Observational Evidence for Constant Gas Accretion Rate Since $z = 5$

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ABSTRACT

Star formation rate density (SFRD) has not been constant throughout the history of the Universe. The rate at which stars form greatly affects the evolution of the Universe, but the factors which drive SFRD evolution remain uncertain. There must be sufficient amount of gas to fuel the star formation, either as a reservoir within a galaxy, or as inflow from the intergalactic medium (IGM). This work explores how the gas accretion rate onto galaxies over time has affected star formation rate. We propose a novel method of measuring cosmic gas accretion rate. This involves comparing the comoving densities of available $\text{H}_1$ and $\text{H}_2$ gas and the densities of existing stars at different redshifts. We constrained gas accretion until $z = 5$, and we found that the gas accretion rate density (GARD) is relatively constant in the range from $z = 5$ to $z = 0$. This constancy in the GARD is not reflected by the SFRD, which declines significantly between $z = 1.0$ and $z = 0$. This work suggests that the decline is not due to a reduction in GARD.

Key words: galaxies: evolution, intergalactic medium, galaxies: ISM, galaxies: star formation

1 INTRODUCTION

One of the most important issues of the evolution of the Universe is how galaxies acquire gas which fuels star formation. Numerical galaxy formation models require significant gas inflows from the intergalactic medium (IGM) to fuel star formation (Dekel & Birnboim 2006; Dekel et al. 2009; Schaye et al. 2010), and indeed the current gas reservoirs in many galaxies are too low to sustain the current level of star formation, even for normal galaxies like the Milky Way (Draine 2009). This is reinforced by simulations of l’Huillier et al. (2012), who found that most galaxies assemble their mass through steady gas accretion, and only most massive galaxies grow predominately due to dramatic merger events. However, such inflow process cannot be studied in details because it is very difficult to directly detect it. Only for a few galaxies was the observational indication of gas inflow obtained (Martin et al. 2014; Turner et al. 2015; Rauch et al. 2016), and indirect evidence was reviewed by Sancisi et al. (2008).

Michałowski et al. (2015, 2016) provide evidence for gas inflow directly fueling star formation. This was achieved by reporting the first 21 cm line observations for long gamma-ray burst galaxies. These observations implied high levels of $\text{H}_1$ gas in areas of recent star formation, whereas low molecular gas content was reported for GRB hosts (Hatsukade et al. 2014; Stanway et al. 2015; Michałowski et al. 2016, but see Perley et al. 2017). This in turn suggests that star formation is either directly fueled by $\text{H}_1$ gas, or that there is a very efficient conversion process between $\text{H}_1$ and $\text{H}_2$ underway (Michałowski et al. 2015).

As reported by Sancisi et al. (2008) within the Milky Way itself, rate of star formation has been very constant over the course of its life. This clearly demonstrates that the gas being used up in star formation is somehow being replaced. Whilst it is obvious that gas accretion must be happening for almost all galaxies, it is very unclear how much is taking place.

Whilst there is a wide range of theories regarding the evolution of star formation rate, there is little observation based evidence available to study the details of this process. Observations suggest that it is the accretion of metal-poor gas that drives the formation of disc galaxies (Sanchez-Almeida et al. 2014, 2013; Cresci et al. 2010). There has been a lot of work done to measure the densities of $\text{H}_1$ and $\text{H}_2$ mass in galaxies at varying redshifts. In order to detect $\text{H}_2$ gas, the CO molecule is generally used as a tracer (Carilli & Water 2013; Bolatto et al. 2013).

The aim of this paper is to provide the first observational measurement of the cosmic gas accretion rate density (GARD) by applying a novel method, and comparing it to...
the measurement of the star formation rate density (SFRD). A cosmological model with $h = 0.7$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ is assumed.

2 DATA

The compilations of $\rho_{\text{HI}}$ and $\rho_{\text{H}_2}$ from Lagos et al. (2014) and Hoppmann et al. (2015) were used. Significantly more $\rho_{\text{HI}}$ data was available than $\rho_{\text{H}_2}$, over a wider redshift range. We used the compilation of $\rho_{\text{stellar}}$ (including stellar remnants) from Michalowski et al. (2010).

The HI densities were obtained by a variety of methods over the redshift range. These included spectral stacking of the 21-cm Hydrogen emission line and damped Lyman-α (DLA) absorbers. The complete compilation of $\rho_{\text{HI}}$ measurements is presented in table B1. All density values are densities per unit of comoving volume.

The values from Zwaan et al. (2005) and Martin et al. (2010) were for the local universe, at $z = 0$. The Martin et al. (2010) value was based on the Arecibo Legacy Fast ALFA (ALFALFA) survey, which at that time had completed source extraction for 40% of the total sky area, allowing the value to be calculated from a sample of 10119 galaxies. In comparison, the Zwaan et al. (2005) value was based on the Hi Parkes All Sky Survey (HIPASS) which was based on 4315 extra galactic emission-line detections. As such, it was reasonable to assume that the Martin et al. (2010) value is superior to the Zwaan et al. (2005) value. The Freudling et al. (2011) value was given relative to $z = 0$, so required a conversion using an established value of $\rho_{\text{HI}}$ at $z = 0$. The Lah et al. (2007) was based on observations from the Giant Metrewave Radio Telescope (GMRT) in order to measure $\rho_{\text{HI}}$ at $z = 0.24$. The Delhaize et al. (2013) values were based on a combination of detected sources and the spectral stacking technique. Contrary to previous estimates, they also suggested that $\rho_{\text{HI}}$ evolution over the last 1 Gyr was minimal. The Rhee et al. (2013) values were obtained using Hi signal stacking technique. The Hoppmann et al. (2015) values also relied upon the detection of hydrogen 21-cm emission with Arecibo Ultra Deep Survey.

Chang et al. (2010) used the Hi intensity mapping based on the DEEP2 optical galaxy redshift survey. The Masui et al. (2013) value was obtained by cross-correlating hydrogen 21-cm information with data from the WiggleZ Dark Energy Survey.

The Péroux et al. (2003), Rao et al. (2006), Noterdaeme et al. (2012), Zafar et al. (2013), and Prochaska & Wolfe (2009) values were all obtained using data from surveys of damped Lyman-α (DLA) absorbers.

The $\rho_{\text{HI}}$ values were sourced from Kereš et al. (2003) for $z = 0$, and Decarli et al. (2016) for other redshifts.

3 METHOD: GAS ACCRETION RATE DENSITY (GARD) ESTIMATE

In the calculations presented below care must be taken in consistently treating the extent of the gas and stellar components which are considered to lie inside or outside a galaxy. Here we broadly define a galaxy extent as the size of the atomic gas disk, which is usually a few times larger than the stellar disk, i.e. extends for a few tens of kpc. In this definition the hot gas in the dark matter halo is not considered.

Absorption measurements of $\rho_{\text{HI}}$ in principle could trace the gas outside galaxies, but the DLA systems used for these studies are dense enough to safely assume that they are associated with galaxies. Indeed, DLAs have SFRs and velocity dispersions characteristic for galaxies, and metallicities higher than that of the IGM (e.g. Möller et al. 2004; Wolfe et al. 2005; Ledoux et al. 2006; Fynbo et al. 2010, 2011, 2013; Krogager et al. 2012, 2013). Moreover within the error bars there is no step change from HI-line- to DLA-derived $\rho_{\text{HI}}$ values (Fig. A1 and Table B1), which would be expected if DLAs probed additional neutral gas component in the IGM. Finally, the sizes of the absorbing gas of DLAs are ~ 10–20 kpc (Möller et al. 2004; Péroux et al. 2005; Wolfe et al. 2005; Monier et al. 2009; Fynbo et al. 2010, 2011, 2013; Krogager et al. 2012, 2013), safely within our limit of a few tens of kpc. There are some known DLAs with impact parameters from the background quasar of 50–100 kpc (right part of Fig. 18 in Rao et al. 2011), but these DLAs are rare (three out of 27 DLAs in the sample of Rao et al. 2011), so their impact on the measured $\rho_{\text{HI}}$ is minor. Moreover, they all have low identification confidence. Similarly, simulations show that the hydrogen density required to classify as a DLA (2 × 10^20 cm^-2; Wolfe et al. 2005) is only present within ~ 20 kpc from the galaxy centre (Li et al. 2016 fig. 7 and 18; Shen et al., in prep.).

Calculating the GARD involves the following steps. The total matter density inside galaxies for each redshift bin was calculated as:

$$\rho_{\text{total}} = \rho_{\text{HI}} + \rho_{\text{H}_2} + \rho_{\text{stellar}}.$$  \hspace{1cm} (1)

Over time this density changes only by inflows and outflows:

$$\rho_a = \rho_b + \rho_{\text{inflow}} - \rho_{\text{outflow}}.$$  \hspace{1cm} (2)

Where $a$ and $b$ represent total $\rho$ at different epochs. We do not distinguish different mechanisms of inflow and outflow, so these terms include all processes that add to and remove gas from galaxies, respectively. The inflow processes include cold and hot mode accretion, as long as the gas ends up inside galaxies (as defined above) during the relevant time span. It also includes gas expelled to the galactic halo during star-formation episodes which is subsequently re-accreted. Galactic fountains eject cold high-metallicity gas into the corona, and by mixing, cool the low-metallicity gas of the corona sufficiently that fountain clouds form and inflow back into the galactic disc (Fraternali, 2014). Gas accreted from fountain clouds is considered inflow. Accretion of gas into intra-cluster medium is not included, as such gas does not end up inside galaxies, and is not included in the HI and H2 measurements. The outflows include supernova and AGN feedback, gas stripping, etc.

The average density of gas accreted by galaxies between two epochs (i.e. the difference between the gas flowing in and out) can be calculated as:

$$\text{GAD} = \rho_{\text{inflow}} - \rho_{\text{outflow}} = \rho_a - \rho_b.$$  \hspace{1cm} (3)

By calculating the difference in $\rho_{\text{total}}$ between consecutive epochs, represented in equation 3 by $\rho_a$ and $\rho_b$, only the
gas remaining within the galaxy — either free or as stars — is accounted for. This quantity was labelled the gas accretion density (GAD). From there, the GARD could then be calculated using:

\[
\text{GARD} = \frac{\text{GAD}}{\Delta \text{time}}. \tag{4}
\]

Where \(\Delta \text{time}\) was the time elapsed between neighboring redshift bins.

4 RESULTS

The binned values for all three data sets are presented in Table 1 and can be seen in Figure 1 extending between \(z = 0\) to \(z = 5\). The first six bins cover points where \(\rho_{\text{HI}}, \rho_{\text{H}_2}\) and \(\rho_{\text{stel}}\) data were all available. The seventh and final bin centred at \(z = 4.6\) does not include \(\rho_{\text{HI}}\) data, as none was available at that redshift. It seemed legitimate to continue to seven bins, as the contribution to \(\rho_{\text{tot}}\) from \(\rho_{\text{HI}}\) was already very minimal in the sixth bin, relative to those of \(\rho_{\text{H}_2}\) and \(\rho_{\text{stel}}\). There is a clearly decreasing trend in \(\rho_{\text{tot}}\). This is primarily due to the \(\rho_{\text{stel}}\) data dominating at \(z < 2\).

Both GAD and GARD are presented in Table 2. The value of GAD (see Equation 3) represents the density present at a lower redshift that had not been present previously, either as a fresh gas reservoir or newly formed star. For plots of GAD against redshift, \(z\) see Appendix A. Figure 2 compares the GARD with SFRD. It can be seen that the GARD values seem to by relatively constant. This does not tally with the clear drop in SFRD observed from between \(z = 1.5\) to \(0\).

The errors in GAD and GARD were calculated by propagating the errors of individual densities in a standard manner, whereas the errors of these densities are the errors of the means of the densities in relevant redshift ranges reported in other studies.

| \(z\) | \(\log(\rho_{\text{HI}})\) | \(\log(\rho_{\text{H}_2})\) | \(\log(\rho_{\text{stel}})\) | \(\log(\rho_{\text{tot}})\) |
|------|-----------------|-----------------|-----------------|-----------------|
| 0.0  | 7.70 ± 0.01     | 7.36 ± 0.18     | 8.70 ± 0.01     | 8.76 ± 0.01     |
| 0.45 | 7.95 ± 0.12     | 7.16 ± 0.60     | 8.40 ± 0.01     | 8.55 ± 0.04     |
| 0.93 | 7.89 ± 0.06     | 7.28 ± 0.45     | 8.25 ± 0.01     | 8.44 ± 0.04     |
| 1.37 | 8.10 ± 0.13     | 7.81 ± 0.28     | 7.98 ± 0.01     | 8.46 ± 0.09     |
| 2.55 | 8.04 ± 0.02     | 7.99 ± 0.30     | 7.78 ± 0.03     | 8.43 ± 0.12     |
| 3.74 | 8.11 ± 0.06     | 6.56 ± 1.03     | 7.49 ± 0.13     | 8.21 ± 0.06     |
| 4.60 | 8.09 ± 0.07     | —               | 7.37 ± 0.05     | 8.16 ± 0.06     |

Table 1. Binned comoving gas and stellar mass densities.

| \(z\) | \(\Delta \text{time}\) | \(\text{GAD}\) | \(\text{GARD}\) |
|------|-----------------|-----------------|-----------------|
| 0.45 - 0.0 | 4.76           | 22.59 ± 3.51    | 4.83 ± 0.75     |
| 0.93 - 0.45 | 2.75           | 7.88 ± 3.96     | 2.86 ± 1.44     |
| 1.37 - 0.93 | 1.51           | -1.25 ± 6.07    | -0.83 ± 4.03    |
| 2.55 - 1.37 | 2.01           | 1.81 ± 8.81     | 0.90 ± 4.38     |
| 3.74 - 2.55 | 0.88           | 10.56 ± 7.11    | 12.02 ± 8.09    |
| 4.60 - 3.74 | 0.36           | 1.78 ± 2.91     | 4.92 ± 8.06     |

Table 2. Gas accretion density (GAD) and gas accretion rate density (GARD). The time spanned by each of the redshift bins is included under \(\Delta \text{time}\).
expected result as it does not tally up with the SFRD which increases relatively steadily from $z = 5$ to $z = 1.5$, and then declines from around $z = 1.5$ to $z = 0$. Therefore, the decline in SFRD observed cannot be attributed to a change in gas accretion rate. It seems that galaxies in the earlier universe used up their gas supplies faster than the accretion of fresh gas could maintain (SFRD > GARD). SFRD no longer drops beneath the GARD, so the current SFRD is now sustainable. This drop in SFRD is therefore not due to a decrease in gas supply. It could be because average density of gas in galaxies dropped, leaving significant amounts of gas below the star-formation threshold.

In order to compare our unexpected results with those from a well established simulation Figure 2 compares GARD from this work with that obtained from a smoothed particle hydrodynamics simulation including dark matter, gas, and stars from Kereš et al. (2005). Simulated GARD shows a distinctive decline from $z < 4$ which more closely echoes SFRD than the GARD from this work, however, there is a convincing order of magnitude consistency between the GARD and SFRD. This can be explained by a few feasible explanations for the discrepancies between the simulation and the results from this work: it is possible that the HI densities based on DLA data led to underestimations at higher redshifts for GARD. It is also possible that the simulation did not properly account for gas which infows but is then expelled shortly after, so is not present inside galaxies at later epochs. Finally, the simulated GARD denote the gas accreted onto dark matter halos, whereas we measure gas accretion onto galaxies, as explained in Section 3. Assuming that some gas accretes onto halos, but does not end up inside galaxies, it is not surprising that the simulated GARD is higher than the measured one.

This work could be considerably improved upon by a wider range of data. The lack of $H_2$ data at higher redshifts might have affected the gas accretion determination. This will be improved by the Atacama Large Millimeter Array (ALMA) and the Northern Extended Millimeter Array (NOEMA) which will perform CO-line scans leading to the determination of $\mu H_2$ (Walter et al. 2014, 2016). On the other hand the Square Kilometre Array (SKA) will deliver direct measurements of $\mu H_2$ at least at $z < 1$, which will make it possible to test the result of a constant GARD in this regime.

We do not include the ionized medium in eq. 1 because, even though its filling factor is large (fig. 11 of Kalberla & Kerp 2009), its mass fraction is minor. In the Milky Way by mass the fraction of the ionized ISM ranges from ~ 2% (from integrating ISM phase profiles in table 5 of Wolfire et al. 2003) to ~ 23% (table 1.2 of Draine 2011). If this is common among galaxies, then the contribution of the ionized medium to the changes of the total densities we measure is therefore likely smaller than the uncertainties involved.

## 6 CONCLUSIONS

Star formation rate has not been constant throughout the history of the Universe. This work sought to demonstrate whether the gas accretion onto galaxies over time has affected star formation rate. GARD in this work represents a simply calculated value that shows how much gas mass density has been accreted by galaxies over a certain redshift interval. If there was a tight correlation between GARD and SFRD then it might suggest that the rate of gas accretion is the limiting factor on SFR. However, a constant GARD, which we measured, might suggest that factors other than the quantity of gas being accreted affect SFRD.

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Figure A1. Atomic gas density $\rho_{HI}$ (blue crosses) vs redshift, and the average $\rho_{HI}$ for each redshift bin (black squares).

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APPENDIX A: FURTHER PLOTS

We plot here the complete data sets for $\rho_{HI}$ and $\rho_{H2}$, overlapped with the binned data. The $\rho_{HI}$ data followed an increasing trend from z = 0 to 1.5, after which it seems to remain constant.

APPENDIX B: $\rho_{HI}$ DATA COMPILATION

The $\rho_{HI}$ data came from Kereš et al. (2003) and Decarli et al. (2016). The full $\rho_{H2}$ compilation was sourced from Michałowski et al. (2010). Our complete $\rho_{HI}$ compilation is presented in full in table B1.

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Table B1. Compilation of atomic gas mass densities, $\rho_{HI}$. DLA indicates damped Lyman-$\alpha$.

| $z$   | $z$ width | log $\rho_{HI}$ $[M_\odot Mpc^{-3}]$ | lower error log $\rho_{HI}$ $[M_\odot Mpc^{-3}]$ | upper error log $\rho_{HI}$ $[M_\odot Mpc^{-3}]$ | Type of $\rho_{HI}$ measurement | Reference                        |
|-------|-----------|-------------------------------------|---------------------------------|---------------------------------|---------------------------------|----------------------------------|
| 0.0   | 0.0       | 7.80 0.05                           | 0.05                            | 0.05                            | Ht                              | Zwaan et al. (2005)              |
| 0.0   | 0.0       | 7.92 0.03                           | 0.03                            | 0.03                            | Ht                              | Martin et al. (2010)             |
| 0.125 | 0.0       | 7.92 0.15                           | 0.12                            | 0.12                            | Ht                              | Freudling et al. (2011)          |
| 0.065 | 0.0       | 7.66 0.01                           | 0.01                            | 0.01                            | Ht                              | Hoppmann et al. (2015)           |
| 0.1   | 0.1       | 7.71 0.02                           | 0.02                            | 0.02                            | Ht                              | Hoppmann et al. (2015)           |
| 0.24  | 0.0       | 8.09 0.27                           | 0.16                            | 0.16                            | Ht stacking                      | Lah et al. (2007)                |
| 0.02  | 0.02      | 7.74 0.10                           | 0.04                            | 0.04                            | Ht stacking                      | Delhaize et al. (2013)           |
| 0.085 | 0.045     | 7.79 0.09                           | 0.05                            | 0.05                            | Ht stacking                      | Delhaize et al. (2013)           |
| 0.1   | 0.0       | 7.65 0.07                           | 0.06                            | 0.06                            | Ht stacking                      | Rhee et al. (2013)               |
| 0.2   | 0.0       | 7.67 0.13                           | 0.10                            | 0.10                            | Ht stacking                      | Rhee et al. (2013)               |
| 0.37  | 0.0       | 7.76 0.21                           | 0.14                            | 0.14                            | Ht stacking                      | Rhee et al. (2016)               |
| 0.8   | 0.0       | 7.87 0.14                           | 0.10                            | 0.10                            | Ht intensity mapping             | Chang et al. (2010)              |
| 0.8   | 0.2       | 7.83 0.13                           | 0.10                            | 0.10                            | Ht intensity mapping             | Masui et al. (2013)              |
| 1.0   | 1.0       | 7.94 0.10                           | 0.10                            | 0.10                            | DLA                             | Péroux et al. (2003)             |
| 2.35  | 0.35      | 8.15 0.10                           | 0.10                            | 0.10                            | DLA                             | Péroux et al. (2003)             |
| 3.1   | 0.4       | 8.13 0.10                           | 0.10                            | 0.10                            | DLA                             | Péroux et al. (2003)             |
| 2.95  | 0.55      | 8.19 0.10                           | 0.10                            | 0.10                            | DLA                             | Péroux et al. (2003)             |
| 0.609 | 0.0       | 8.12 0.20                           | 0.14                            | 0.14                            | DLA                             | Rao et al. (2006)                |
| 1.219 | 0.0       | 8.10 0.15                           | 0.11                            | 0.11                            | DLA                             | Rao et al. (2006)                |
| 2.15  | 0.15      | 8.13 0.02                           | 0.02                            | 0.02                            | DLA                             | Noterdaeme et al. (2012)         |
| 2.45  | 0.15      | 8.07 0.02                           | 0.02                            | 0.02                            | DLA                             | Noterdaeme et al. (2012)         |
| 2.75  | 0.15      | 8.15 0.02                           | 0.02                            | 0.02                            | DLA                             | Noterdaeme et al. (2012)         |
| 3.05  | 0.15      | 8.18 0.03                           | 0.03                            | 0.03                            | DLA                             | Noterdaeme et al. (2012)         |
| 3.35  | 0.15      | 8.24 0.05                           | 0.04                            | 0.04                            | DLA                             | Noterdaeme et al. (2012)         |
| 1.75  | 0.25      | 8.09 0.14                           | 0.10                            | 0.10                            | DLA                             | Zafar et al. (2013)              |
| 2.25  | 0.25      | 8.13 0.14                           | 0.11                            | 0.11                            | DLA                             | Zafar et al. (2013)              |
| 2.75  | 0.25      | 8.19 0.12                           | 0.10                            | 0.10                            | DLA                             | Zafar et al. (2013)              |
| 3.25  | 0.25      | 8.20 0.12                           | 0.10                            | 0.10                            | DLA                             | Zafar et al. (2013)              |
| 3.75  | 0.25      | 8.15 0.10                           | 0.08                            | 0.08                            | DLA                             | Zafar et al. (2013)              |
| 4.5   | 0.5       | 8.12 0.14                           | 0.11                            | 0.11                            | DLA                             | Zafar et al. (2013)              |
| 2.55  | 0.15      | 7.87 0.05                           | 0.05                            | 0.05                            | DLA                             | Prochaska & Wolfe (2009)         |
| 2.85  | 0.15      | 7.87 0.05                           | 0.04                            | 0.04                            | DLA                             | Prochaska & Wolfe (2009)         |
| 3.25  | 0.25      | 8.01 0.04                           | 0.03                            | 0.03                            | DLA                             | Prochaska & Wolfe (2009)         |
| 3.75  | 0.25      | 8.08 0.08                           | 0.07                            | 0.07                            | DLA                             | Prochaska & Wolfe (2009)         |
| 4.75  | 0.75      | 8.07 0.09                           | 0.08                            | 0.08                            | DLA                             | Prochaska & Wolfe (2009)         |
Observational Evidence For Constant Gas Accretion Rate Since $z = 5$

Figure A2. Stellar mass density $\rho_{\text{stel}}$ (green crosses) vs redshift, and the average $\rho_{\text{stel}}$ for each redshift bin (black squares).

Figure A3. Gas Accretion Density (GAD) against redshift, $z$. Due to a slight increase in $\rho_{\text{tot}}$ between the bins centred at $z = 1.37$ and $0.93$ in an otherwise downward trend (see Table 1) the GAD value spanning these bins is negative.