Redshift Evolution of the H_2/HI Mass Ratio In Galaxies

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ABSTRACT

In this paper we present an attempt to estimate the redshift evolution of the molecular to neutral gas mass ratio within galaxies (at fixed stellar mass). For a sample of five nearby grand design spirals located on the Main Sequence (MS) of star forming galaxies, we exploit maps at 500 pc resolution of stellar mass and star formation rate ($M_\star$ and SFR). For the same cells, we also have estimates of the neutral ($M_{\rm HI}$) and molecular ($M_{\rm H_2}$) gas masses. To compute the redshift evolution we exploit two relations: *i)* one between the molecular-to-neutral mass ratio and the total gas mass ($M_{\rm gas}$), whose scatter shows a strong dependence with the distance from the spatially resolved MS, and *ii)* the one between $\log(M_{\rm H_2}/M_\star)$ and $\log(M_{\rm HI}/M_\star)$. For both methods, we find that $M_{\rm H_2}/M_{\rm HI}$ within the optical radius slightly decreases with redshift, contrary to common expectations of galaxies becoming progressively more dominated by molecular hydrogen at high redshifts. We discuss possible implications of this trend on our understanding of the internal working of high redshift galaxies.

Key words: galaxies: evolution – galaxies: star formation – galaxies: spirals

1 INTRODUCTION

Our understanding of galaxy formation and evolution is strictly connected to the accretion of cold gas on galaxies across cosmic time: this gas coming from the cosmic web cools down to form atomic hydrogen (HI) first, and then molecular hydrogen (H_2), that can eventually collapse under gravitational instability to form new stars. Feedback from star formation also plays a crucial role, as it is a necessary ingredient to ensure a low efficiency of the star formation process itself: without feedback the gas in a galaxy would be consumed almost completely over a free-fall time, turning most baryons into stars, as opposed to the $\sim$ 10 per cent of baryons being locked into stars as actually observed in the local Universe (e.g. Bigiel et al. 2008; Krumholz et al. 2012; Hayward & Hopkins 2017). Feedback

HI-MaNGA (Masters et al. 2019). At higher redshift, the HIGHz survey (Catinella & Cortese 2015) targeted the HI emission of massive galaxies at $z \sim 0.2$, while the CHILES survey pushed the limit of individual detections up to $z \sim 0.4$ (Fernández et al. 2016). At even higher redshift our knowledge of HI content is entirely obtained by stacking analysis: Kanekar et al. (2016) at $z \sim 1.3$ and Chowdhury et al. (2020, C20 hereafter) at $z \sim 1$. Damped Lyα or MgII absorption line systems give us the chance to estimate the HI content at $z \gtrsim 1.5$, with the caveat that they trace HI located well outside the optical disk of galaxies, hence revealing little about what is going on inside their star-forming body.

Recently, in Morselli et al. (2020, M20 hereafter) we analyzed the HI and H_2 content of five nearby, grand-design, massive main sequence (MS) galaxies on scales of $\sim$ 500pc and linked the

- Содержание молекулярного газа (H2/HI) зависит в основном от двух факторов: плотности газа и feedback. Это звенья одой цепи саморегуляции процесса SF.
- Проблема HI на больших Z. Предел индивидуальных измерений – z=0.4. С использованием stacking - до   z ~ 1 (Chowdhury et al. (2020), 7653 галактик).
- It is generally assumed that this ratio increases with redshift, because galaxies are more gas rich and as the gas surface density increases, recombination is favored. However, galaxies at high redshift are also more star forming, and higher levels of star formation favor photo-dissociation of the H2 molecule, hence it is not a priori obvious which trend would dominate over the other.
- In this paper we exploit tight correlations to estimate the evolution with redshift of the H2/HI mass ratio within galaxies.

- В предыдущей работе [1] Morselli et al. (2020) для 5 MS-галактик рассмотрена зависимость локального (в масштабе 0.5 kpc) отношения H2/HI от поверхностной плотности газа (растет) и от удельного SFR (падает) . Плотность звездного диска и SFR- по SED, для которого использовались фотом.оценки в 18 полосах

SF-Gas relations in nearby spirals 5

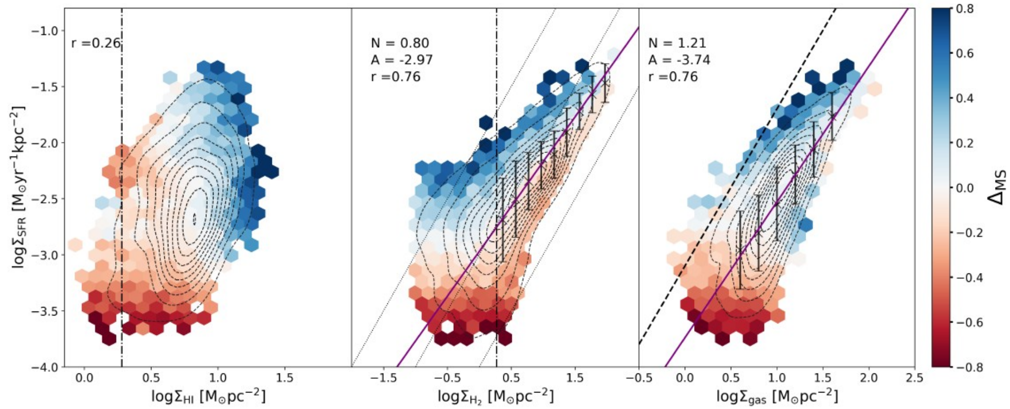
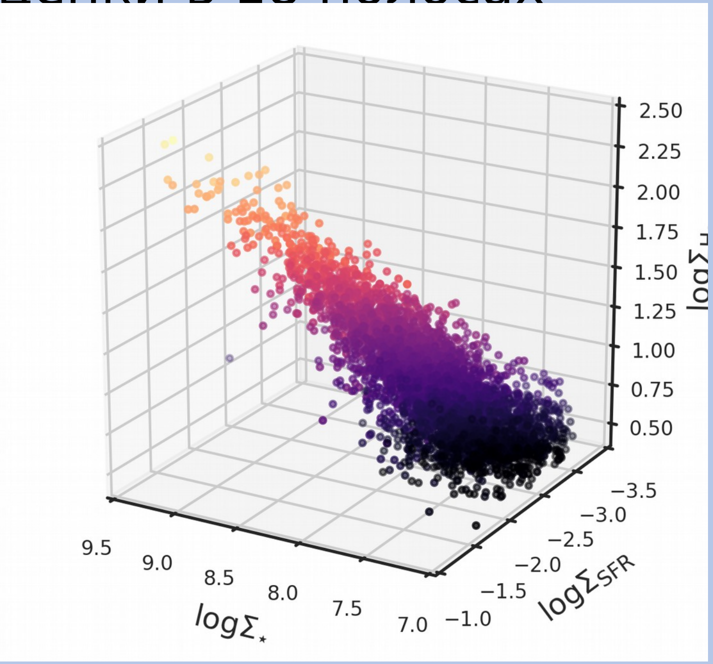


Figure 2. Relations between Σ_{SFR} and Σ_{HI} (left panel), Σ_{H_2} (middle panel) and Σ_{gas} (for the total HI+H$_2$ gas, right panel) colour coded as a function of the median value of Δ_{MS} in each bin. Only bins containing a minimum number of 3 cells are shown in the plot. The dashed contours encircle the areas of the plane containing from 10% to 90% of the data, at steps of 10%. The sensitivity limits are represented by the dotted-dashed black lines. The purple solid lines in the middle and right panel represent the best fit to the data obtained fitting the points marked with crosses; the corresponding slope (N) and intercept (A) are written in the panels, together with the Spearman correlation coefficient r. In the central panel, the dotted lines mark constant molecular t_{depl} of 10^8, 10^9, and 10^{10} yr from top to bottom. In the right panel, the dashed black line is the fit to local ULIRGs and SMGs taken from Daddi et al. (2010).



Correlation	Slope			Intercept			Scatter		
	const α_{CO}	O3N2	N2	const α_{CO}	O3N2	N2	const α_{CO}	O3N2	N2
$\log\Sigma_{H_2}$ - $\log\Sigma_{SFR}$	0.80±0.12	0.83±0.12	0.83±0.11	-2.97±0.87	-2.97±0.93	-2.94±0.94	0.19	0.20	0.19
$\log\Sigma_{gas}$ - $\log\Sigma_{SFR}$	1.21±0.18	1.24±0.16	1.25±0.18	-3.74±1.15	-3.74±1.15	-3.73±1.14	0.17	0.18	0.18
$\log\Sigma_{\star}$ - $\log\Sigma_{H_2}$	0.91±0.29	0.84±0.29	0.87±0.27	-6.15±2.11	-5.66±2.12	-5.93±2.07	0.22	0.24	0.23
$\log\Sigma_{\star}$ - $\log\Sigma_{gas}$	0.50±0.14	0.49±0.14	0.49±0.13	-2.64±0.97	-2.62±1.08	-2.72±1.05	0.24	0.25	0.25

Два метода экстраполяции к большим Z.

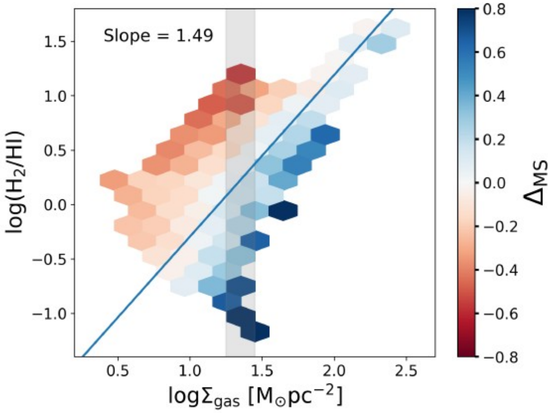
Метод 1.

- Использование соотношений Tacconi et al (2018 $\frac{d\log M_{H_2}}{d\log(1+z)} = 2.6$

и Speagle et al (2014) $\frac{d\log SFR}{d\log(1+z)} = 3.5.$

Учет фотодиссоциации H2.

Нормировка – из полученного ранее соотношения между H2/HI - $\sum_{gas}$ -Δ_{MS} для Z=0.



Итог:

$$\frac{dY}{d\log(1+z)} = -\frac{1.35}{1+1.5\left(1+\frac{M_{H_2}}{M_{HI}}\right)^{-1}} \quad .$$

где Y = log (MH2/MHI).

- **Метод 2**
- Постулировалось найденное по 5 галактикам работы [1] локальное соотношение

$$\log\frac{M_{\rm HI}}{M_\star} \propto 1.13 \log\frac{M_{\rm H_2}}{M_\star}$$

- А для эволюции массы молекулярного газа – то же, как и в Методе 1, соотношение Tacconi et al (2018):

$$\frac{d\log M_{\rm H_2}}{d\log(1+z)} = 2.6$$

- Итог: $\frac{M_{\rm H_2}}{M_{\rm HI}} \propto (1+z)^{-0.34}$

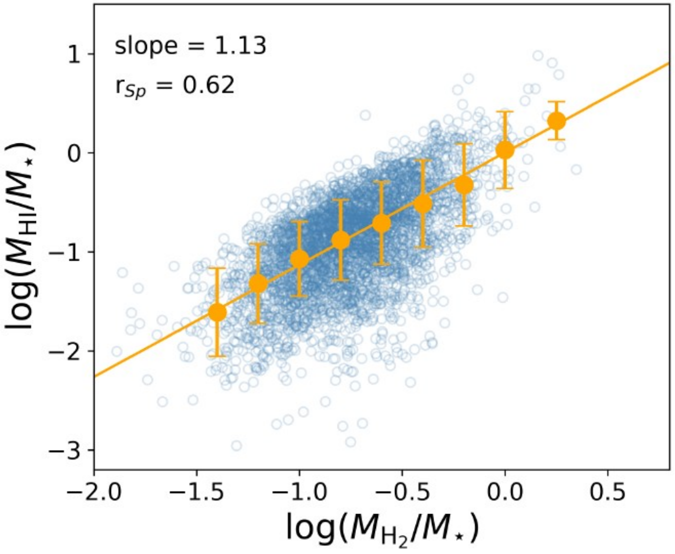


Figure 3. Correlation between $\log(M_{\rm HI}/M_\star)$ and $\log(M_{\rm H_2}/M_\star)$ at 500 pc resolution, for the 5 galaxies of M20. The best fit correlation (solid orange line) has a slope of 1.13 and a Spearman coefficient of 0.62.

$M = 10^{10} M_\odot$
Два метода и три начальных значения для Z=0

$(M_{H_2}/M_{HI})_{z=0}$= 1/3 (turquoise), 1 (gray) and 3 (black).

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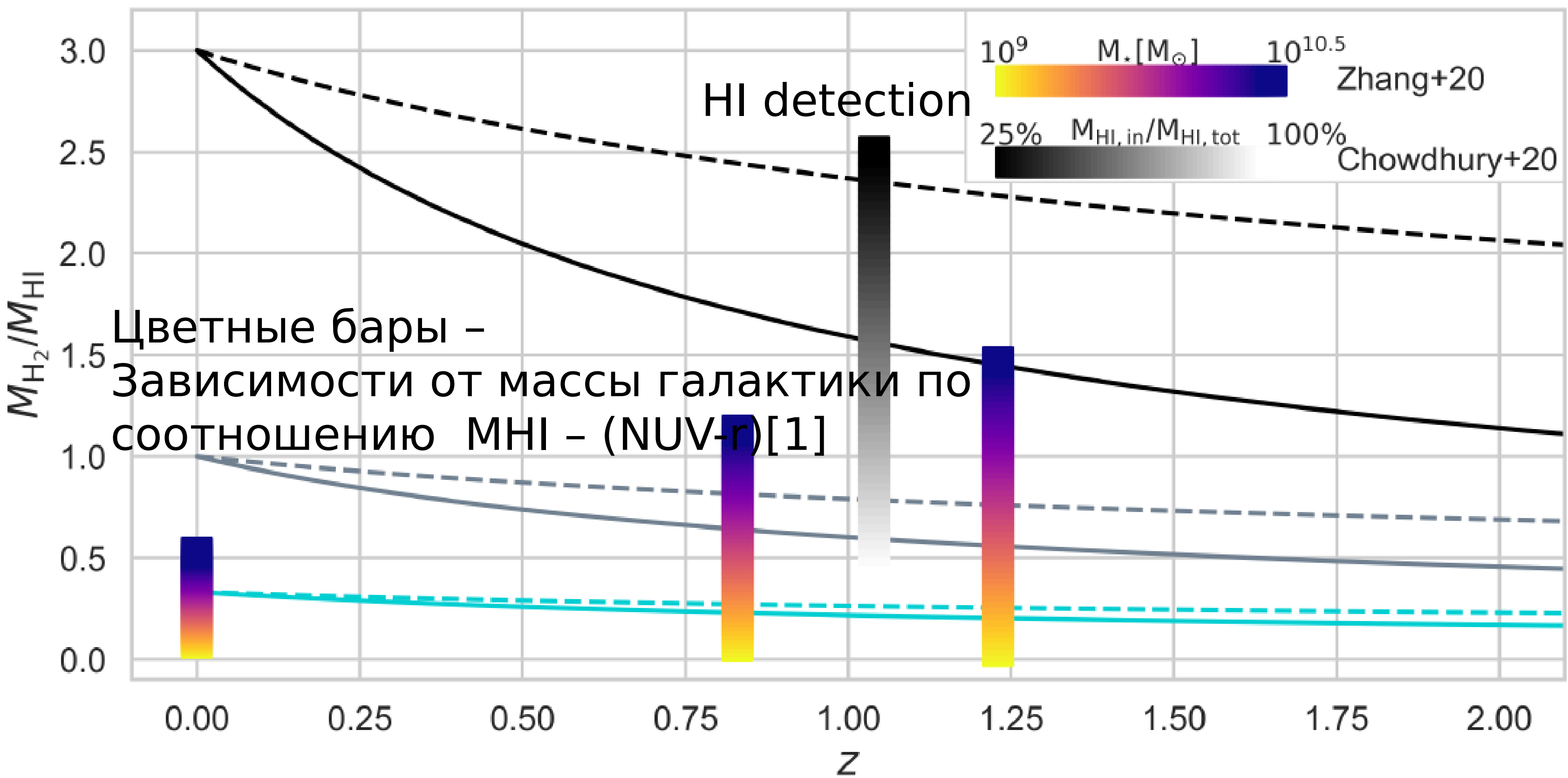

Figure 2. Redshift evolution at fixed stellar mass of the H_2/HI mass ratio, obtained applying Method 1 (solid lines) and Method 2 (dashed lines), for three different values of $(M_{H_2}/M_{HI})_{z=0}$= 1/3 (turquoise), 1 (gray) and 3 (black). The values obtain from the HI detection of C20 at z=1.04 are marked with the white-to-black colored bar, with the gradient indicating variations of the fraction of HI inside the optical radius. The values estimated from the correlations of Zhang et al. (2020) at z=0, 0.83 and 1.23 are indicated with the yellow-to-purple colored bar, with the gradient indicating the variations in stellar mass.

- Для галактик с M*=10^{10}Mc наблюдения дают характерное значение M_{H2}/M_{HI}~ 0.1.
- Для Z = 1 этому соответствует M_{H2}/M_{HI}~ 0.48. Если в пределах D25 содержится более 40% массы HI, то в этих пределах преобладает нейтральный водолод.

Выводы

- Отношение M_{H2}/M_{HI} должно с ростом Z быть или почти постоянным, или медленно падать.
- Оценка времени исчерпания газа должна быть из-за этого раза в два выше, чем в случае чисто молекулярного газа.
- Полное количество газа должно примерно вдвое превосходить массу H2, что делает диск более неустойчивым (по Toomre).
- For a direct assessment of the HI content of star forming galaxies at high redshifts we will have to wait for the planned surveys with the Square Kilometer Array (SKA).