The baryonic Tully-Fisher relation and galactic outflows

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ABSTRACT

Most of the baryons in the Universe are not in the form of stars and cold gas in galaxies. Galactic outflows driven by supernovae/stellar winds are the leading mechanism for explaining this fact. The scaling relation between galaxy mass and outer rotation velocity (also known as the baryonic Tully-Fisher relation, BTF) has recently been used as evidence against this viewpoint. We use a ΛCDM based semi-analytic disk galaxy formation model to investigate these claims. In our model, galaxies with less efficient star formation and higher gas fractions are more efficient at ejecting gas from galaxies. This somewhat counter intuitive result is due to the (observational) fact that galaxies with less efficient star formation and higher gas fractions tend to live in dark matter haloes with lower circular velocities, from which less energy is required to escape the potential well. In our model the intrinsic scatter in the BTF is ≃ 0.15 dex, and mostly reflects scatter in dark halo concentration. The scatter is largely independent of galaxy structure because of the large radius within which galaxy rotation velocities are measured. The observed scatter, equal to ≃ 0.24 dex, is dominated by measurement errors. The best estimate for the intrinsic scatter is that it is less than 0.15 dex, and thus our ΛCDM based model (which does not include all possible sources of scatter) is only just consistent with this. Future observations of the BTF scatter could be made with a more stringent measurement of the intrinsic scatter, and thus provide a strong constraint to galaxy formation models. In our model, gas rich galaxies, at fixed virial velocity (V_{vir}), with lower stellar masses have lower baryonic masses. This is consistent with the expectation that galaxies with lower stellar masses have had less energy available to drive an outflow. However, when the outer rotation velocity (V_{flat}) is used the correlation has the opposite sign, with a slope in agreement with observations. This is due to the fact there is scatter in the relation between V_{flat} and V_{vir}. In summary, contrary to some previous claims, we show that basic features of the BTF are consistent with a ΛCDM based model in which the low efficiency of galaxy formation is determined by galactic outflows.

Key words: galaxies: formation – galaxies: fundamental parameters – galaxies: haloes – galaxies: spiral – galaxies: kinematics and dynamics

1 INTRODUCTION

The cosmic baryon fraction is extremely well determined from observations of the CMB plus other cosmological probes, with the latest results from WMAP finding f_{bar} ≡ \Omega_b/\Omega_m = 0.167 ± 0.004 (Komatsu et al. 2011). However, on galaxy scales a significant fraction of the baryons are “missing”. Stars and cold gas in galaxies account for just ≃ 8% of the cosmic baryons (e.g., Bell et al. 2003; Fukugita & Peebles 2004; Read & Trentham 2005), while hot intracluster gas accounts for just ≃ 4% (Fukugita & Peebles 2004).

The vast majority of the cosmic baryons (≃ 88%) are thought to be in the form of hot gas in the haloes of galaxies or between galaxies in the so called warm-hot-intergalactic medium (WHIM) at temperatures between 10^5 and 10^7 K (Cen & Ostriker 1999). However, only a fraction of these baryons have been detected (e.g., Bregman 2007, Shull et al. 2011), and the amount of baryons that reside in hot haloes around the Milky Way and other nearby galaxies is a subject of current debate (e.g., Grevevich & Putman 2009; Anderson & Bregman 2010).

This raises the question: Why are most of the cosmic baryons in hot haloes or the WHIM? There are two basic answers: 1) Most of the baryons accreted into galaxies and were then expelled (into haloes or the WHIM) by feedback...
processes (stellar and/or AGN); or 2) Most baryons never accreted into galaxies in the first place.

The answer to this question is of interest beyond the realm of baryon accounting. Outflows have been invoked to explain a number of apparent problems with galaxy formation in a ΛCDM context. These include the predicted central density cusps, which are not observed, but can be softened with galactic outflows (e.g., Read & Gilmore 2005; Mashchenko et al. 2006; Governato et al. 2010; Macciò et al. 2012), and the excess of low-angular momentum material which needs to be removed in order to produce bulgeless disk galaxies with exponential density profiles (e.g., Maller & Dekel 2002; Dutton 2009; Governato et al. 2010; Brook et al. 2011). Thus if galactic outflows are not the explanation of why galaxy formation is so inefficient, other mechanisms will need to be found to reconcile ACDM with observations on galaxy scales.

A clue to the origin of the missing baryons comes from the fact that the galaxy formation efficiency\(^1\) is not a constant. It is observed to peak at \(\epsilon_{\text{GF}} \sim 30\%\) in haloes of mass \(M_{\text{vir}} \sim 10^{12} M_\odot\), and declines to both higher and lower masses (e.g., Hoekstra et al. 2005; Conroy & Wechsler 2009; Dutton et al. 2010; Moster et al. 2010; More et al. 2011). In high mass haloes \(M_{\text{vir}} \gtrsim 10^{12} M_\odot\), cooling is progressively more inefficient (e.g., Blumenthal et al. 1984), which results in the correct qualitative trend. However, additional heating mechanisms (such as AGN feedback) are needed in order to reproduce the rapid decline in galaxy formation efficiency with increasing halo mass (e.g., Croton et al. 2006). In haloes of mass \(10^{10} \lesssim M_{\text{vir}} \lesssim 10^{12} M_\odot\), most of the cosmically available baryons should accrete onto central galaxy (e.g., Blumenthal et al. 1984; Keres et al. 2009). In this mass range, galactic outflows driven by supernovae or stellar feedback are the leading mechanism for explaining why the galaxy formation efficiencies are so low, and decline with decreasing halo mass.

Galactic outflows appear ubiquitous in galaxies that are undergoing, or have recently undergone, significant star formation (e.g., Shapley et al. 2003; Martin 2005; Tremonti et al. 2007; Weiner et al. 2009; Rubin et al. 2010; Steidel et al. 2010). At least some of the outflowing gas is observed to be moving faster than the escape velocity of the halo. However, measuring outflow mass rates is challenging, and at present it is not clear how much mass is actually removed (e.g., Rubin et al. 2010). Thus, while galactic outflows undoubtedly exist, their role in determining the baryonic masses of galaxies is unclear.

The scaling relations between baryonic mass, outer rotation velocity and gas fraction have been used as arguments against galactic outflows being the explanation for the observed low galaxy formation efficiencies. Anderson & Bregman (2010) argue that outflows should result in a negative correlation between galaxy mass and stellar mass at fixed velocity, while no such correlation is observed. They cite this as strong evidence against galactic outflows. McGaugh (2012) shows that the efficiency of outflows needs to be higher in galaxies with higher gas fractions and lower past average star formation rates. McGaugh (2012) argues that in the context of feedback models this is apparently puzzling because of the notion that galaxies with more star formation should have more energy to drive an outflow. Hence the galaxies that are most efficient at removing baryons are expected to have the highest star formation efficiencies and lowest gas fractions. As we show below the resolution of this puzzle is the fact that it is not just the amount of star formation that determines the efficiency of feedback. The depth of the potential well is also important — it is much easier to remove baryons from lower mass haloes. In addition McGaugh (2011, 2012) has argued that the scatter in the BTF is consistent with being zero, which is hard to explain in a ΛCDM context.

It should be noted that until the details of star formation and feedback are understood it will not be possible to talk of definitive predictions for the BTF in the ΛCDM paradigm. The question we can ask at the present time is whether the properties of the BTF can be reproduced in a ΛCDM context using plausible models for star formation and feedback. In this paper we address this question using the semi-analytic disk galaxy formation model of Dutton & van den Bosch (2009). This paper is organized as follows: In §2 we give a brief outline of the galaxy formation model; In §3 we discuss the correlations between ejection efficiency, galaxy velocity and gas fraction; In §4 we discuss the scatter in the baryonic Tully-Fisher relation; A summary is given in §5.

\(1\) We define the galaxy formation efficiency as the fraction of the cosmically available baryons, \(f_{\text{bar}}\), that end up as stars and cold gas in a galaxy: \(\epsilon_{\text{GF}} = M_{\text{gal}}/(f_{\text{bar}} M_{\text{vir}})\).
known as a galactic fountain (e.g., Brook et al. 2012a). All of these effects create scatter in the mass accretion histories of baryons and dark matter onto galaxies, which one would nominally expect to result in more scatter in the BTF.

3 EJECTION EFFICIENCY

We define the ejection fraction as the fraction of the cosmically available baryons that have been ejected from the galaxy: $\epsilon_{\text{eject}} \equiv M_{\text{eject}}/(f_{\text{bar}} M_{\text{vir}})$. Similarly we define the stellar mass fraction as the fraction of the cosmically available baryons that end up in stars (or stellar remnants): $\epsilon_{\text{star}} \equiv M_{\text{star}}/(f_{\text{bar}} M_{\text{vir}})$. Note that due to return of gas from stars into the ISM, $\epsilon_{\text{star}}$ is less than the integral of the star formation rate for any given galaxy. The ratio of these two quantities is the mass loading factor: $\eta \equiv \epsilon_{\text{eject}}/\epsilon_{\text{star}}$, which is a way to parametrize how “efficient” feedback is in ejecting gas from a galaxy with a given amount of star formation.

The left panel of Fig. 1 shows the mass loading factor vs outer galaxy circular velocity, $V_{\text{vir}}$, for our model. Galaxies with lower circular velocities have high mass loading factors (i.e., lower mass galaxies are more efficient at ejecting their baryons). As in the observations (McGaugh 2012) the effect is not subtle: galaxies with $V_{\text{vir}} \sim 40 \text{ km} \text{s}^{-1}$ have $\eta \sim 100$, while galaxies with $V_{\text{vir}} \sim 200 \text{ km} \text{s}^{-1}$ have $\eta \sim 1$. The scaling between mass loading factor and circular velocity $\eta \propto V^{-2}$ (dashed line) results from our assumptions of energy conservation and that the outflow moves at the local escape velocity. We note that momentum driven winds (e.g., Murray et al. 2005) are expected to result in $\eta \propto V^{-1}$, while constant wind velocity models (e.g., Springel & Hernquist 2003) result in a constant mass loading factor. Thus as long as the wind velocity scales with the galaxy velocity, the lower energy/momentum input from stars/supernovae in lower mass galaxies is more than compensated by the shallower potential wells.

The middle panel of Fig. 1 shows the mass loading factor vs gas-to-stellar mass ratio, $M_{\text{gas}}/M_{\text{star}}$. Where $M_{\text{gas}}$ is the mass in cold gas (atomic and molecular). This shows that galaxies with higher gas fractions have higher mass loading factors, and are thus more “efficient” at ejecting their baryons, in qualitative agreement with observations (McGaugh 2012). A comparison between the left and middle panels shows that there is less scatter in the relation between mass loading factor and galaxy velocity, than between mass loading factor and gas fraction. This suggests the relation between mass loading and galaxy velocity (left panel) is more fundamental than the relation between mass loading and gas fraction (middle panel). The reason galaxies with higher gas fractions have higher mass loading is simply a result of the anti-correlation between gas fraction and galaxy velocity (right panel): $(M_{\text{gas}}/M_{\text{star}}) \propto V_{\text{flat}}^{-1.6}$. As before, the solid line shows the median of the model (grey points) which is in good agreement with the observations (open circles) from Stark et al. (2009) and McGaugh (2012).

This raises the question: Why do lower mass galaxies have, on average, higher gas fractions? Observationally we know that lower mass galaxies are on average less dense (e.g., Kauffmann et al. 2003), and that lower density galaxies are less efficient at turning gas into stars (Kennicutt 1998). This leads naturally to higher gas fractions in lower mass galaxies. However, to reproduce the observations in detail requires, in addition to the standard Schmidt-Kennicutt star formation law, a threshold density for star formation (van den Bosch 2000). On the theory side, a correlation between galaxy density and galaxy mass occurs naturally in a ΛCDM context. The simplest disk galaxy formation model (in which the galaxy formation efficiency and spin parameters are constant) results in disk sizes $R_{\text{d}} \propto M_{\text{gal}}^{1/3}$ and thus disk densities $\Sigma_{\text{d}} \propto M_{\text{gal}}^{1/3}$ (e.g., Mo, Mao, & White 1998). Including outflows typically results in shallower size-mass relations (e.g., Dutton & van den Bosch 2009), and thus an even stronger mass – gas density relation.

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In our model we measure $V_{\text{flat}}$ at the radius at a radius which encloses 80% of the cold gas.

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4 THE BARYONIC TULLY-FISHER RELATION

The baryonic Tully-Fisher relation (BTF) is the relation between the baryonic mass of a galaxy, $M_{\text{gal}}$ (stars and cold gas), and the rotation velocity at large galactic radii, typically referred to as $V_{\text{vir}}$. It is an extension of the original Tully-Fisher relation which is a correlation between HI linewidth and galaxy luminosity (Tully & Fisher 1977). The BTF was first studied by McGaugh et al. (2000), and subsequently by numerous authors, both observationally (e.g., Bell & de Jong 2001; McGaugh 2005; Geha et al. 2006; Avila-Reese et al. 2008; Begum et al. 2008; Stark et al. 2009; Trachternach et al. 2009; Gurovich et al. 2010; Hall et al. 2011; Catimella et al. 2012); and theoretically (e.g., Dutton & van den Bosch 2009; de Rossi et al. 2010; Dutton et al. 2011; Piontek & Steinmetz 2011; Trujillo-Gomez et al. 2011; Brook et al. 2012b). In this section we discuss aspects of the slope and scatter in the context of ΛCDM.

It has been argued that the "true" BTF should include the contribution of ionized gas (Gnedin 2011). However, this is both hard to measure and hard to model. In this paper we restrict the baryonic mass (of both our models and the data) to be that of the stars and cold gas in a galaxy. Since the vast majority of the ionized gas will be at radii beyond the HI disk, the baryonic mass that we use, $M_{\text{gal}}$, is close to the baryonic mass within the HI radius of the galaxy. As such, $M_{\text{gal}}$ is expected to be more strongly correlated to $V_{\text{vir}}$ than the total baryonic mass inside the virial radius of the dark matter halo, $M_{\text{fbar}}$. Indeed, in our model the relation between $M_{\text{fbar}}$ and $V_{\text{vir}}$ has a slightly larger scatter than the regular BTF. Likewise the relation between $M_{\text{bar}}$ and $V_{\text{vir}}$ has smaller scatter than the relation between $M_{\text{bar}}$ and $V_{\text{flat}}$.

4.1 Slope and zero point of the BTF in LCDM

In ΛCDM the underlying origin of the BTF is the $M_{\text{vir}} \propto V_{\text{vir}}^3$ relation of dark matter haloes. This relation has no scatter by definition. Predicting the BTF from this relation requires understanding how baryonic mass is related to virial mass ($f_3 = M_{\text{gal}}/M_{\text{vir}}$); and how galaxy velocity is related to virial velocity: $f_3 = V_{\text{flat}}/V_{\text{vir}}$. Galaxy formation efficiencies depend on the details of gas cooling, feedback and recycling – none of which can be predicted from first principles. The relation between galaxy and halo velocities is better constrained (thanks to cosmological N-body simulations), but it too depends on a couple of unknown factors: the response of the halo to galaxy formation, and the galaxy formation efficiency. Because the enclosed dark matter fractions increase with increasing galactico-centric distance, these two unknowns are minimized by using velocities measured at large radii. Given there are no unique predictions for the BTF in ΛCDM cosmologies, and are unlikely to be so for some time, its main utilization is likely to be as a constraint to galaxy formation models, and in particular models for feedback. Indeed the feedback efficiency and angular momentum loss in our model have been tuned to match the galaxy formation efficiency as a function of halo mass.

4.2 Scatter in the BTF

The intrinsic scatter in the BTF is observed to be small and is consistent with zero. This is a potential problem for ΛCDM (McGaugh 2011, 2012). Fig. 2 shows three Tully-Fisher relations from our galaxy formation model: Baryonic mass vs virial velocity (left); Baryonic mass vs galaxy velocity (BTF, middle); and Stellar mass vs galaxy velocity (STF, right). All relations have small, but non-negligible, scatter of $\sim 0.1 - 0.2$ dex, with the BTF having a scatter of 0.15 dex. There is also a velocity dependence to the scatter in all three relations. For the BTF the scatter ranges from $\sim 0.20$ dex at $V_{\text{vir}} \sim 30$ km s$^{-1}$ to $\sim 0.11$ dex for $V_{\text{fbar}} \sim 200$ km s$^{-1}$.

What is the source of the scatter? In our models the majority ($\sim 75\%$) of the scatter in the BTF comes from variation in the concentration of the dark matter halo, which mostly effects $V_{\text{vir}}/V_{\text{fbar}}$. The scatter in halo concentrations is constrained by cosmological simulations (e.g., Macciò et al. 2008), and so there is little freedom to change this in the context of ΛCDM. The remainder of the scatter comes from variation in the halo spin parameter, which in our model effects the galaxy formation efficiency. We note

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that while variation in the halo spin parameter is the primary source of variation in the distribution of baryons in galaxies (i.e., galaxy sizes), this does not significantly affect $V_{\text{flat}}$ because we are measuring circular velocity at a radius which encloses most of the baryons. Since there are likely other sources of scatter that are not taken into account in our models, we expect that our models provide a lower limit to the BTF scatter in $\Lambda$CDM.

**What is the intrinsic scatter of the observed BTF?**

The observed scatter in the BTF is $\sim 0.24$ dex (McGaugh et al. 2011; Hall et al. 2011), and is dominated by measurement errors on baryonic masses (McGaugh 2011; Foreman & Scott 2011). Unfortunately, the errors have uncertainties, so we currently do not have a robust measurement of the intrinsic scatter. Nevertheless, McGaugh (2012) finds the intrinsic scatter to be $< 0.15$ dex, which our model is just consistent with.

Thus the intrinsic scatter of the BTF has the potential to be a powerful constraint on galaxy formation models. In order to make progress a BTF sample needs to be constructed for which the measurement errors are controlled to be smaller than the scatter one is trying to measure. There are two primary sources of measurement errors: distance uncertainties and stellar mass uncertainties. Rotation velocity errors are typically small when resolved H$\alpha$ rotation curves are obtained, and gas masses can be measured reliably. Distance uncertainties can be minimized by using galaxies at large enough distances such that peculiar velocities are not important (i.e., $\gtrsim 100$ Mpc). But obtaining resolved H$\alpha$ rotation curves for such galaxies is currently a challenge, and may have to wait until the next generation radio telescopes. H$\alpha$ line widths or H$\alpha$ rotation curves can be measured for large (~1000’s) samples of galaxies (e.g., Courteau et al. 2007; Hall et al. 2012), but these are not as straightforward to interpret as $V_{\text{flat}}$, and thus $V_{\text{flat}}$ is the appropriate correlation between baryonic mass and stellar mass. Anderson & Bregman (2010) found no such correlation, and thus argued this was strong evidence against galactic outflows being responsible for the low galaxy formation efficiencies. We investigate the validity of this reasoning using BTF and STF relations from a semi-analytic model. Fig. 3 shows the correlations between the mass residuals of these BTF and STF relations. We show results using TF relations constructed using both virial velocity of the dark matter halo, $V_{\text{vir}}$, (which is not observable for individual galaxies), and the velocity in the outer part of a galaxy, $V_{\text{flat}}$, (which is observable for individual galaxies). We split the models into gas rich and gas poor, since gas poor galaxies are expected to have a positive correlation between baryonic mass and stellar mass for a galaxy in a given dark matter halo, $V_{\text{vir}}$, (which is observable for individual galaxies). At fixed $V_{\text{vir}}$, gas rich galaxies do indeed have a positive correlation between baryonic mass and stellar mass (Fig. 3). The upper left panel shows that at fixed $V_{\text{vir}}$, gas rich galaxies do indeed have a positive correlation between baryonic mass and stellar mass. However, at fixed $V_{\text{flat}}$, the correlation has the opposite sign (middle panel), with a slope in good agreement with observations from Stark et al. (2009) and McGaugh et al. (2012) (right panel). Thus the simple reasoning used by Anderson & Bregman (2010) to argue against outflow models, while correct in principle, is not valid in practice.

**Figure 3.** Correlations between residuals of the baryonic TF and stellar mass TF relations for gas rich galaxies ($M_{\text{gas}}/M_{\text{star}} > 1$). At fixed dark matter halo virial velocity, $V_{\text{vir}}$, lower stellar masses result in higher baryonic masses (left panel), as might be expected by the lower energy available to drive an outflow. However, when computed at fixed galaxy rotation velocity, $V_{\text{flat}}$, this correlation has the opposite sign (middle panel), with a slope in agreement with observations (right panel).
5 SUMMARY

We have used a ΛCDM based galaxy formation model to investigate the observable signatures of galactic outflows in the baryonic Tully-Fisher relation (BTF). We summarize our results as follows:

- Observations indicate that galaxies with lower star formation efficiencies and higher gas fractions have higher ejection efficiencies (e.g., McGaugh 2011). We show that these trends can be explained by energy driven feedback models.
- In our model feedback is more efficient in galaxies with lower circular velocities (and shallower potential wells). This is in spite of the significantly lower star formation efficiencies in lower velocity galaxies.
- In our model, as well as observations, lower velocity galaxies have higher gas fractions. This results in a (non-causal) correlation between ejection efficiency and gas fraction, such that ejection efficiencies are higher in galaxies with higher gas fractions.
- Lower mass galaxies are predicted to have higher gas fractions. This is a generic prediction for galaxy formation in ΛCDM, which is strengthened by feedback.
- The scatter our model BTF is ≃ 0.15 dex, and is mostly due to variations in the dark matter concentration parameter. While this scatter is significantly smaller than the observed scatter of 0.24 dex, most of the observed scatter is due to measurement uncertainties. McGaugh (2012) finds the intrinsic scatter in the BTF is < 0.15 dex, which our model is only just consistent with.
- In principle, future observations of the BTF could be made where the measurement uncertainties are controlled to less than 0.1 dex, and thus to provide stringent constraints to the intrinsic scatter, and ΛCDM based galaxy formation models.
- In our model, at fixed virial velocity (V_{vir}), gas rich galaxies with lower stellar masses have higher baryonic masses. This is consistent with the idea that less star formation should result in less energy (or momentum) available to drive an outflow (e.g., Anderson & Bregman 2010). However, at fixed galaxy velocity (V_{flat}), the correlation is of the opposite sign due to the scatter in V_{flat}/V_{vir}. Furthermore the slope of the correlation in our model is in agreement with observations.

In summary, we find that there is currently no conflict between the observed baryonic Tully-Fisher relation (slope, scatter, and residual correlations) and predictions of ΛCDM based models in which galaxy formation efficiencies are determined by galactic outflows.

ACKNOWLEDGEMENTS

We thank Stacy McGaugh, Stéphane Courteau, Andrea Macciò and Frank van den Bosch for valuable discussions.

REFERENCES

Anderson, M. E., & Bregman, J. N. 2010, ApJ, 714, 320
Avila-Reese, V., Zavala, J., Firmani, C., & Hernández-Toledo, H. M. 2008, AJ, 136, 1340
Begum, A., Chengalur, J. N., Karachentsev, I. D., & Sharina, M. E. 2008, MNRAS, 386, 138
Bell, E. F., & de Jong, R. S. 2001, ApJ, 550, 212
Bell, E. F., McIntosh, D. H., Katz, N., & Weinberg, M. D. 2003, ApJL, 585, L117
Bregman, J. N. 2007, ARA&A, 45, 221
Brook, C. B., et al. 2011, MNRAS, 415, 1051
Brook, C. B., Stinson, G., Gibson, B. K., et al. 2012a, MNRAS, 419, 771
Brook, C. B., Stinson, G., Gibson, B. K., Wadsley, J., & Quinn, T. 2012b, arXiv:1201.3359
Blumenthal, G. R., Faber, S. M., Primack, J. R., & Rees, M. J. 1984, Nature, 311, 517
Bullock, J. S., Kolatt, T. S., Sigad, Y., Somerville, R. S., Kravtsov, A. V., Klypin, A. A., Primack, J. R., & Dekel, A. 2001a, MNRAS, 321, 559
Bullock, J. S., Dekel, A., Kolatt, T. S., Kravtsov, A. V., Klypin, A. A., Porciani, C., & Primack, J. R. 2001b, ApJ, 555, 240
Catinella, B., Kauffmann, G., Schiminovich, D., et al. 2012, MNRAS, 420, 1959
Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
Conroy, C., & Wechsler, R. H. 2009, ApJ, 696, 620
Courteau, S., Dutton, A. A., van den Bosch, F. C., MacArthur, L. A., Dekel, A., McIntosh, D. H., & Dale, D. A. 2007, ApJ, 671, 203
Croton, D. J., Springel, V., White, S. D. M., et al. 2006, MNRAS, 365, 11
de Rossi, M. E., Tissera, P. B., & Pedrosa, S. E. 2010, A&A, 519, A89
Dutton, A. A. 2009, MNRAS, 396, 121
