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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 gas[1] mass is the sum of atomic and molecular hydrogen corrected for the hydrogen fraction X:

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

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 H_2 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

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

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:

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

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

$$X = 0.75 - 38.2(O/H). \tag{4}$$

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

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

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[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.

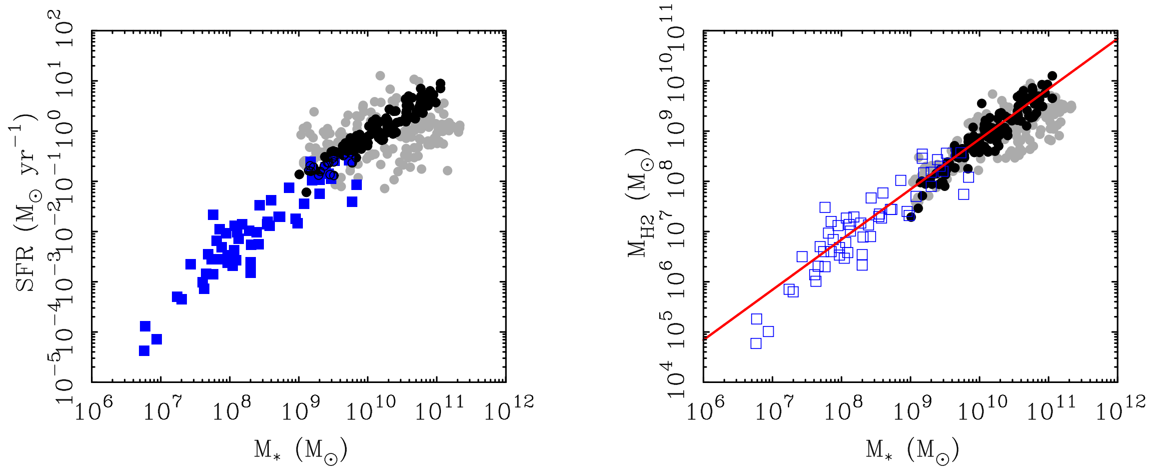

Figure 1. The star formation rate (left) and molecular hydrogen mass (right) as a function of stellar mass. Round points are xGASS data (Catinella et al. 2018, assuming constant x_{CO}), with darker points being galaxies that follow a line of constant star-formation rate ($\dot{M}_* = M_* H_0$) within a factor of two. Square points are low surface brightness galaxies (McGaugh et al. 2017). Solid squares are star formation rates measured with Hα 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 $A = 52 \pm 4$ $M_\odot\,\mathrm{km}^{-4}\,\mathrm{s}^4$. This corresponds to a characteristic acceleration scale $\mathrm{g}_{\mathrm{TF}} = \zeta V_f^4/(G M_b) = 1.16 \pm 0.09 \times 10^{-10}$ $\mathrm{m\,s}^{-2}$ assuming a geometric factor $\zeta = 0.8$ for disks of finite thickness (McGaugh & de Blok 1998; Lelli et al. 2016).

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