THE MASS-METALLICITY RELATION IN COSMOLOGICAL HYDRODYNAMIC SIMULATIONS

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Abstract. We use cosmological hydrodynamic simulations with enriched galactic outflows to compare predictions for the galaxy mass-metallicity ($M_* - Z$) with observations at $z \approx 2$ from Erb et al. (2006). With no outflows included galaxies are over-enriched, indicating that outflows are required not only to suppress star formation and enrich the IGM but also to lower galaxy metal content. The observed $M_* - Z$ slope is matched both in our model without winds as well as our favored outflow model where the outflow velocity scales as the escape velocity, but is too steep in a model with constant outflow speeds. If outflows are too widespread at early times, the IGM out of which smaller galaxies form can become pre-polluted, resulting in a low-mass flattening of the $M_* - Z$ relation that is inconsistent with data. Remarkably, the same momentum-driven wind model that provides the best agreement with IGM enrichment data also yields the best agreement with the $z \approx 2$ $M_* - Z$ relation, showing the proper outflow scaling and strength to match the observed slope and amplitude. In this model, the $M_* - Z$ relation evolves slowly from $z = 6 \rightarrow 2$; an (admittedly uncertain) extrapolation to $z = 0$ broadly matches local $M_* - Z$ observations. Overall, the $M_* - Z$ relation provides critical constraints on galactic outflow processes during the heydey of star formation in the Universe.

1 Introduction

Galactic outflows are observed to carry mass and metals into the intergalactic medium (e.g. Veilleux, Cecil & Bland-Hawthorne 2006). At high redshift, outflows are ubiquitous from star-forming galaxies (Pettini et al. 2001), and the metals that they carry are seen in a wide range of environments (Pettini 2006). Pettini (1999) originally noted the missing metals problem, namely that the amount of metals present in Lyman break galaxies at $z \sim 2.5$ falls far short of the amount

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expected to be produced by their stars (see Davé & Oppenheimer 2006 for an up-
dated discussion). Hence outflows appear to have a large impact on the evolution
of galaxies during the heydey of star formation in the Universe, and metals provide
a convenient avenue with which to trace and quantify ejected gas.

In Oppenheimer & Davé (2006) (hereafter OD06) we implemented a number
of parameterized models for galactic outflows into GADGET-2 cosmological hy-
drodynamic simulations. We tested these models against observations of C iv
quasar absorption line systems at \( z \approx 2 - 6 \), and found that only a relatively
narrow range of outflow parameters were capable of enriching the diffuse inter-
galactic medium (IGM) early enough while not overheating it. Intriguingly, the
most successful models were ones that employed a momentum-driven wind sce-
nario (Murray, Quatert, & Thompson 2005) that is also favored by local observa-
tions of starburst outflows (Martin 2005). Hence it is plausible that distant
outflow-driving galaxies obey scalings similar to local ones.

Another critical test of such outflow models is measuring the metals that get
left behind in galaxies rather than driven into the IGM. Observationally, this can
be traced using the galaxy mass-metallicity relation. Tremonti et al. (2004) using
the Sloan Digital Sky Survey, found that low-redshift emission-line galaxies had
a gas-phase metallicity that increased with stellar mass up to \( \sim 10^{10.5} \, M_\odot \), and
then flattened to higher masses. At \( z \sim 1 \), smaller survey areas make it difficult to
track the high-mass flattening, but indications are that galaxies at a given mass
are only mildly underenriched compared to present-day ones (Savaglio et al. 2005).
This evolution was extended out to \( z \sim 2 \) by Erb et al. (2006) who found that
galaxies back then are roughly one-half as metal-rich as galaxies today at a given
stellar mass. This is mildly surprising as only about one-quarter of all stars
(and therefore, presumably, metals) have formed by then (Rudnick et al. 2003).
However, most models of cosmic chemical evolution predict earlier enrichment in
the highly biased environments that form early stars (e.g. Cen & Ostriker 1999,
Davé, Finlator & Oppenheimer 2006). In any case, if the solution to the missing
metals problem is that the majority of metals have been ejected from galaxies (e.g.
Davé & Oppenheimer 2006), then the amount and distribution of metals left be-
hind in galaxies likely offers key insights into the nature of outflows.

In these proceedings we test our outflow models in OD06 against the \( z \approx 2 \)
mass-metallicity data of Erb et al. (2006) and study the evolution of the mass-
metallicity relation. We show that the same outflow model that best matches the
IGM data also best matches the mass-metallicity relation, and furthermore the
models that do not match the IGM data provide a poorer fit. This lends further
support to the idea that momentum-driven galactic winds in a hierarchical galaxy
formation setting can explain a wide range of observables at \( z \geq 2 \).

2 Simulations

We employ the suite of GADGET-2 cosmological hydrodynamic simulations de-
scribed in OD06. Briefly, these use the entropy-conservative PM-Tree-SPH code
GADGET-2 (Springel & Hernquist 2003) with improvements as described in OD06
Simulations of the Mass-Metallicity Relation

including metal-line cooling. An $\Omega = 0.3$ ΛCDM cosmology was assumed, and cubi-
c random volumes of 16 and $32h^{-1}\text{Mpc}$ on a side were represented with $2 \times 256^3$ particles (the $8h^{-1}\text{Mpc}$ runs are not useful for the present study). The minimum resolved galaxy stellar masses in these runs, corresponding to 64 star particles, are $1.24 \times 10^8 M_\odot$ and $9.9 \times 10^8 M_\odot$, respectively.

For conciseness, we focus on three of the six outflow models in OD06: “no winds” (nw), “constant winds” (cw), and “momentum-driven winds” (vzw). The no winds case is shown for illustrative purposes, the constant winds case is the out-
flow model in the runs of Springel & Hernquist (2003) and the vzw momentum-
driven winds case is the one that, overall, best matches the IGM metal line ob-
servations. The mzw momentum-driven model of OD06 gives very similar results
to vzw, and vzw seems mildly more plausible based on observations of local star-
burst outflows (Rupke, Veilleux & Sanders 2005). As a reminder, vzw assumes $v_{\text{wind}} \propto \sigma$ and mass loading factor $\eta \propto \sigma^{-1}$ (where $\sigma$ is the galaxy velocity disper-
sion), while cw assumes $v_{\text{wind}} = 484 \text{ km/s}$ and $\eta = 2$ for all galaxies.

To compare to the mass-metallicity relation observed in galaxies, we c alculate
the star formation rate (SFR)-weighted metallicity of gas particles in galaxies
identified in our simulations. This weighting is intended to emulate how galaxy
metallicities are typically measured, using nebular emission lines that arise from
warm ionized gas in star forming regions. In Erb et al. (2006), gas ma sses are
obtained from star formation rates using the Kennicutt relation togeth er with the
Hα radius, whereas in our simulations gas masses are obtained as bound cold,
dense gas. These measures are quite different and their relation is unclear, and
further there are possible systematics in both simulations and data, so we caution
that comparisons to gas mass relations are highly preliminary. On the other hand,
comparisons to the stellar mass-metallicity relation should be reason ably robust,
and that will be the main focus of these proceedings.

3 Outflows and Mass-Metallicity Relation

Figure 1 shows galaxy metallicities versus stellar mass (left panels) and gas mass
(right panels), for the vzw, cw, and nw models (top to bottom). Overplotted are
data points from Erb et al. (2006) and the median stellar mass-metallicity relation
in SDSS from Tremonti et al. (2004) (solid line). The $z \approx 0$ relation is shifted up
by about $\times 2$ in metallicity at a given stellar mass but has a similar slope, as noted
in Erb et al. (2006).

Figure 1 demonstrates, at its most basic level, that the outflow model has
a significant impact on the mass-metallicity relation. Therefore both the slope
and the amplitude of this relation provide critical constraints on outflows. If no
outflows are included (nw model), not only are too many stars produced (see
e.g. OD06), but too many of the metals remain locked into galaxies at a given
stellar mass. Hence not only are outflows required to enrich the IGM, they are
concurrently required to de-enrich galaxies.

Comparing our two outflow models reveals some interesting and perhaps sur-
prising insights into the nature of the mass-metallicity relation. Given that the
Fig. 1. Stellar mass-metallicity (left panels) and gas mass-metallicity (right panels) relations from the vzw, cw, and nw runs (top to bottom panels) at $z = 2$. Red and green points show $16h^{-1}\text{Mpc}$ and $32h^{-1}\text{Mpc}$ box galaxies, respectively. Data points shown are from Erb et al. (2006); the thick solid line in the left panels is the median $M_* - Z$ relation at $z \approx 0$ from Tremonti et al. (2004).

A constant wind (cw) model (middle panels) assumes a constant outflow velocity of 484 km/s, one might expect a characteristic feature in the $M_* - Z$ relation corresponding to halos of this escape velocity ($\sim 2 \times 10^{13}M_\odot$). In particular, halos above that mass should have a flat $M_* - Z$ relation (because they produce metals in proportion to their stellar content), while below that mass there should be a slope arising from the fact that outflows can escape more easily from smaller halos. Indeed, the overall shape of the local $M_* - Z$ relation has been qualitatively explained using such a scenario. However, at face value, the trend produced in the cw model is exactly the opposite: At low masses, there is a constant $M_* - Z$ relation, while at $M_* > 10^{10}M_\odot$ it begins to rise sharply.
Why does this happen? The answer is not entirely clear. A preliminary idea that we are now investigating is that because the constant wind model so widely enriches the IGM at an early epoch (see OD06, Figure 10), it pre-pollutes the gas out of which the smaller galaxies later form. In fact, the smallest galaxies forming most recently actually have a slightly higher metallicity, i.e. there is an inversion in $M_\ast - Z$ at low masses, because the IGM becomes more enriched overall with time. This suggests that environmental effects and clustering must also be taken into account when interpreting mass-metallicity relations. It is also worth noting that, although the $z \approx 2$ data at $M < 10^{10}M_\odot$ are too uncertain to definitively rule out such a flattening at low masses, locally the $M_\ast - Z$ slope is seen to continue relatively unbroken to quite small masses [Lee et al. 2006], which would clearly rule out such a high level of pre-pollution.

Next, there is the issues of the slope of the $M_\ast - Z$ relation at $M_\ast > 10^{10}$; it is far too steep compared with observations, agreeing at $M_\ast \sim 10^{10}$ but being a factor of two too high by $M_\ast \sim 10^{11}$. Hence a constant outflow velocity actually produces an incorrect $M_\ast - Z$ slope by being over-efficient at expelling metals from small galaxies as compared to large ones. This favors a scenario where smaller galaxies have smaller outflow velocities. At some large mass, the cw model is expected to produce a flattened $M_\ast - Z$ slope, but halos with an escape velocity of $\sim 500$ km/s are rare within our volume by $z = 2$ so it is not apparent here.

The vzw model (top left panel) agrees quite well with observations, matching both the observed slope and the amplitude at $z \approx 2$. The amplitude agreement reflects a proper balance between metals retained in galaxies and expelled into the IGM, and is related to the fact that vzw broadly reproduces the stellar mass density evolution. The agreement in the slope, more interestingly, may be indicating that galaxies lose a fixed fraction of their expelled material. This is precisely the scenario in the vzw model because the outflow speed scales with the escape velocity, and hence all halos (to first order) lose material equally efficiently. It also happens in the no-wind case, in the sense that the fraction lost is essentially zero for all galaxies, and despite its other failings it does reproduce the slope of the $M_\ast - Z$ relation. Outflow models like cw, where small galaxies lose a higher fraction of their expelled material, result in too steep a slope. Interestingly, [Erb et al. (2006)] finds that observationally there is no evidence that small galaxies at $z \approx 2$ have preferentially lost more of their baryons as compared to more massive ones.

Turning to the gas mass-metallicity relation (right panels), the observations span a rather limited range in gas mass, and both cw and vzw are in broad agreement with data given the level of uncertainties discussed earlier. In contrast, with no outflows the gas is too quickly converted into stars, leaving no objects with gas masses as observed. This shows that outflows are required in order to keep galaxies as gas-rich as observed at these epochs. The predicted trends in metallicity versus gas mass and versus stellar mass are similar, which reflects the steady conversion of gas into stars in simulations.

In summary, comparisons of various outflow models to the stellar mass-metallicity relation of galaxies shows that outflows must be strong enough to eject significant amounts of metals, but not be so strong as to over-pollute the diffuse IGM out of
which later galaxies form. The slope of the mass-metallicity relationship suggests that galaxies should lose a fixed fraction of their outflowing metals to the IGM, favoring a scenario where the outflow speed scales as the escape velocity. It is fairly remarkable that our momentum-driven wind model naturally produces the correct strength and scaling of outflows in order to reproduce the observed $M_* - Z$ relation. It is even more remarkable when one considers that this model is fairly uniquely succesful at enriching the IGM to observed levels at these epochs, and suggests that such models are on the right track towards understanding the basic scaling relations of outflows at all epochs.

4 Mass-Metallicity Evolution

Figure 2 shows galaxy metallicities versus stellar mass (left panels) and gas mass (right panels), at $z = 2, 3, 6$ (top to bottom) from the vzw model. The amplitude of the mass-metallicity relation in this model evolves slowly, with galaxies already being substantially enriched by $z = 6$ (Davé, Finlator & Oppenheimer 2006), while the slope is set early on and remains essentially constant at $Z \propto M_*^{0.3}$ (in agreement with the $z \approx 0$ determination by Lee et al. 2006).

A simple linear time-based extrapolation from $z = 6 \rightarrow 2 \rightarrow 0$ indicates that this model would be very close to matching the $z \approx 0$ data from Tremonti et al. (2004). The increase in amplitude is about 0.06 dex per Gyr from $z = 6 \rightarrow 2$. At $z = 0$ this extrapolation would predict $[Z/H]_\odot = 0.2$ at $M_* = 10^{10} M_\odot$. However, a linear extrapolation may not be appropriate given that outflows are likely less prevalent at low-$z$. It is also worth putting in a cautionary note about systematics in observed metallicity indicators; commonly-used indicators may differ by $\sim \times 2$ from the true gas-phase metallicity (Ellison et al. 2005), so one must be cautious not to over-interpret the precise values.

Overall, it is interesting that galaxies seem to move towards higher masses predominantly along the $M_* - Z$ relation. The slope of this relation ($\approx 0.3$), does not appear to have a natural physical explanation. Although Tremonti et al. (2004) interpreted it in terms of a leaky closed box model, such a scenario seems overly simplistic, as it does not incorporate hierarchical growth and environmental effects, both of which are important in our simulations for establishing the $M_* - Z$ relation. Instead, the slope probably reflects some particular balance between outflows and galaxy growth, further emphasizing that the slope, amplitude, and evolution of the mass-metallicity relation all provide critical tests of outflow models.

5 Conclusions

Using our cosmological hydrodynamic simulations incorporating galactic outflows, we investigate the nature of the mass-metallicity relation in galaxies at high redshift, and compare it to $z \approx 2$ observations by Erb et al. (2006). We find that:

- Outflows are required in order to reduce the metallicity of galaxies at $z = 2$. With no outflows, galaxies at a given stellar mass are twice as enriched as...
Fig. 2. Stellar mass-metallicity (left panels) and gas mass-metallicity (right panels) relations from the vzw runs at $z = 2, 3, 6$ (top to bottom). $16h^{-1}\text{Mpc}$ box is shown as red points, $32h^{-1}\text{Mpc}$ box as green points ($>10^9M_\odot$). Data points shown are from Erb et al. (2006); the thick solid line in the left panels is the median $M^* - Z$ relation at $z \approx 0$ from Tremonti et al. (2004).

The slope and amplitude of the $M^* - Z$ relation is naturally reproduced in our momentum-driven wind model that is also favored from comparisons to IGM enrichment observations from $z \approx 5 \rightarrow 2$.

The constant wind-speed outflow model produces an $M^* - Z$ relation that is flat at low masses, possibly owing to pre-pollution from early widespread winds, and rises too steeply at high masses, both of which are in disagreement with observations. Hence it does not appear that smaller galaxies preferentially lose more material to outflows at these epochs.
• The mass-metallicity slope is established at early times ($z > 6$) and remains constant at $Z \propto M_\star^{0.3}$, while the amplitude evolves slowly with redshift ($\approx 0.06$ dex per Gyr). Galaxies tend to evolve mostly along the $M_\star - Z$ relation towards higher stellar masses.

• A simple, albeit questionable, extrapolation to $z = 0$ yields a relation that is in good agreement with data from Tremonti et al. (2004). The unbroken slope to the lowest observed masses (Lee et al. 2006) provides another non-trivial constraint that is met in our momentum-driven wind scenario.

In summary, the mass-metallicity relation provides another critical constraint on galactic outflows across cosmic time. Understanding the complex processes that establish the shape and evolution of the $M_\star - Z$ relation will likely require moving beyond simple closed box model variants, and may benefit from insights gained using numerical simulations that include metal production and distribution mechanisms. The comparisons here strengthen our claim that momentum-driven wind scalings (whether or not they actually arise from momentum-driven winds) are able to properly distribute metals throughout the Universe at high redshifts.

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