Astro2020 Science White Paper

Mapping the Circumgalactic Medium in Emission

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

Principal Author:
Name: Sarah Tuttle
Institution: University of Washington, Seattle
Email: tuttlese@uw.edu
Phone:

Co-authors: (names, institutions, and emails)
Lauren Corlies, LSST, `lcorlies@lsst.org`
Erika Hamden, University of Arizona, `hamden@email.arizona.edu`
Nicolas Lehner, University of Notre Dame, `nlehner@nd.edu`
John M. O'Meara, W. M. Keck Observatory, `jomeara@keck.hawaii.edu`
Molly S. Peeples, Space Telescope Science Institute / Johns Hopkins University, `molly@stsci.edu`
Marc Rafelski, Space Telescope Science Institute / Johns Hopkins University, `mrafelski@stsci.edu`
Jason Tumlinson, Space Telescope Science Institute / Johns Hopkins University, `tumlinson@stsci.edu`
Q. Daniel Wang, University of Massachusetts, `wqd@umass.edu`
Jessica Werk, University of Washington, Seattle, `jwerk@uw.edu`

Intergalactic space is filled with networks of low density gas, forming superhighways of material that funnels into galaxies and galaxy clusters. This gaseous intergalactic medium (IGM) traces the underlying structure of the observable universe, imprinted on the cosmic microwave background and created by quantum fluctuations at the earliest of times. The quantum fluctuations eventually filter down to become material guided by the IGM onto galaxies through the circumgalactic medium (CGM) to fuel galaxy growth and star formation, and to mix with material that has been ejected by galaxies during violent evolutionary times.

We know that galaxies are not isolated stellar systems; they require access to a fresh source of fuel, and likewise a sink for depositing metal-enriched ejecta. However, the processes that negotiate the relationship between the galaxy, its CGM, and the IGM are still poorly understood. Galaxy outflows are observed and studied both on scales large enough to remove material from the virial radius, as well as smaller scales that create fountain flows and gas recycling. Observers have been able to measure these outflows for large samples of star-forming galaxies (e.g. Martin et al., 2013; Rubin et al., 2014). The inflows required to balance them are much harder to detect. Observing these inflows, and the reserves of the CGM that create them, continues to be at the edge of our capabilities. We know the gas itself exists. We are able to observe it in absorption where quasars serendipitously provide a background source. Studies carried out with these pencil beams have provided a statistical framework for connecting the CGM to large scale structure (e.g. Chen et al., 2010; Prochaska et al., 2011; Tejos et al., 2014; Tumlinson et al., 2013; Stocke et al., 2013; Werk et al., 2014). But we need to better map the local gas distributions to understand the role it plays in galaxy evolution. We must move from statistical tracing to cosmocartography.

1 Mapping the CGM

Recent studies of the circumgalactic medium (CGM) have raised pressing questions regarding the physical processes that determine how and when gas cycles into and out of galaxies, igniting and quenching the star formation in their disks. To answer these questions, theorists have begun to directly trace the origin and lifecycle of the CGM gas using both cosmological zoom-in simulations of individual halos and cosmological hydrodynamic simulations with statistical samples of galaxies (e.g., Hummels et al. 2013, Ford et al. 2014, Christensen et al. 2016, Suresh et al. 2017, Anglés-Alcázar et al. 2017). From these simulations, we have learned that in order to reproduce the observed gas column densities out to 200 kpc, bursty star-formation and feedback able to generate significant outflows are required (Liang et al., 2016) or new methods of feedback such as cosmic rays need to be invoked (Salem et al., 2016). Cosmological hydrodynamical simulations that incorporate strong galactic winds indicate that at any given time, 65-80% of the total baryons in a galactic halo reside outside of the galaxy stellar disk, and $>$50% of these CGM baryons recycle through the ISM of the galaxy, typically on one-Gyr timescales. Nonetheless, crucial questions remain regarding the physical timescales and the spatial extent of gas outflow, inflow, and recycling. In particular, simulations have been unable to resolve the small-scale structure believed to be present in the CGM under various physical conditions (McCourt & Madigan, 2016). Detection of the CGM in emission would be a groundbreaking first step toward understanding the rich structure of the material that drives galaxy evolution. Absorption studies are typically limited to only one sightline per galaxy (but see Rubin et al. (2018)). Thus, observers strategically collect large samples of galaxies nearby bright QSOs in projection to create a statistical map of the CGM composed of many single sightlines.

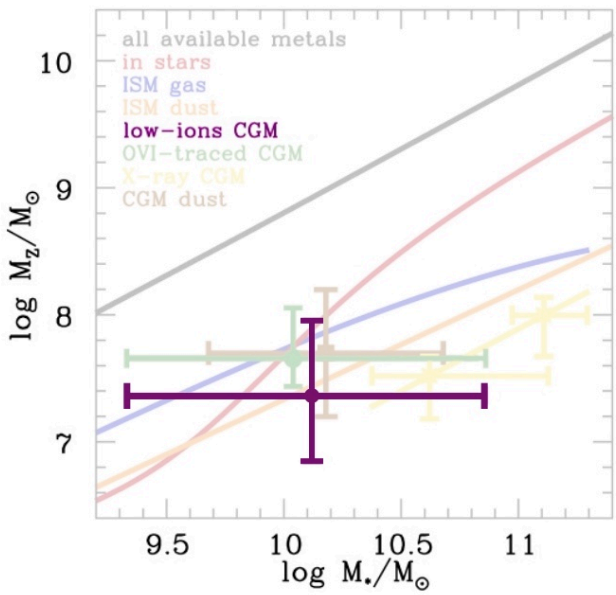

Figure 1: Here we show Figure 6 from Peeples et al. (2014) modified to emphasize the low-ion contribution to the CGM which is traced via CIV emission.

Mapping the gas in emission would circumvent many of the uncertainties inherent in such population-wise studies. First, a detection of extended halos of gas in emission would present the immediate opportunity to determine gas volume densities from surface brightness measurements directly. Second, mass estimates could be pinned down, along with cooling times and the ultimate fate of the material. Our ability to detect and map the distribution of this component of our universe is a significant step in identifying the location and phase of gas beyond galaxies. As you can see in Figure 1, the material we are searching for (shown in purple) is a significant contribution to the universal metals budget.

2 Predicting the Distribution of the Cosmic Web

Because the surface brightness of emission from the CGM and IGM is so low thanks to the gas's diffuse nature, predictions from theoretical studies are particularly important for motivating and guiding future observations. Overall, the simulations suggest that emission from the CGM is more likely to be detected than the IGM because of its generally higher density, though dense filaments are not completely out of contention (Frank et al., 2012; Bertone & Schaye, 2012). Emission is biased towards high density, high metallicity gas with temperature at the peak of the cooling curve of a given emission line (Bertone et al., 2013). This may imply that brighter, more easily detectable emission may be skewed towards more recently star bursting galaxies (Sravan et al., 2016). However, this bias also means that predictions for detectable emission are less sensitive to the specifics of feedback prescriptions (Bertone et al., 2010) and assumptions about the extragalactic UV background (Corlies & Schiminovich, 2016). It also indicates that a

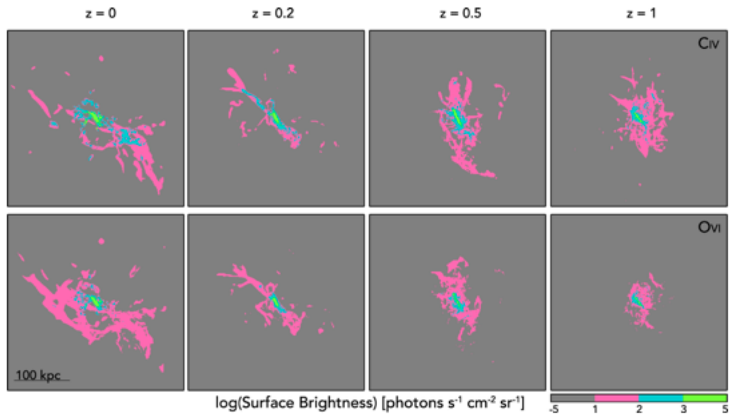

Figure 2: This modified version of Figure 11 from Corlies & Schiminovich (2016) shows surface brightness of both CIV and OVI from redshift of z=1 to z=0. You can see the evolution of structure with time, as well as the variation from ion to ion.

combination of emission lines can be combined to trace the spatial distribution of this multiphase medium and the galaxy's metal enrichment history.

For the CGM and IGM with temperatures between $10^4 - 10^7$ K, cooling is dominated by emission lines in the rest-frame ultraviolet and into the X-ray for the most massive galaxies CITE. Stacking galaxies within a cosmological volume, van de Voort & Schaye (2013) showed that, with technology-pushing low surface brightness limits, emission from multiple metal lines (CIV, OVI, SIII, SiIV) can be detected out to 10-20% of the galaxy's virial radius while the brightest line, CIII, can potentially be detected out as far as 60% of the virial radius.

Corlies & Schiminovich (2016) echoed these results while looking in specific detail at the evolution of the emission around a single Milky Way-like galaxy for $1 < z < 0$. However, looking at a single galaxy instead of stacking, bright dense features in the halo are not smoothed out and for the brightest lines (CIII, CIV, OVI), this means that detectable emission can extend as far as 120 kpc at z=0, as can be seen in Figure 2. At low redshift, closer distances means that emission is more extended on the sky and lower densities can be probed. At higher redshifts, the emission remains possible to detect because while the redshift dimming is stronger, the emission itself is intrinsically brighter because of the higher densities and lower temperatures of the galactic halo at earlier times. At all redshifts, low surface brightness limits are required to observe the hot, diffuse medium filling most of the virial volume at all redshifts.

In addition to these surface brightness limits, resolution, in particular, is important for determining the source of the gas generating the emission. If pixels are too large, it becomes impossible to distinguish halo emission from the main galactic disk. At high redshift, dense IGM filaments are still feeding the galaxy and drive the extended emission while at low redshift, gas stripped from in falling satellites seems to be the main source because of its higher density. Having enough resolution to probe these structures will provide a more complete picture of the origin of dense gas in the galactic halo.

Thus, **simulations are all suggesting that this emission can be detected within a significant volume of a galaxy halo and with high enough spatial resolution can be a new window into understanding how gas flows into and out of galaxies and how these galaxies connect to the**

larger IGM environment.
One major missing theoretical prediction is the brightness and distribution of Lyman-α emission from the CGM and IGM. As the brightest emission line by far, it is the most obvious target for searches of such emission around galaxies. Indeed, Lyman-α emitters, blobs, and halos have already been successfully detected in varying numbers at high-z where the line has shifted into the optical (Prescott et al., 2013; Xue et al., 2017). However, any model of the extent and distribution of Lyman-α emission requires successfully modeling the radiative transfer of the strong resonant scattering of the photons. Idealized simulations looking at the role of self-shielding but with no feedback (Faucher-Giguère et al., 2010) and simulations that look in the more diffuse IGM where scattering is less important (Frank et al., 2012) have been performed but predictions for a realistic CGM which are likely the source of the detected Lyman-α emission remain the next crucial step in the theoretical study of emission.

3 Current CGM Constraints and Detections

The IGM is incredibly faint and notoriously difficult to detect. But as we get closer to galaxies ($< 120\,\mathrm{kpc}$), gas density increases. The CGM is polluted with metals from supernovae powered blowouts or AGN driven winds which slightly ease its detection. Recently observed at intermediate redshifts in both emission (Cantalupo et al., 2014; Martin et al., 2014, 2015) and absorption (Stocke et al., 2014; Werk et al., 2014) the CGM is the interface through which gas enters and leaves the galaxy, and likely fuels star formation. Recent simulations (Corlies et al., 2018) show that current integral field spectrographs on 8–10 meter telescopes (e.g Keck+KCWI, VLT+MUSE) show great promise to directly observe the brighter $z > 2$ CGM knots and filaments. Higher throughput instruments on these and larger telescopes, along with larger observing campaigns, will be required in the future to probe the fainter CGM in emission at these redshifts. At lower redshifts ($z < 2$), metal emission lines fall into the near ultraviolet bandpass.

4 Moving Forward

Even with HST still working hard, a project like this requires an instrument designed specifically to target this faint and diffuse emission, as well as the ability to devote all available observing time to the detection of this important understudied component of the baryon budget.
One of the current difficulties in attempting a detection has been the broad nature of predictions from simulations along with their rapid evolution and improvement. Although we have managed to use simulations to design experiments and constrain emission (Milliard et al., 2010; Tuttle et al., 2010), technological constraints (detectors, filters, and platforms) have so far not provided results. There are several approaches underway to attempt to resolve this issue - including expanded absorption measurements, ground-based higher redshift observations in the optical with larger telescopes, and spectroscopic approaches. We think this valuable scientific detection should be approached by all possible methodologies until a detection provides a measurement to provide a link into our current understanding of galaxy evolution and the interactions between gas and galaxies.

References

Anglés-Alcázar, D., Faucher-Giguère, C.-A., Kereš, D., et al. 2017, MNRAS, 470, 4698

Bertone, S., Aguirre, A., & Schaye, J. 2013, MNRAS, 430, 3292

Bertone, S., & Schaye, J. 2012, MNRAS, 419, 780

Bertone, S., Schaye, J., Booth, C. M., et al. 2010, MNRAS, 408, 1120

Cantalupo, S., Arrigoni-Battaia, F., Prochaska, J. X., Hennawi, J. F., & Madau, P. 2014, Nature, 506, 63

Chen, H.-W., Helsby, J. E., Gauthier, J.-R., et al. 2010, ApJ, 714, 1521

Christensen, C. R., Davé, R., Governato, F., et al. 2016, ApJ, 824, 57

Corlies, L., & Schiminovich, D. 2016, ApJ, 827, 148

Corlies, L. B., Peeples, M. S., Tumlinson, J., et al. 2018, ApJ, submitted, arXiv:1811.05060

Faucher-Giguère, C.-A., Kereš, D., Dijkstra, M., Hernquist, L., & Zaldarriaga, M. 2010, ApJ, 725, 633

Ford, A. B., Davé, R., Oppenheimer, B. D., et al. 2014, MNRAS, 444, 1260

Frank, S., Rasera, Y., Vibert, D., et al. 2012, MNRAS, 420, 1731

Hummels, C. B., Bryan, G. L., Smith, B. D., & Turk, M. J. 2013, MNRAS, 430, 1548

Liang, L., Durier, F., Babul, A., et al. 2016, MNRAS, 456, 4266

Martin, C. L., Shapley, A. E., Coil, A. L., et al. 2013, ApJ, 770, 41

Martin, D. C., Chang, D., Matuszewski, M., et al. 2014, ApJ, 786, 107

Martin, D. C., Matuszewski, M., Morrissey, P., et al. 2015, Nature, 524, 192

McCourt, M., & Madigan, A.-M. 2016, MNRAS, 455, 2187

Milliard, B., Martin, D. C., Schiminovich, D., et al. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7732, Space Telescopes and Instrumentation 2010: Ultraviolet to Gamma Ray, 773205

Peeples, M. S., Werk, J. K., Tumlinson, J., et al. 2014, ApJ, 786, 54

Prescott, M. K. M., Dey, A., & Jannuzi, B. T. 2013, ApJ, 762, 38

Prochaska, J. X., Weiner, B., Chen, H. W., Cooksey, K. L., & Mulchaey, J. S. 2011, The Astrophysical Journal Supplement Series, 193, 28

Rubin, K. H. R., Diamond-Stanic, A. M., Coil, A. L., Crighton, N. H. M., & Stewart, K. R. 2018, ApJ, 868, 142

Rubin, K. H. R., Prochaska, J. X., Koo, D. C., et al. 2014, ApJ, 794, 156

Salem, M., Bryan, G. L., & Corlies, L. 2016, MNRAS, 456, 582

Sravan, N., Faucher-Giguère, C.-A., van de Voort, F., et al. 2016, MNRAS, 463, 120

Stocke, J. T., Keeney, B. A., Danforth, C. W., et al. 2013, ApJ, 763, 148

—. 2014, ApJ, 791, 128

Suresh, J., Rubin, K. H. R., Kannan, R., et al. 2017, MNRAS, 465, 2966

Tejos, N., Morris, S. L., Finn, C. W., et al. 2014, MNRAS, 437, 2017

Tumlinson, J., Thom, C., Werk, J. K., et al. 2013, ApJ, 777, 59

Tuttle, S. E., Schiminovich, D., Grange, R., et al. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7732, Space Telescopes and Instrumentation 2010: Ultraviolet to Gamma Ray, 773227

van de Voort, F., & Schaye, J. 2013, MNRAS, 430, 2688

Werk, J. K., Prochaska, J. X., Tumlinson, J., et al. 2014, ApJ, 792, 8

Xue, R., Lee, K.-S., Dey, A., et al. 2017, ApJ, 837, 172