ON THE BARYONIC CONTENTS OF LOW-MASS GALAXIES

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\textbf{ABSTRACT}

The baryonic Tully–Fisher relation is an important observational constraint on cosmological and galactic models. However, it is critical to keep in mind that in observations only stars and molecular and atomic gas are counted, while the contribution of the ionized gas is almost universally missed. The ionized gas is, however, expected to be present in the gaseous disks of dwarf galaxies simply because they are exposed to the cosmic ionizing background and to the stellar radiation that manages to escape from the central regions of the galactic disks into their outer layers. Such an expectation is, indeed, born out both by cosmological numerical simulations and by simple analytical models.

\textbf{Key words}: galaxies: dwarf – galaxies: irregular – galaxies: kinematics and dynamics – galaxies: spiral – methods: numerical

1. INTRODUCTION

The baryonic Tully–Fisher relation (BTFR; Freeman 1999; McGaugh et al. 2000) extends the classical Tully–Fisher relation (Tully & Fisher 1977) by including, in addition to stars, all the baryonic content of galaxies. The physical reason for such an extension is very sound—in galactic halos that maintain the universal fraction of baryons, the baryonic mass becomes a linear proxy of the total mass. A deviation from the expected total mass–rotational velocity relation may indicate missing baryons (although such deviations may be degenerated with the effect of stellar feedback, e.g., Dutton & van den Bosch 2009); hence BTFR becomes a powerful test of galaxy formation models.

It is not surprising, therefore, that a significant effort has been expended over the years in measuring the BTFR in a diverse set of galaxies (Verheijen 2001; Bell & de Jong 2001; Gurovich et al. 2004, 2010; McGaugh 2005; Pfenniger & Revaz 2005; Begum et al. 2008; Stark et al. 2009; Trachternach et al. 2009; Torres-Flores et al. 2011). The current state of affairs is well synthesized by McGaugh (2012). The remarkable power-law behavior of BTFR over four decades in mass indicates a substantial fraction of “missing” baryons in the lowest mass galaxies. The observed “baryonic” components of these galaxies are dominated by atomic gas, and the decreasing “baryonic” fraction with galaxy mass is often interpreted as a substantial mass loss from the dwarf galaxies.

A limitation of such an argument, however, is that no observation actually measures the baryonic contents of galaxies; only stars and molecular and atomic gas are accounted for in observational studies, but not the ionized gas (with a handful of exceptions). In other words, in dwarf, H\textsc{I} dominated galaxies, the observed BTFR is, in fact, a H\textsc{I} Tully–Fisher relation. One needs, therefore, to be careful to distinguish the total BTFR that accounts for all of the baryons within the virial radius of a galaxy, and the observed BTFR that only includes stars and molecular and atomic gas but does not account for the ionized gas.

In this paper I demonstrate that dwarf galaxies are expected to contain warm ionized gas (to be distinguished from hot halos)—simply because the gaseous disks of galaxies are exposed to the cosmic background radiation (plus whatever of their own ionizing radiation escapes into the outer layers of their disks), which is going to ionize the outer layer of atomic disks down the column density \(N_{\text{HI}} \sim 10^{19} \text{ cm}^{-2}\), comparable to the transition column density between Lyman limit systems (which are mostly ionized) and damped Ly\(\alpha\) (DLA) systems (which are mostly neutral).

Hence, the interpretation of the observed BTFR is rather non-trivial, nor can it easily be used to deduce the fraction of baryons ejected by the feedback from dwarf galaxies.

2. SIMULATIONS

The simulation used in this paper is similar to the one described in Gnedin & Kravtsov (2010). Specifically, the adaptive refinement tree (ART) code (Kravtsov 1999; Kravtsov et al. 2002; Rudd et al. 2008) is employed to model a 6 \(h^{-1}\) Mpc cube centered on a typical 20\(L_\odot\) (at \(z = 0\)) galaxy. The Lagrangian region of a sphere with radius equal to 5\(R_{\text{vir}}\) at \(z = 0\) (a “region of interest”) is sampled in the initial conditions with the effective 512\(^3\) resolution, while the rest of the simulation volume is sampled more crudely. This setup results in the mass resolution in the region of interest of 1.3 \(\times 10^8 \ M_\odot\) in dark matter. This region of interest is then allowed to refine adaptively as the simulation proceeds in a quasi-Lagrangian manner, all the way down to additional six levels of refinement (total spatial dynamic range of about 30,000), maintaining spatial resolution of 260 pc in comoving reference frame. The simulation adopts \(\Lambda CD\)M cosmology similar to the WMAP1 one (\(\Omega_M = 0.3\), \(\Omega_B = 0.046\), \(\sigma_8 = 0.9\), and \(h = 0.7\)).

The physical processes modeled in the simulation are exactly the same as described in Gnedin & Kravtsov (2010), with one exception. In particular, the simulation incorporates gas cooling (including cooling on metals, molecular hydrogen, and dust), a phenomenological model for molecular hydrogen formation, full time-dependent and spatially variable three-dimensional radiative transfer of ionizing and Lyman-Werner band radiation (both from local sources and from the incident cosmic background of Haardt & Madau 2001) using the Optically Thin Variable Eddington Tensor approximation of Gnedin & Abel (2001), and star formation in the molecular gas using Krumholz & Tan (2007) recipe. The only difference from the Gnedin & Kravtsov (2010) simulation is that the supernova feedback is disabled.
The dotted line gives a relation between the product of the universal baryon fraction $f_{uni}M_{200}$ vs. $V_{max}$ for dark matter halos in the ΛCDM cosmological model, while the dashed line is $M_{HI}$ vs. $V_{max}$ obtained by abundance matching of the theoretical halo mass function and the observed $H_1$ mass function (see text for details).

The observed BTFR in the simulation (solid squares) is not far from the best-fit line to the observational data, but is above it by about a factor of two for smallest galaxies. It is important to remember that the simulation should only be treated as an upper limit to the baryonic content of galaxies, because the stellar feedback is deliberately disabled in the simulation (except the feedback of ionizing radiation, which is included in the simulation by virtue of following the full spatially variable and time-dependent three-dimensional radiative transfer). The fact that the simulation results are not falling on the observed relation for $V_f \lesssim 200$ km s$^{-1}$ simply illustrates the well-known fact that the stellar feedback processes are important for determining the baryonic contents of sub-$L_*$ galaxies.

In order to illustrate the crucial difference between the total baryonic fraction and the observed (stars + molecular + atomic gas) baryonic fraction in model galaxies, I show the two fractions in Figure 2. As one can see, the total baryonic fraction in model galaxies remains close to universal all the way to $V_f \sim 40$ km s$^{-1}$, and at lower $V_f$ the effect of photoevaporation of gas from dark matter halos due to heating by the cosmic ionizing background radiation becomes important. That effect in this simulation is approximately described by a fitting formula of Gnedin (2000),

$$\frac{f_{bar}}{f_{uni}} = \left[1 + (2^{2/3} - 1) \left(\frac{M_c}{M_{200}}\right)^{\alpha}\right]^{-3/\alpha},$$

with parameter values $\alpha = 1$ and $M_c = 7 \times 10^9 M_\odot$. The latter value is the same as that found by Okamoto et al. (2008), converted from the virial overdensity of 97 with respect to the critical used there to the overdensity of 200 used here, for
the halo concentration of 14).\footnote{1} This function (plotted against $V_{\text{max}}$) is shown in Figure 2 as a dotted line. In agreement with McGaugh & Wolf (2010), this line alone is unable to explain the baryonic contents of dwarf galaxies.

It is also possible to construct a simple analytical model that approximately reproduces these results for the observed BTFR, following the ideas of Mo et al. (1998). Let us consider an exponential gaseous disk with the surface density run:

$$\Sigma(R) = \Sigma_0 e^{-R/R_d},$$

such that the disk scale length is a given fraction $\mu$ of the halo virial radius $R_{200}$,

$$R_d = \mu R_{200},$$

and the disk mass is a fraction $\nu$ of the total halo mass of $M_{200}$,

$$2\pi \Sigma_0 R_d^2 = \nu M_{200},$$

so that

$$\Sigma_0 = \frac{\nu M_{200}}{2\pi \mu^2 R_{200}^2}.$$

(expressions for $\mu$ and $\nu$ are given in Mo et al. 1998 as functions of other parameters). The disk is exposed to the cosmic ionizing background, which ionizes hydrogen (from both sides) in a slab of gas below the surface density $\Sigma_{\text{H}^\text{II}}$. Then the mass of the neutral gas in the disk is

$$M_{\text{H}^\text{I}} = 2\pi \int_0^{R_{\text{H}^\text{II}}} (\Sigma(R) - \Sigma_{\text{H}^\text{II}}) R dR,$$

(2)

where $R_{\text{H}^\text{II}}$ is the edge of the H$^\text{I}$ disk ($\Sigma(R_{\text{H}^\text{II}}) = \Sigma_{\text{H}^\text{II}}$). The minus $\Sigma_{\text{H}^\text{II}}$ term under the integral in Equation (2) appears because both sides of the disk are exposed to the ionizing radiation, and hence each side has an ionized layer of thickness

The fraction of ionized gas outside the H$^\text{I}$ disk is then simply one minus the sum of Equations (3) and (4). The long-dashed line in Figure 2 shows Equation (4) as a function of $V_{\text{max}}$.

The ionized gas starts dominating the disk mass only for $V_{\text{max}} < 30 \text{ km s}^{-1}$, but makes a $> 20\%$ contribution all the way to $V_{\text{max}} \approx 100 \text{ km s}^{-1}$.

\footnote{5 This is also the column density of a typical sub-DLA absorption system.}
Finally, one may ask where the ionized gas, apparent in Figures 1 and 2, is actually located in model galaxies? To answer that question, I show in Figure 3 surface density profiles for the total, ionized, and neutral (atomic and molecular, although the molecular fraction in the shown galaxies is small) gas in two galaxies, in which the ionized gas contribution is large. In both galaxies neutral gas forms an approximately exponential disk, while the surface density of the ionized component remains approximately constant well outside the scale length of the neutral disk. These trends are consistent with the simple analytical model presented above. The choice of \( \Sigma_{H_2} = 0.4 \, M_\odot \, pc^{-2} \) is the actual value of the fixed surface density of the ionized gas found in the simulation.

The top panel of Figure 3 also shows the circular velocity profiles for the two galaxies and the rotational velocity of H\(_{\text{I}}\) gas. The difference between the two is due to non-circular motions in the gas; this difference is consistent with the prior theoretical conjecture—it is unavoidable from purely physical grounds, since their surface densities (and, hence, column densities) are too low. Even more importantly, the outer layers of the inner disks are also ionized because they are exposed to the cosmic ionizing background and to the stellar radiation that manages to escape from the central regions of the galactic disks into their outer layers. These layers are direct analogs of the Reynolds layer observed in the Milky Way (Reynolds 1993), but their relative contribution to the total mass budget becomes progressively larger as galactic disks become less massive, less dense, and allow ionizing radiation to reach deeper.

The existence of this ionized gas is not just a theoretical conjecture—it is unavoidable from purely physical grounds, since the cosmic ionizing background must ionize the outer layers of galactic H\(_{\text{I}}\) disks (on both sides) down to column densities of Lyman limit systems, \( N_{\text{H}_1} \gtrsim 10^{19} \, \text{cm}^{-2} \) (in my simulation it is \( \Sigma_{\text{H}_1} = 0.2 \, M_\odot \, pc^{-2} \) or, equivalently, H\(_{\text{I}} = 2.5 \times 10^{19} \, \text{cm}^{-2} \)).

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