalidate the calibrations derived for star-forming galaxies because of the different ionizing continua involved (see

Supplementary information).

Near-infrared spectroscopic observations of the galaxies were obtained with the integral field spectrometer SINFONI [14] on the Very Large Telescope of the European Southern Observatory. The spectra cover the $1.45 - 2.41 \mu m$ wavelength range, where strong rest frame optical emission lines, such as [OIII]λ5007, [OIII]λ4959, Hβ, [NeIII]λ3870 and [OII]λ3727, are shifted at the redshift of the observed galaxies. The flux ratio between the (rest-frame) optical nebular lines observed in SINFONI spectra depend on gas metallicity, and have been calibrated for local low and high metallicity galaxies [15]. In particular, we use a combination of three independent metallicity diagnostics [9], [OIII]λ5007/Hβ, [OIII]λ5007/[OII]λ3727 and, when available, [NeIII]λ3870/[OII]λ3727, to derive the gas phase metallicity in our spectra. Even if a single line ratio can constraint the metallicity in a broad interval of ~ 0.4 dex or more, the use of three independent diagnostics helps us in removing the degeneracies and reducing the uncertainties, determining for each spatial pixel the combination of metallicity and extinction that best fit the observed line ratios with our calibrations (see Supplementary information for the details).

The derived metallicity maps are shown in Fig. 1. An unresolved region with lower metallicity is evident in each map, surrounded by a more uniform disk of higher metal content. In CDFa-C9 the lower metallicity region is coincident with the galaxy center, as traced by the continuum peak, while it is offset by $\sim 0.60''$ (4.6 kpc) in SS22a-C16 and $\sim 0.45''$ (3.4 kpc) in SS22a-M38. On the other hand, in all the galaxies the area of lower metallicity is coincident or closer than $0.25''$ (1.9 kpc, half of the PSF FWHM) to the regions of enhanced line emission, tracing the more active

star forming regions. The average difference between high and low metallicity regions in the three galaxies is 0.55 in units of 12+log(O/H), larger than the $\sim 0.2 - 0.4$ dex gradients measured in the Milky Way and other local spirals [16] on the same spatial scales. The measured gas phase abundance variations have a significance between 98% and 99.8% (see Tab. 1).

The observed line ratios depend on metallicity both directly and indirectly through the ionization parameter U (the ratio between the flux of ionizing photons and the gas density), with lower metallicity star forming regions generally have higher U [15]. In principle, the observed variation of line ratios across galaxies could still be due to variations of U unrelated to the metallicity distribution. As local galaxies show a broad range of ionization parameter, this dependence on U is responsible for the spread included in our calibrations. In order to exclude the possibility that the line ratios in our galaxies are biased due to significantly different values of ionization parameter at high redshift, we have examined their dependence on U based on the latest photoionization models available [17] [18] [19]. These models are not able to simultaneously reproduce the different observed line ratios with a variation of the ionization parameter alone at constant metallicity: in this case, the observed line ratios differ from models predictions by ~ 0.2 dex. This demonstrate that different metallicities are required to reproduce the observations, and even if other effects are present, they are not dominant.

Observed gradients in local disk galaxies show metallicities decreasing outward from the galactic centers. In contrast, our high redshift sources show "inverted" gradients, with lower metallicity in a well defined active region closer to the galaxy center. Current models of chem-

4

ical enrichment in galaxies [20] [21] cannot reproduce our observations at the moment, as they assume radially isotropic gas accretion onto the disk and the instantaneous recycling approximation [22]. Nevertheless, the detected gradients can be explained in the framework of the cold gas accretion scenario [23] recently proposed to explain the properties of gas rich, rotationally supported galaxies observed at high redshift [24] [3]. In this scenario, the observed low metallicity regions are created by the local accretion of metal-poor gas in clumpy streams [1], penetrating deep onto the galaxy following the potential well, and sustaining the observed high star formation rate in the pre-enriched disk. Stream-driven turbulence is then responsible for the fragmentation of the disks into giant clumps, as observed at $z \geq 2$ [25] [10], that are the sites of efficient star formation and possibly the progenitors of the central spheroid. This scenario is also in agreement with the dynamical properties of our galaxies, which appear to be dominated by gas rotation in a disk with no evidence of the kinematical asymmetries typically induced by mergers .

If infall and outflows are not present, metallicity is directly related to the fraction of gas present in the galaxy. For this reason additional hints on the presence of infall and outflows can be obtained considering these two quantities. We can derive an estimate of gas fractions in each single region of our galaxies assuming that the relation between SFR and gas density observed in the local universe (the Schmidt-Kennicutt relation [26]) also applies to high redshift galaxies [27]. The gas fractions obtained for the two regions in each galaxy are shown in Fig. 2 plotted againts metallicities Z. It is evident that our results do not support the closed box model (black line) where galaxies have no contribution from infalls and outflows. Our data can be reproduced only by including either outflows of very enriched material, such as the ejecta from SNe, which extract

5

metals and decrease Z, or infalls of pristine gas which increase f_{gas} and decrease Z. In particular, if strong infall of pristine gas is present, we would expect higher gas fractions in the low metallicity regions, as observed. Using simple models [28] [10], we estimate the amount of infall and outflow required to reproduce the observations. We take into account two opposite scenarios. If inflows are dominant, we require ~ 3.5 times more pristine gas infall in the low metallicity regions than in the high metallicity part. On the other hand, if outflows are dominant, high metallicity regions can be explained with outflow ~ 2 times the SFR, while unrealistic outflows ~ 12 times the SFR would be needed to explain the properties of low metallicity regions. We therefore conclude that the differences in gas fractions as derived by our estimates are not only reasonable given the measured metallicity differences, but are also consistent with expectations from massive infalls of low metallicity gas in the central regions of the galaxies. They are unlikely to be explained using outflows only.

Our observations of low metallicity regions in three galaxies at $z \sim 3$ therefore provide the evidence for the actual presence of accretion of metal-poor gas in massive high-z galaxies, capable to sustain high star formation rates without frequent mergers of already evolved and enriched sub-units. This picture was already indirectly suggested by recent observational studies of gas rich disks at $z \sim 1 - 2$ [3] [5], by the study of the variation of metallicity as a function of gas fraction [10] and star formation rate [29]. The data presented here are now directly revealing the metal poor accreted gas responsible for fueling the star formation rate in massive galaxies in the early Universe.

Although the three galaxies discussed here are the only $z \sim 3$ sources for which a metallicity gradient has been measured at the moment, the detection of lower metallicity clouds in all three galaxies suggests that metal poor gas accretion is probably a common feature in actively rotationally supported star forming galaxies at this early cosmic epoch. However, it is hard to speculate how much this accretion mechanism is dominant in the global star forming population, as the relative number of rotationally supported and more dynamically complex galaxies is still unknown, and similar observations are still missing in different classes of galaxies.

[1] Dekel, A., et al., Cold streams in early massive hot haloes as the main mode of galaxy formation, Nature, **457**, 451-454 (2009)

[2] Bournaud, F., & Elmegreen, B. G., Unstable disks at high redshift: evidence for smooth accretion in galaxy formation, Astrophys. J. Lett., **694**, L158-L161 (2009)

[3] Förster Schreiber, N. M., et al., The SINS survey: SINFONI integral field spectroscopy of $z \sim 2$ star-forming galaxies., Astrophys. J., **706**, 1364-1428 (2009)

[4] Daddi, E., et al., Multiwavelength study of massive galaxies at $z \sim 2$. I. Star formation and galaxy growth, Astrophys. J., **670**, 156-172 (2007)

[5] Tacconi, L. J., et al., High molecular gas fractions in normal massive star forming galaxies in the young Universe, Nature, **7282**, 781-784 (2010)

[6] Garnett, D. R., Shields, G. A., Skillman, E. D., Sagan, S. P., & Dufour, R. J., Interstellar abundance gradients in NGC 2403: comparison to M33, Astrophys. J., **489**, 63-86 (1997)

[7] Magrini, L., Sestito, P., Randich, S., & Galli, D., The evolution of the Galactic metallicity gradient from high-resolution spectroscopy of open clusters, Astron. Astrophys., **494**, 95-108 (2009)

[8] Steidel, C. C., et al., Lyman Break Galaxies at redshift $z \sim 3$: survey description and full data set, Astrophys. J., **592**, 728-754 (2003)

[9] Maiolino, R., et al., AMAZE. I. The evolution of the mass-metallicity relation at $z > 3$, Astron. Astrophys., **488**, 463-479 (2008)

[10] Mannucci, F., et al., LSD: Lyman-break galaxies Stellar populations and Dynamics - I. Mass, metallicity and gas at $z \sim 3.1$, Mon. Not. R. Astron. Soc., **398**, 1915-1931 (2009)

[11] Hopkins, A. M., & Beacom, J. F., On the normalization of the cosmic star formation history, Astrophys. J., **651**, 142-154 (2006)

[12] Pozzetti, L., et al., The VIMOS VLT deep survey. The assembly history of the stellar mas in galaxies: from the young to the old universe, Astron. Astrophys., **474**, 443-459 (2007)

[13] Kennicutt, R. C., Jr., Star Formation in Galaxies Along the Hubble Sequence, Annual Review of Astron. Astrophys., **36**, 189-232 (1998)

[14] Eisenhauer, F., et al., SINFONI - Integral field spectroscopy at 50 milli-arcsecond resolution with the ESO VLT, SPIE, **4841**, 1548-1561 (2003)

[15] Nagao, T., Maiolino, R., & Marconi, A., Gas metallicity diagnostics in star-forming galaxies, Astron. Astrophys., **459**, 85-101 (2006)

[16] van Zee, L., Salzer, J. J., Haynes, M. P., O'Donoghue, A. A., & Balonek, T. J., Spectroscopy of Outlying H II Regions in Spiral Galaxies: Abundances and Radial Gradients, Astron. J., **116**, 2805-2833 (1998)

[17] Dopita, M. A., et al., Astrophys. J. Suppl., **167**, 177-200 (2006)

[18] Levesque, E. M., Kewley, L. J., & Larson, K. L., Theoretical Modeling of Star-Forming Galaxies. I. Emission-Line Diagnostic Grids for Local and Low-Metallicity Galaxies, Astron. J., **139**, 712-727 (2010)

[19] Martín-Manjón, M. L., García-Vargas, M. L., Mollá, M., & Díaz, A. I., POPSTAR evolutionary synthesis models II: optical emission-line spectra from giant HII regions, Mon. Not. R. Astron. Soc., **403**, 2012-2032 (2010)

[20] Molla, M., Ferrini, F., & Diaz, A. I., Evolution of spiral galaxies. VII. Time evolution of the radial distributions of abundances, Astrophys. J., **475**, 519-533 (1997)

[21] Hou, J. L., Prantzos, N., & Boissier, S., Abundance gradients and their evolution in the Milky Way disk, Astron. Astrophys., **362**, 921-936 (2000)

[22] Tinsley, B. M., Stellar lifetimes and abundance ratios in chemical evolution, Astrophys. J., **229**, 1046-1056 (1979)

[23] Kereš, D., Katz, N., Weinberg, D. H., & Davé, R., How do galaxies get their gas?, Mon. Not. R. Astron. Soc., **363**, 2-28 (2005)

[24] Cresci, G., et al., The SINS survey: modeling the dynamics of $z \sim 2$ galaxies and the high-z Tully-Fisher relation, Astrophys. J., **697**, 115-132 (2009)

[25] Genzel, R., et al., From Rings to Bulges: Evidence for Rapid Secular Galaxy Evolution at $z \sim 2$ from Integral Field Spectroscopy in the SINS Survey, Astrophys. J., **687**, 59-77 (2008)

[26] Kennicutt, R. C., Jr., The Global Schmidt Law in Star-forming Galaxies, Astrophys. J., **498**, 541-552 (1998)

[27] Bouché, N., et al., Dynamical Properties of $z \sim 2$ Star-forming Galaxies and a Universal Star Formation Relation, Astrophys. J., **671**, 303-309 (2007)

[28] Erb, D. K., Astrophys. J., A Model for Star Formation, Gas Flows, and Chemical Evolution in Galaxies at High Redshifts, **674**, 151-156 (2008)

[29] Mannucci F., Cresci, G., Maiolino, R., Marconi, A., & Gnerucci, A., A fundamental relation between mass, SFR and metallicity in local and high redshift galaxies, Mon. Not. R. Astron. Soc., in print, arXiv:1005.0006 (2010)

[30] Chabrier, G., Galactic Stellar and Substellar Initial Mass Function, Publ. Astr. Soc. Pac., **115**, 763-795 (2003)

the Paranal Observatories. We would like to thank the ESO staff for their work and support. This work has

been supported by INAF and ASI.

Competing Interests   The authors declare that they have no competing financial interests.

Correspondence   Correspondence and requests for materials should be addressed to G.C. (email: gcresci@arcetri.astro.it).

Name	z	$\log(M_*/M_\odot)$	12+log(O/H) (tot)	12+log(O/H) (low Z)	12+log(O/H) (high Z)
SSA22a-C16	3.065	$10.68^{+0.16}_{-0.54}$	$8.36^{+0.06}_{-0.06}$	$8.18^{+0.13}_{-0.14}$	$8.52^{+0.14}_{-0.07}$
CDFa-C9	3.219	$10.03^{+0.40}_{-0.08}$	$8.36^{+0.06}_{-0.05}$	$7.98^{+0.14}_{-0.16}$	$8.56^{+0.12}_{-0.12}$
SSA22a-M38	3.288	$10.86^{+0.18}_{-0.41}$	$8.26^{+0.09}_{-0.11}$	$7.84^{+0.22}_{-0.23}$	$8.59^{+0.05}_{-0.07}$

Table 1: Properties of the sample galaxies. z is the source redshift, M_* the stellar mass derived from multi band photometry and spectral energy distribution fitting assuming a Chabrier [30] Initial Mass Function [9], while the last three columns show the metallicity integrated for the whole galaxy, for the low metallicity regions and for the high metallicity regions respectively, in units of 12+log(O/H). The amplitude and significance of the detected gradients were evaluated extracting 1D spectra integrated over apertures comparable to the PSF (FWHM=$0.5''$) in both the lowest and highest metallicity region, and using them to measure the line ratios (see Supplementary information). The uncertainties are the 1σ confidence intervals.

Figure 1: Surface brightness and velocity of the [OIII]λ5007 line, and metallicity maps. The data for SSA22a-C16 ($z = 3.065$, *upper panels*), CDFa-C9 ($z = 3.219$, *central panels*) and SSA22a-M38 ($z = 3.288$, *lower panels*) were obtained with the SINFONI spectrograph using the $0.125 \times 0.250''$ pixel scale in seeing-limited conditions, resulting in a spatial resolution of $\sim 0.5''$ (Full Width Half Maximum of the Point Spread Function, PSF). The maps were extracted from the SINFONI datacube after a Gaussian smoothing with FWHM=3 pixels ($0.375''$). The *left panels* in each row show normalized surface brightness in the [OIII]λ5007 emission line. The same line has been used to derive the velocity maps shown in the *central panels*; the observed gas kinematics is compatible with a rotating disk, with no evidence of merger-induced complex dynamics. The *right panels* show maps of gas phase metallicity, as relative abundances of oxygen and hydrogen parameterized in units of $12+log(O/H)$. Lower metallicity region, corresponding to a higher [OIII]/[OII] ratio, are surrounded by a more enriched disk. The crosses in each panel mark the position of the continuum peak.

Figure 2: Gas fractions for the different regions in the observed galaxies. To estimate gas masses in the low metallicity regions and in the rest of the galaxies, we used the Hβ flux corrected for extinction. We convert measured star formation rate densities from Hβ to a gas mass inverting the Kennicutt-Schmidt law [26]. To estimate stellar masses, we have to relay on the continuum flux from our SINFONI data, as we are still missing deep and high resolution continuum images of the sources. In the datacubes of our galaxies the continuum is detected, although at a lower S/N than the emission lines, making this estimate more uncertain. We have to further assume that the stellar mass scales as the K-band continuum light (V band rest frame). We thus measure the total K band continuum flux on the whole galaxy and the flux in the lower metallicity regions, using these relative flux measurements to rescale the total stellar mass from SED fitting [9], and estimate the stellar mass in the metal poor and metal rich regions. The blue dots in the figure denotes the low metallicity regions, while the red ones the high metallicity part of the galaxy. The black dashed line shows the expectations from a closed-box model. The difference between the regions can be explained by a simple model including only infall of gas, which is, respectively, 3.5 and 1 times the SFR for the regions of lower and higher metallicity. The dashed cyan lines are for a model of pure outflow, 12 times the SFR. The observed difference in gas fraction it is consistent with the expectation from a massive infall of low metallicity gas in the central regions. The error bars are 1σ formal uncertainties on the measurements, given the assumptions discussed.