Metals: Nature's Tracer Particles

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Nearly as soon as it was first realized that stars and supernovae are the formation sites for the heavy elements, metals have been used to trace the history of star formation, and of gas flowing out of and back into galaxies. The distribution of "nature's tracer particles" in and around galaxies provides a snapshot of the cumulative history of these processes driving how galaxies evolve.

We have recently conducted an accounting of the metals in and around $z \sim 0$ star-forming galaxies (Peeples et al. 2014), comparing this empirical census to the budget of metals that galaxies have produced[1] in their lifetimes. We derive as empirical a budget of available metals as possible by convolving empirically derived star-formation histories with recent estimates for supernova rates and nucleosynthetic yields; this allows us to account for the fact that bigger galaxies are also older, and thus have had a larger contribution from evolved stars and Type Ia supernovae. On the accounting side of the ledger, the metals contained in galaxies are found in stars and the interstellar medium (ISM). We take the mass of metals in stars to be the stellar metallicity times the stellar mass, while the mass of metals in interstellar gas is the gas-phase metallicity times the gas mass, and the mass of metals in interstellar dust is just the dust mass.[2]

A surprising result from this analysis is that star-forming galaxies contain a nearly constant ~20–25% of the metals they have produced in their lifetimes (Figure 1). In massive galaxies (stellar masses $>10^{10}$ $M_\odot$), the bulk of these metals are trapped in stars, but in less massive galaxies, more metals can be found in the ISM. Strikingly, star-forming dwarf galaxies (stellar masses $<10^9$ $M_\odot$) have more metals in interstellar dust than they do in stars! That the "retained fraction" is so constant over ~3 decades in stellar mass goes against the intuitive expectation that massive galaxies' deep potential wells cause them to be better at retaining (or re-accreting) supernova ejecta and other wind material. Most models of galaxy evolution assume or predict that low-mass galaxies are more efficient at driving galaxy winds, with an understanding that a steep scaling of the wind-driving efficiency is required in order to reproduce other galaxy population properties such as the galaxy stellar-mass function. Such a steep scaling of outflow efficiency, however, is in tension with this new empirical result.

The challenge for models is greater than just retaining the observed fraction of metals. For example, galactic winds expel metals into the circumgalactic medium (CGM), which comprise the diffuse gaseous halos extending hundreds of kiloparsecs around galaxies. By targeting UV-bright quasars whose sightlines pierce the CGM of foreground galaxies, we can systematically characterize the metallic (and baryonic) content of the CGM of low-redshift galaxies (Figure 2). The Cosmic Origins Spectrograph (COS), installed on *Hubble* in 2009, has greatly increased the number of such viable background sources, revolutionizing this field. The COS-Halos team (PI J. Tumlinson, GO 11598, 134 prime orbits) has used COS to measure the extent

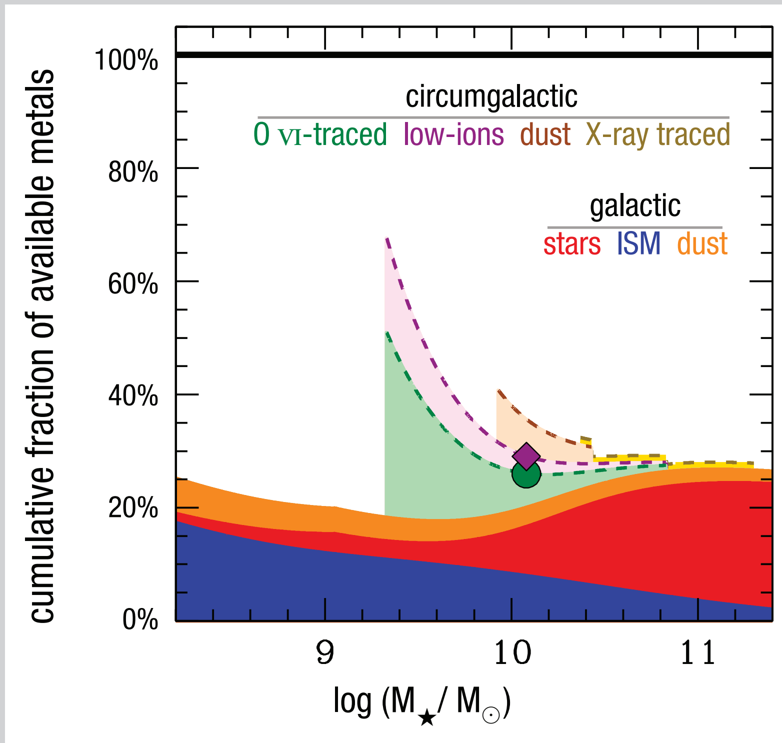

Figure 1: Cumulative fraction of metals in interstellar gas (blue), stars (red), interstellar dust (orange), the highly ionized circumgalactic medium (CGM; green), the low-ionization CGM (purple), circumgalactic dust (brown), and the hot X-ray–traced CGM (yellow) of star-forming galaxies. The points correspond to the median stellar mass of the COS-Halos galaxies. The total mass of metals a typical star-forming galaxy of a given stellar mass has produced in its lifetime corresponds to 100%. Though limited by a small sample of a few dozen galaxy-QSO pairs, in the CGM, COS-Halos does not find a dependence of the column density of gas (and thus the mass traced by that material) on the mass of the galaxy the gas is around; this constant mass is a much larger fraction of the total available metals in low-mass galaxies than in massive galaxies, hence the "wedge" shape seen here. Adapted from Peeples et al. (2014).

[1] We ignore metals that have only ever been in stellar remnants, as they are neither included in nucleosynthetic yields, nor easily accounted for.

[2] While our results are based primarily on scaling relations, extensive tests with cosmological hydrodynamic simulations have shown that such population averages accurately describe a "typical" galaxy.

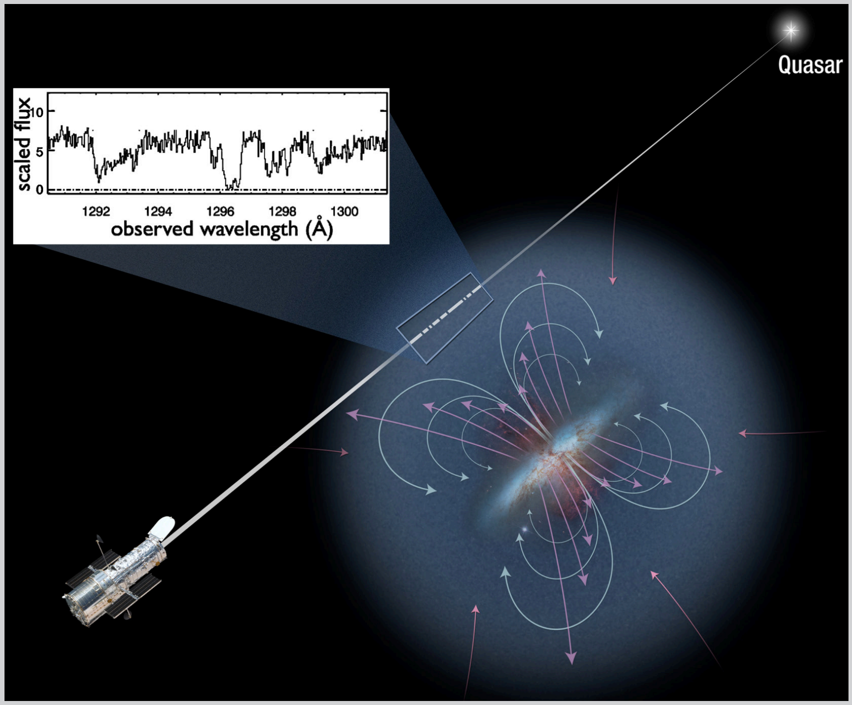

Figure 2: The diffuse gas surrounding galaxies, the circumgalactic medium (CGM) plays host to gas accreting from the intergalactic medium and gas being expelled from galaxies via superwinds that may eventually recycle back into the interstellar medium. Too rarefied to be observed in emission, the CGM is instead studied via absorption along the line of sight to bright background sources, such as quasars. As the dominant transitions are in the rest-frame ultraviolet, the installation of the Cosmic Origins Spectrograph (COS) aboard *Hubble* has revolutionized astronomers' ability to characterize the CGM at low redshift. Adapted from Tumlinson et al. (2011). Illustration credit: Ann Feild.

and kinematics of metals and baryons in neutral, low-ionization, and highly-ionized states out to 150 kpc around Milky Way-mass galaxies at $z \sim 0.25$. While it is relatively straightforward to calculate the mass traced by a single ionic species (surface density $\times\ \pi \times$ [150 kpc]^2), detailed ionization modeling is required to convert this to a *total* mass (Werk et al. 2014). These data uniquely constrain the fates of the ~75% of the metals that galaxies have produced, but are no longer in stars or the ISM: the circumgalactic medium is massive, extended, and "multiphase" (i.e., the gas traced by low-ionization species such as C II and Si II is not in ionization equilibrium with—and is often kinematically distinct from—the gas traced by more highly ionized species such as O VI).

We find that, within 150 kpc of star-forming galaxies, there is at least as much metal mass in a highly ionized phase as remains in their ISM (Tumlinson et al. 2011; Peeples et al. 2014). We also find that there is a substantial mass of cool, low-ionization, circumgalactic gas that appears bound to the halo. Surprisingly, however, this cool material appears to be several orders of magnitude less dense than predicted by "two-phase" models invoking pressure equilibrium with a virialized ($\sim 10^6$ K) ambient medium (Werk et al. 2014). Moreover, the circumgalactic dust-to-metals ratio is somehow at least as high as it is in the ISM, if not higher (Peeples et al. 2014; Peek et al. 2014).

Combined, these results pose a new set of conundrums for astronomers' understanding of how galaxies acquire and process gas: how do galaxies retain a fixed fraction of their metals despite residing in a wide range of potential well depths? Is this fixed fraction of retained metals a low-redshift conspiracy, or have galaxies retained ~25% of their metals throughout time? How can the CGM maintain a massive reservoir of such low-density yet cool, low-ionization gas that by all accounts should not be pressure supported against falling back into the galaxy on short timescales? In aggregate, what new constraints do these results place on models of galaxy winds, and what new insights can these puzzles of circumgalactic gas physics shed on our understanding of galaxy evolution?

References

Peek, J. E. G., et al. 2014, arXiv:1411.3333
Peeples, M. S., et al. 2014, ApJ, 786, 54
Tumlinson, J., et al. 2011, Science, 334, 948
Werk, J. K., et al. 2014, ApJ, 792, 8