

Scaling Relations for Molecular Gas and Metallicity: Impact on the Baryonic Tully-Fisher Relation

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INTRODUCTION

A fundamental quantity of galaxies is their baryonic mass: the sum of stars and interstellar gas, $M_b = M_* + M_g$. This mass correlates well with a galaxy's rotation speed, forming the Baryonic Tully-Fisher Relation (BTFR: [McGaugh et al. 2000](#); [Verheijen 2001](#)). The dominant forms of mass in disk galaxies are stars and atomic gas ([Lelli et al. 2019](#)). The contribution of molecular gas is usually smaller ([Catinella et al. 2018](#)), and is often less than the uncertainty in the stellar mass (e.g., [McGaugh & Schombert 2015](#)). As the accuracy of stellar mass measurements improves ([Schombert et al. 2019](#)), it becomes useful to have an estimator for the molecular gas mass.

MOLECULAR GAS: THE SEVEN PERCENT SOLUTION

The cold gas¹ mass is the sum of atomic and molecular hydrogen corrected for the hydrogen fraction X :

$$M_g = X^{-1}(M_{HI} + M_{H_2}). \quad (1)$$

The mass of atomic hydrogen is well traced by the 21 cm spin-flip transition. Molecular hydrogen is less accessible. It is traditionally traced by CO, with considerable uncertainty in the conversion x_{CO} from CO flux to H₂ mass ([Bolatto et al. 2013](#)). However, CO is rarely detected in low mass galaxies ([Schombert et al. 1990](#); [Leroy et al. 2008](#)). Here we derive a readily accessible estimator for the molecular gas mass in late-type galaxies with stellar masses ranging from below 10^7 to over $10^{11} M_\odot$. We combine two known scaling relations: that between molecular gas mass and the star formation rate (equation 1 of [McGaugh & Schombert 2015](#)) and that between the star formation rate and stellar mass ([McGaugh et al. 2017](#)). This leads to

$$\log(M_{H_2}) = \log(M_*) - 1.16. \quad (2)$$

To a good approximation, the molecular gas mass is 7% of the stellar mass (Figure 1).

METALLICITY DEPENDENCE OF THE HYDROGEN FRACTION

As chemical evolution proceeds, the hydrogen fraction should slowly decline with increasing metallicity:

$$X = 1 - (Y + Z) = 1 - (Y_p + \frac{dY}{dZ}Z + Z) \quad (3)$$

where Y_p is the primordial helium abundance. [Fukugita & Kawasaki \(2006\)](#) estimate $Y_p = 0.25$ and $dY/dZ = 1.1$. Using oxygen as a proxy for metallicity ($dY/d(O/H) = 18.2(dY/dZ)$: [Izotov & Thuan 2004](#)) yields

$$X = 0.75 - 38.2(O/H). \quad (4)$$

Combining this with the mass-metallicity relation of [de los Reyes et al. \(2015\)](#) leads to

$$X = 0.75 - 38.2 \left(\frac{M_*}{M_o} \right)^\alpha, \quad (5)$$

¹ Ionized gas contributes negligibly to the baryonic mass in the disk ($M_{ion} \approx 10^{-3} M_*$: [Qu & Bregman 2019](#)), only becoming significant in the circumgalactic medium at much larger radii.

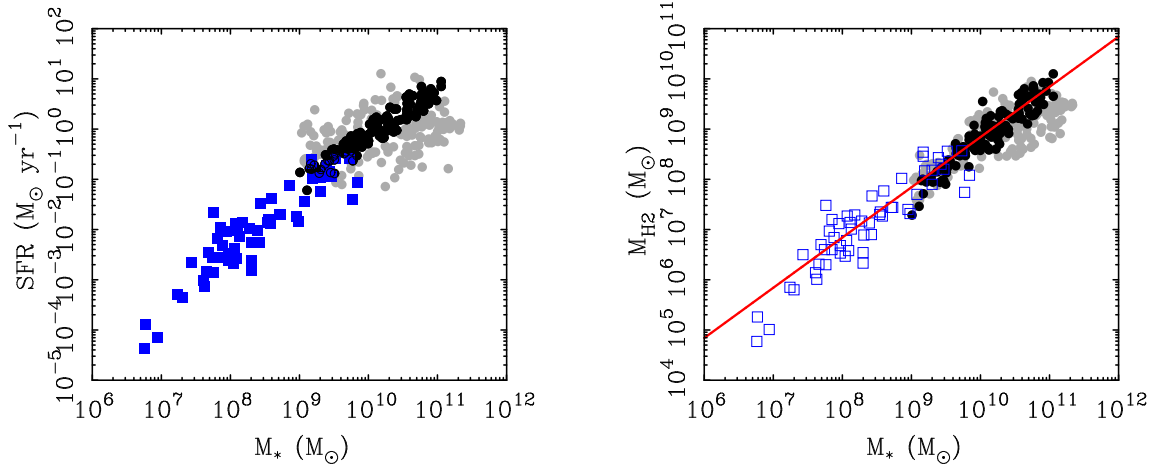


Figure 1. The star formation rate (left) and molecular hydrogen mass (right) as a function of stellar mass. Round points are xGASS data (Catinella et al. 2018, assuming constant x_{CO}), with darker points being galaxies that follow a line of constant star-formation rate ($\dot{M}_* = M_* H_0$) within a factor of two. Square points are low surface brightness galaxies (McGaugh et al. 2017). Solid squares are star formation rates measured with H α luminosities; open squares are the corresponding amount of H $_2$ required to sustain the observed star formation with constant efficiency (Leroy et al. 2008). The solid line is equation 2: to a good approximation over a large range in mass, $M_{H_2} = 0.07 M_*$.

where $\alpha = 0.22$ and $M_o = 1.5 \times 10^{24} M_\odot$. The uncertainty in the mass dependence is considerable, but the variation in the hydrogen fraction is minuscule: for a dwarf galaxy with $M_* = 5 \times 10^7 M_\odot$, $X^{-1} = 1.34$, while for a Milky Way mass galaxy with $M_* = 5 \times 10^{10} M_\odot$, $X^{-1} = 1.41$.

IMPACT ON THE BTFR

Lelli et al. (2019) fit the BTFR assuming a primordial hydrogen fraction and neglecting molecular gas, obtaining a slope of 3.85 ± 0.09 . Using the same data but adopting equation 2 for molecular gas and equation 5 for the hydrogen fraction, we now find a slope of 3.91 ± 0.09 . Consequently, systematic uncertainties in the metallicity and molecular gas have an impact on the fit that is smaller than the random error.

Constructing a subsample restricted to galaxies with the most accurate distances ($\sigma_D/D < 20\%$), the sample size becomes 75 out of an initial 123 galaxies. The slope fit to this subsample is 3.98 ± 0.10 . None of these fitted slopes are meaningfully different from 4. Fixing the slope to this integer value, the intercept is $A = 52 \pm 4 M_\odot \text{ km}^{-4} \text{ s}^4$. This corresponds to a characteristic acceleration scale $g_{\text{TF}} = \zeta V_f^4 / (GM_b) = 1.16 \pm 0.09 \times 10^{-10} \text{ m s}^{-2}$ assuming a geometric factor $\zeta = 0.8$ for disks of finite thickness (McGaugh & de Blok 1998; Lelli et al. 2016).

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