Group 2: Modeling the outskirts of galaxies

Formation and Evolution of Galaxy Outskirts
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Probing the Baryon Cycle in Galaxy Outskirts

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Abstract. Galaxies are born and grow within a cosmic ecosystem, in which they receive material from surrounding intergalactic gas via gravitationally-driven inflows and expel material via powerful galactic outflows. These processes, collectively referred to as the baryon cycle, are increasingly believed to govern galaxy growth over cosmic time. I discuss new insights on the baryon cycle using analytic models and hydrodynamical simulations of galaxy evolution, particularly emphasizing how galaxy outskirts are the prime locale within which to observe these processes in action by examining observational tracers such as rest-ultraviolet absorption lines and the neutral and molecular gas content of galaxies.

Keywords. galaxies: formation, galaxies: evolution, galaxies: absorption lines, galaxies: ISM, methods: n-body simulations

1. Introduction

Galaxy formation involves a wide range of complex processes that connect large-scale structure with sub-parsec scale processes of stellar evolution and black hole growth. With the growth of structure now well-specified within the concordance ΛCDM paradigm, the baryonic processes that govern galaxy evolution have now emerged as the key to solving how the vast diversity of galaxies arises from primordial mass perturbations.

An obvious yet crucial point is that galaxies are constantly drawing in gas via gravity, since they typically lie at the bottom of their dark matter potential wells. Unabated gravitationally-driven accretion has long been known to lead to the *overcooling problem,* in which galaxies such as the Milky Way should have formed the majority of their halo's baryons into stars by today, yet are observed to only have converted 20-25% into stars. Galaxies at higher and lower masses have even lower conversion efficiencies. This leads to the central problem in modern galaxy formation: Understanding the energetic *feedback* processes within galaxies that self-regulate their growth (Somerville & Davé 2015).

Galaxies that vigorously form stars are seen to drive powerful outflows, with mass loss rates that are comparable to or exceeding their star formation rates. These outflows are the leading candidate to suppress star formation by expelling the cold gas from galaxies, and heating the surrounding gas via shocks. The physics of what drives outflows remains unclear, with supernovae, stellar radiation, and cosmic rays all potential candidates. By studying the physical properties of gas in and around galaxies, we can obtain insights into the nature of outflow driving.

The outskirts of galaxies offers opportunities to see inflows and outflows happening directly in the gaseous component. However, such gas is tenuous, multi-phase, and often lacking ordered motion, making its detection complicated. Only by using a multitude of techniques to study galaxy outskirts by tracing ionized, neutral, and molecular gas

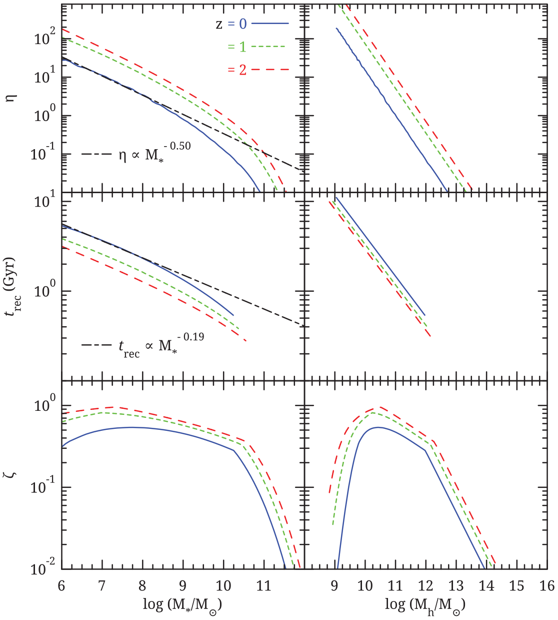

Figure 1. Best-fit baryon cycling parameters η (outflow mass loading factor), $t_{\rm rec}$ (wind recycling time), and ζ (preventive feedback) as a function of stellar mass (left panels) and halo mass (right panels). From Mitra *et al.* (2015).

can we obtain a full picture of how the *baryon cycle* of inflows and outflows serves to modulate galaxy growth over cosmic time.

2. Quantifying the Baryon Cycle

A key question we would like to know is, how much material is participating in the baryon cycle? For this, we need to know the inflow rate of gas into galaxies, the outflow rate from galaxies, as well as how much of the outflow material is eventually able to rejoin the inflow. Given that these processes are highly challenging to quantify observationally at present, an alternative approach is to utilize observations of the galaxy population across cosmic time within a ΛCDM framework to quantify the baryon cycle.

To do so, we must first develop a quantitative framework for connecting galaxy formation to the baryon cycle. The recently-developed *equilibrium model* (Davé *et al.* 2012) provides just such a framework. The basic equation is one of mass balance: The amount of material flowing into the interstellar medium (ISM) of galaxies must be equal to the sum of the amount formed into stars, the amount expelled into outflows, and the amount added to the gas reservoir. A key insight from simulations by Finlator & Davé (2008) was that the rate of change in the gas reservoir over cosmic time is small compared to other terms in the mass balance equation. This *equilibrium assumption* simplifies the equations and yields a more intuitive and insightful model.

Within such a framework, it is immediately possible to write down the equation for star formation in a given galaxy (Mitra et al. 2015): SFR$=\frac{\zeta\dot{M}_{\rm grav}+\dot{M}_{\rm recyc}}{1+\eta}$, where $\dot{M}_{\rm grav}$ is the baryon fraction times the halo mass accretion rate, η is the mass loss rate in outflows in units of the star formation rate, ζ is the fraction of gas inflowing into the halo that reaches the ISM, and $\dot{M}_{\rm recyc}$ is the additional contribution to inflow from previously ejected material. Given that $\dot{M}_{\rm grav}$ is well specified within ΛCDM, the problem of understanding galaxy growth reduces to understanding the three *baryon cycling parameters* that quantify ejective feedback (η), preventive feedback (ζ), and wind recycling. A similar formula is derivable for the gas-phase metallicity, but we will not discuss that here.

Mitra *et al.* (2015) constrained these three baryon cycling parameters (using a *recycling time* $t_{\rm rec}$ to quantify wind recycling), by employing simple parameterized functional forms for them as a function of mass and redshift. The free parameters were then constrained via a Bayesian Monte Carlo Markov Chain approach to match three key galaxy scaling relations: The stellar mass–halo mass relation, the mass–metallicity relation, and the star formation rate–stellar mass relation. The final model (after a Bayesian evidence analysis) contained 8 free parameters, and fit these observed relations from $z = 0 - 2$ with a reduced $\chi^2 \approx 1.6$, which is remarkably good given the simplicity of the model, and is typically better than achievable with current highly complex hydrodynamic simulations or semi-analytic models with many more parameters.

The resulting mass dependence for the best-fit baryon cycling parameters is displayed in Figure 1. Under the equilibrium model assumptions, wind ejection (η) is required to be stronger at low masses, following a trend of $\eta \propto M_*^{0.5}$ at low masses. It is also stronger at higher redshifts. These trends make sense physically since low-mass galaxies have smaller potential wells from which the outflows must escape, and galaxies were forming stars much more vigorously (and hence could plausibly drive stronger outflows) out to $z \sim 2$. The qualitative sense of these trends is in general agreement with what many models, both hydrodynamic and semi-analytic, have found to be necessary to match data, but it does so in a more statistically robust manner with Bayesian posterior distributions for each parameter (see Mitra *et al.* 2015).

Wind recycling shows a modest decline with mass, asymptoting to $t_{\rm rec} \propto M_*^{0.2}$ at low masses. This is less steep than what some semi-analytic models require (Henriques *et al.* 2013), but somewhat steeper than is directly predicted by detailed zoom hydrodynamic simulations of individual galaxies that we discuss below.

The preventive feedback parameter ζ shows that there is a "sweet spot" in halo mass for galaxy growth at $10^{10} M_\odot < M_{\rm halo} < 10^{12} M_\odot$. At lower masses, metagalactic photoionization is able to prevent gas from accreting onto halos altogether owing to their low virial temperatures. At higher masses, there is a slight declining trend in ζ owing purely to gravitationally-driven shock heating (Keres *et al.* 2005), but an extra prevention term is required above $M_{\rm halo} > 10^{12} M_\odot$ in order to match the observed galaxy population. Moreover, this extra term must have an onset at a higher halo mass to higher redshift. Putatively, this prevention arises from feedback owing to active galactic nuclei (AGN), though the details of how this operates remains unclear.

One may regard these baryon cycling parameters as being akin to the answer in the back of the book; namely, feedback and recycling must roughly operate in such a manner in order to reproduce the global scaling relations in galaxies as observed. While the answer in the back of the book is helpful to guide further investigations, the full solution requires understanding the *physics* that gives rise to these feedback scalings. For this, we must turn to high-resolution cosmological zoom simulations of galaxy formation.

3. Baryon Cycling in Zoom Simulations

A fundamental difficulty in modeling galaxy formation is one of dynamic range. The processes driving feedback such as supernovae explosions are occuring on sub-pc scales within a dense and inhomogeneous ISM, while the impact of these outflows can be seen in IGM metals distributed over Mpc scales. To fully capture this dynamic range is impossible

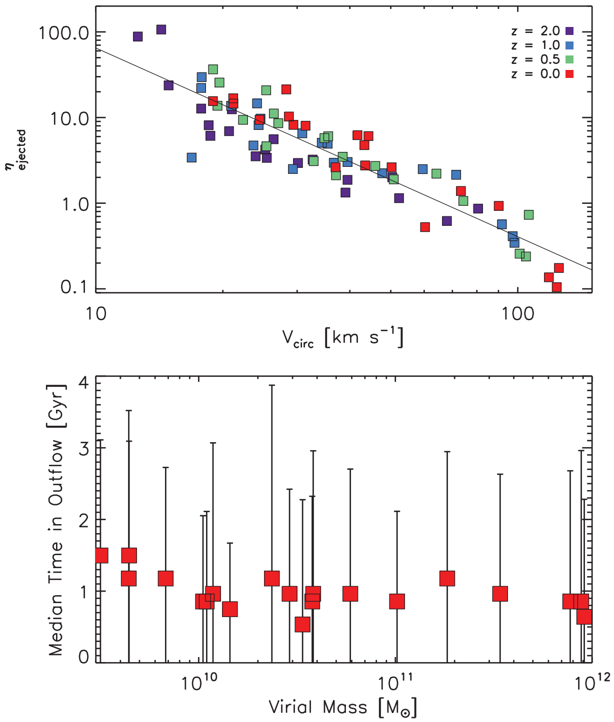

Figure 2. *Top:* Mass loading factor versus galaxy circular velocity for 20 zoom galaxy simulations from Christensen *et al.* (2016). The solid line shows the best-fit power law $\eta \propto v_c^{-2.2}$, which provides a reasonable fit at $z \sim 0 - 2$. *Bottom:* Median time between ejection from ISM and re-accretion (i.e. wind recycling time) as a function of halo mass in those same simulations. There is only a weak trend of $t_{\mathrm{rec}} \propto M_{\mathrm{halo}}^{-0.1}$ evident.

with current computers. Hence the *zoom* simulation technique has been developed to extend the dynamic range at a feasible computational cost.

In zooms, a single galaxy and its surroundings (out to typically several times the final virial radius) is extracted from a larger simulation and re-simulated at higher resolution. The high resolution affords the opportunity to include physical models for driving outflows. In Christensen *et al.* (2016), outflows were driven by adding supernova thermal energy to surrounding gas and turning off cooling for some time to allow a bulk outflow to develop. The resulting galaxies lie along many bulk property scaling relations of galaxies, such as those between stellar mass, halo mass, metallicity, and circular velocity (i.e. the Tully-Fisher relation), making it a highly plausible laboratory to study the motions of gas in and out of galaxies.

Figure 2 shows predictions from the zoom simulations of Christensen *et al.* (2016) for the baryon cycling parameters η and t_{rec}, versus circular velocity and halo mass, respectively. The mass loading factor η is broadly consistent with energy-driven scalings, which is as expected given that the physics driving outflows in these simulations is supernova energy. The recycling time has a quite weak dependence on halo mass, even somewhat weaker than the weak scaling predicted by the equilibrium model, and significantly weaker than that expected from pure gravitational confinement. This suggests that other effects besides gravity determine how wind recycling operates.

Zoom simulations such as these and others like the Feedback in Realistic Environments runs (Muratov *et al.* 2015) can, while giving insights into the physics of feedback, also

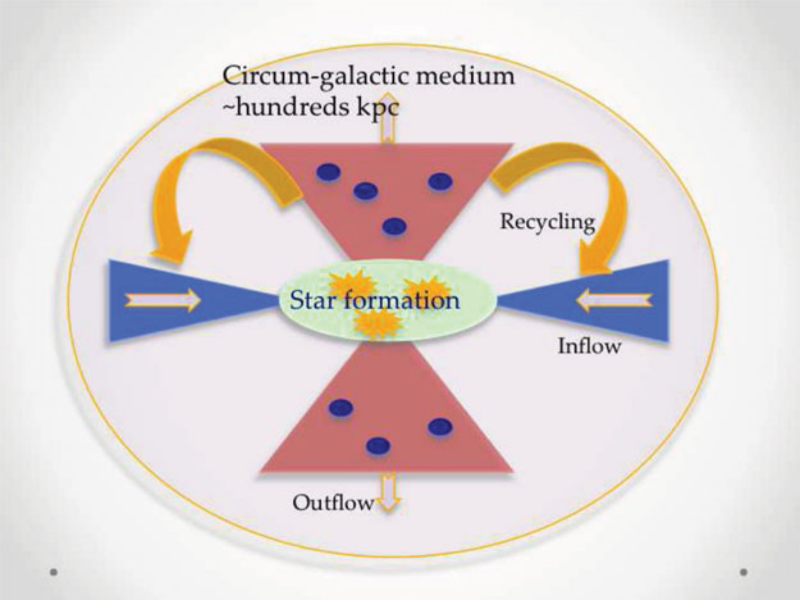

Figure 3. Cartoon representation of the CGM, showing inflows coming in along the major axis of a star-forming disk, and outflows with cold clumps embedded in a hot outflow as qualitatively seen in M82. Some of the outflows provides enriched inflow via wind recycling.

provide inputs to larger-scale cosmological simulations that seek to model representative galaxy populations. The MUFASA simulations used the FIRE scalings, along with preventive feedback scalings from the equilibrium model, and was able to produce an unprecedented match to the observed galaxy stellar mass function across cosmic time (Davé *et al.* 2016). This indicates that the combination of zoom simulations, cosmological simulations, and analytic models can move us towards a fuller understanding of the baryon cycle and its role in galaxy evolution.

4. Observing the Baryon Cycle: CGM Absorption

While it is possible to constrain the baryon cycle indirectly via simple models, or predict it in high-resolution simulations, ultimately it is most desireable to observe it directly in action. As mentioned, this is complicated by the fact that inflows and outflow involve many different phases of gas undergoing complex dynamics. Nonetheless, improving capabilities are enabling various approaches to directly characterize the baryon cycle. Here we discuss two such approaches in galaxy outskirts, namely absorption line probes of the circum-galactic medium (CGM) and HI 21cm emission properties of gas within galaxies.

Figure 3 shows our best current guess of a cartoon depiction of the CGM. If there is a background quasar, the line of sight through this CGM could intercept warm ambient halo gas, inflowing cool (ionized or neutral) gas, outflowing enriched cold material, or outflowing hot gas. Is it possible to distinguish between these possibilities using the information contained in individual absorption features?

Ford *et al.* (2016) examined this question in a series of papers based on cosmological simulations, culminating with a comparison to observations from the *Hubble* COS-Halos project (Tumlinson *et al.* 2013), which obtained UV absorption spectra for over 40 lines of sight probing within ~ 150 kpc of galaxies at $z \sim 0.1 - 0.3$. By determining which gas particles within the simulations were giving rise to absorption in different physical and

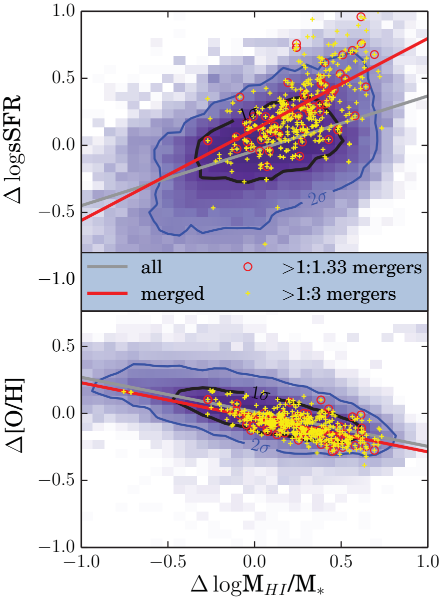

Figure 4. Deviation plot of specific SFR (top) and oxygen abundance (bottom) versus HI fraction from simulations of Rafieferantsoa *et al.* (2015), showing that SFR and HI content are correlated at a given M_*, while metallicity and HI are anti-correlated. Mergers preferentially boost SFR over HI, but metal abundance and HI do not react to mergers more than simple fluctuations in accretion.

dynamical states, they were able to identify some general trends for how various ions trace the state of CGM gas. Preliminary comparisons generally showed broad agreement between their simulations and COS-Halos data, with a notable exception being too little OVI absorption predicted.

A key result was that low ionization metals generally trace gas close to galaxies (within ~ 50 kpc), that will return to the galaxy within the next several Gyr. Hence ions like MgII and SiIII predominantly trace wind recycling. Meanwhile, high ionization lines such as OVI generally trace gas ejected in outflows at early epochs, which have since been heated and therefore suspended within the hot gaseous CGM. HI absorption is quite strong and ubiquitous, even in massive galaxies that have halos putatively dominanted by hot gas (Thom et al. 2012), and arises mostly from (relatively) unenriched ambient gas.

These conclusions likely depend on the particular implementation of galactic outflows in those simulations, in which radiation pressure is assumed to eject material without substantial heating. Outflows driven by thermal over-pressurization may predict substantially different CGM properties and correlations between absorbers and the physical state of CGM gas. Ultimately, CGM absorption offers a new way of discriminating between models that can otherwise reproduce galaxy stellar properties similarly well.

5. Observing the Baryon Cycle: Neutral Hydrogen

As gas flows in from the IGM, it begins mostly ionized far from galaxies, then becomes predominantly neutral once it is dense enough to self-shield typically within 30-50 kpc of galaxies, and finally becomes molecular once it enters deep into the ISM. Similarly, outflows are seen to contain both ionized (hot) and neutral (cold) components, and perhaps even molecular gas. Hence neutral gas in and around galaxies represents a key transient reservoir of gas moving within the baryon cycle.

Hydrodynamic simulations can now do a good job of reproducing the overall neutral hydrogen content of galaxies (e.g. Davé et al. 2013). One interesting prediction from these simulations is that fluctuations in the inflow rate lead to correlated fluctuations between galaxy properties. For instance, if a galaxy accretes a gas cloud, its star formation rate will be boosted while its metallicity is reduced since the infalling material will be less enriched. Hence relative to the stellar mass-metallicity relation (MZR), galaxies with lower metallicity (Z) at a given stellar mass (M_*) should also have higher star formation rates (SFRs). Indeed this is observed, and has come to be known as the fundamental metallicity relation (Mannucci *et al.* 2010, Salim *et al.* 2014). The strength of this $M_* - Z -$SFR relation is approximately reproduced in simulations (Davé et al. 2011). Hence the scatter around the MZR reflects in some way the stochasticity in the baryon cycle.

As discussed in Rafieferantsoa *et al.* (2015), the neutral gas content also shows similar behavior. Accretion events will increase HI, which will correlate with lower metallicity and higher SFR. To quantify this, one can examine *deviation plots*, which quantify such second parameter dependences as the fundamental metallicity relation by depicting the deviation in various quantities from their mean value at a given M_*.

Figure 4 shows two deviation plot related to the HI content of galaxies, as measured by their HI fraction (M_{HI}/M_*). The top panel shows how the deviation in HI fraction relates to the deviation in specific SFR (SFR/M_*), while the bottom panel shows the deviation relative to gas-phase oxygen abundance. As expected from the above arguments, the SFR and HI fraction are correlated, while Z and HI fraction are anti-correlated.

We can further examine how major ($> 1 : 3$) mergers impact these deviations. If a major merger is simply an extension of a normal inflow fluctuation, then the correlation will be independent of whether one selects recent mergers. This is true of the correlation between metallicity and HI fraction; these two quantities appear to simply trace inflow fluctuations. Meanwhile, SFRs in mergers are boosted above the overall correlation, showing that mergers enhance SFR more than they enhance the HI. This is likely because the SFR is driven by internal dynamical processes within mergers as dense material is driven towards the center, but that this process does not impact the HI as much since it predominantly lives in the outskirts of galaxies.

This illustrates how the HI content of galaxies can trace recent variations in the baryon cycle. Moran *et al.* (2012) demonstrated this in observations, showing that galaxies with low metallicities in their outskirts tend to be HI-rich. Quantifying these types of deviations provides new insights into the inner workings of the baryon cycle on timescales over which the accretion is varying.

6. Conclusions

The cycle of gas in and out of galaxies is a governing aspect of galaxy evolution that has yet to be fully understood. While gravity drives inflow of material far from galaxies, many processes can prevent its accretion into the ISM, and even once it gets there, outflows can eject the gas back out to large distances. These baryon cycling processes are expected to be most directly manifested in gas in the outskirts of galaxies and the circum-galactic medium, making galaxy outskirts a key to understanding global galaxy growth.

A simple mass-balance model for galaxy evolution known as the equilibrium model can serve to quantify the baryon cycle by constraining to galaxy observations via an MCMC procedure. This shows, for instance, that the mass ejected from galaxies can substantially exceed that formed into stars. In that sense, the stars are merely the trace amount of matter that precipitates out of the baryon cycle over cosmic time.

Zoom simulations offer the opportunity to study the baryon cycle in more detail, using a full cosmological setting and self-consistent mechanisms for driving outflows. However, the physics of outflows remains poorly understood, so such simulations still must make choices regarding the implementation of key processes. Nonetheless, they can provide informative testbeds for how to connect observations with the physics of the baryon cycle.

Observationally, CGM absorption lines offer a promising approach towards directly characterizing the baryon cycle. Simulations can help interpret such one-dimensional probes of particular ions in terms of a three-dimensional dynamical picture of various gas phases. While various simulations now agree fairly well on the stellar portion of galaxy evolution, predictions for CGM absorption can vary wildly, hence such data can offer crucial constraints on the physics of inflows and outflows.

An interesting addition to the story is provided by observations that are able to trace *fluctuations* in the baryon cycle. The HI reservoir lies in this transient regime for inflowing and perhaps outflowing gas, and thus is a good barometer for examining recent fluctuations. Correlated deviations between HI fraction, SFR, and metallicity set the scatter around key galaxy scaling relations, and thus provide a new avenue for testing models of the baryon cycle and its response to perturbations.

Much work remains to be done in order to fully flesh out the physics and dynamics of the baryon cycle. Combining simulations and observations in galaxy outskirts offers a highly promising approach towards this. Conferences such as this IAU Symposium provide an excellent forum to bring together communities that have historically not interacted at a deep level, enabling the percolation of new ideas and approaches that will inevitably be needed in order to comprehensively tackle the problem of galaxy evolution.

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