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The Baryon Cycle, Resolved: A New Discovery Space for UV Spectroscopy

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

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Abstract:

Galactic gas flows are critical processes in galaxy evolution. Galactic feedback arises from stars, supernovae, black holes, and radiation in a complex interplay that begins at < 100 pc scales but eventually spreads its effects throughout galaxies and the cosmic web. Future advancements in spatially resolved spectroscopy in the UV will provide unprecedented physical resolution in unique and powerful diagnostic features that are not available at other wavelengths. Such a capability would address crucial open questions about how galactic outflows work, how feedback distributes metals, and how stellar and AGN radiation combine to drive feedback and to reveal it to us. UV MOS and IFS capabilities would complement similar resolved spectroscopy from optical and IR wavelengths using technological heritage from OIR instruments. The combination of 100-fold multiplexing at UV wavelengths, 0.1″ spatial resolution, and wide fields will propel studies of the galactic baryon cycle into a new discovery space.
**Gas Flows Are Galaxy Evolution:** Astro2010 asked “How do baryons cycle in and out of galaxies, and what do they do when they are there?” Since then, tremendous progress has been made. Mapping of disks in atomic and molecular ISM gas (e.g., Leroy et al. 2011) has refined the well-defined relationships between gas and SFR in galactic disks (e.g., Krumholz et al. 2012). The Circumgalactic Medium (CGM) has been weighed as a major component of galactic baryons (Werk et al. 2014) that harbors a significant fraction of all metals ever produced (Peeples et al. 2014). Theoretical studies have come to understand better the energetic outflows that push gas, metals, dust, and radiation away from their sources into the CGM, from which they may eventually recycle to form new stars (Christensen et al. 2016). The “baryon cycle” that makes galaxies has assumed a central role in understanding them, but there is much left to be done.

**The State of the Art:** Despite this progress, we still do not know how feedback sets the stellar masses and metallicities of galaxies, and how it might quench star formation entirely (for big-picture reviews see Madau & Dickinson 2014; Somerville & Davé 2015; Tumlinson, Peeples, & Werk 2017). Between these big questions and good empirical answers lies a major disconnect in scale: we usually cannot trace the complex interplay of gas, dust, SN energy, and radiation back to their sources in star clusters and AGN. Rather, “down-the-barrel” observations average over much of a galaxy’s disk, mixing together information from scales below $\lesssim 1 - 10$ kpc (e.g., Martin 2012; Kornei et al. 2012; Rubin et al. 2014). Variations in winds well below the kiloparsec scale have already been established in cases where gravitational magnification helps (e.g., Bordoloi et al. 2016). Recent deployments of Integral Field Spectrographs (IFS) such as VLT/MUSE, Keck/KCWI, SAMI, and SDSS/MaNGA have now begun to spatially resolve feedback in the optical, where classical H II region lines provide kinematic and metallicity estimates in warm ionized gas (e.g., Ho et al. 2014; Venturi et al. 2018; Perna et al. 2019).

To capture the full multi-phase reality of galactic outflows, we must also observe them in the ultraviolet band, where we find uniquely powerful probes ranging from neutral ($T \sim 1000$ K) all the way to highly ionized gas with $T \sim 10^6$ K (Figure 1). Hubble’s Cosmic Origins Spectrograph can obtain down-the-barrel UV spectra of galaxies, such as the rapidly star-forming “green pea” galaxies (Jaskot et al. 2017), where the 2.5$''$ aperture of COS still takes in the whole galaxy. For very nearby galaxies, COS can isolate individual stars or clusters within its single aperture (2.5$''$), but it must observe them one at a time, as has been done for the LMC (Lehner et al. 2009; Barger et al. 2016), M33 (Zheng et al. 2017), and M83 (Aloisi et al. 2016). Each such observation requires a few hours of integration to detect the emission and absorption features, and the lack of multiplexing severely limits the possibilities for examining outflows as they develop at their sources as a function of all the physical parameters that can matter.

By contrast, theoretical studies are able to make specific and detailed predictions. Analytic theory can specify the content and kinematics of outflows, given the energy and momentum of the driving source, even down to the single supernova level and including complex influences of gas, dust, radiation pressure, and cosmic rays (e.g., Murray et al. 2011; Lochhaas et al. 2018). Numerical simulations of outflows within idealized galaxies have advanced rapidly, and now make detailed predictions for flow rates, mass loading, recycling, and observational signatures (Fielding et al. 2018, Schneider et al. 2018). But, for the most part these physically rich models are still being tested against integrated, averaged, and essentially blurred out observations.

**The Driving Science Questions:** A future space observatory could open a new discovery space in the service of unraveling galactic gas flows back to their driving sources, if it can deploy wide-field,
spatially-resolved, ultraviolet spectroscopy. We will focus on three major aspects of the “baryon cycle” which we need to resolve: mechanical feedback, chemical enrichment, and the transport of radiation. Understanding these basic processes involves answering a host of deeper questions:

**How do stars and supernovae drive mechanical feedback?** Mass ejection from galaxies may help account for why galaxies have less than their cosmic share of baryons. Indeed, a large budget of baryons is detected in the CGM. How do these “superwinds” work? Are they driven primarily by the thermal energy of coincident explosions, or do radiation pressure and cosmic rays also provide a push? How does the acceleration profile of these outflows depend on the driving mechanism and other parameters? Can superwinds eject mass at a rate similar to the local SFR (“mass loading”), or is the ratio much higher? How do supernova-driven winds depend on cluster mass, age, metallicity, geometry, and other factors? How far do these winds propagate into the CGM or IGM? Do they turn around and recycle? Can we trace the gas flows back to their source by correlating the wind kinematics, abundances, and mass loading to the cluster age, mass, and metallicity?

**How do outflows influence chemical evolution?** Winds can carry newly created heavy elements away from the sites of their formation and thus greatly influence the chemical enrichment of galaxies. Outflows generally appear to be metal-rich with respect to the local ISM (Chisholm et al. 2018), which helps explain why galaxies over three decades in mass retain only about 20% the metals they have ever produced (Peeples et al. 2014). What is the “metal-loading” factor - the rate of metal ejection in comparison to total mass or the local SFR? Are the metals mixed from the SNe into the entrained gas quickly, or do they remain unmixed into the CGM or beyond? Do these metals recycle into new accretion by the ISM? How do the metallicities of inflows and outflows compare? How does this balance between inflow, outflow, and recycling set the global abundance of metals within galaxies, and their distribution throughout galaxies?

**How do photons drive and trace galactic feedback?** Light from stars is both an influence on the baryon cycle, and naturally our primary means of learning about it. X-ray and UV radiation from stars and black holes can ionize and heat the gas, heat or dissociate the dust, and help push all of...
it out of the galaxy. Ionizing Lyman continuum (LyC) radiation that makes it past the gas and dust can go on to ionize the IGM. What is the relation between outflows and Lyman continuum escape? What do complex Ly$\alpha$ and metal-line profiles (e.g., C II and C II$^+$) tell us about the kinematics of outflows and the escape of ionizing radiation? What fraction of photons escape to the IGM ($f_{\text{esc}}$) and what fraction are absorbed, scattered, or reprocessed before getting that far ($1 - f_{\text{esc}}$)? Answers to these questions are needed not only to understand the propagation of the radiation itself, but also to properly use the radiation as a diagnostic.

**How Information is Encoded:** The things we want to know are encoded in the detailed profiles of UV absorption and emission lines. We can use stars and AGN as background sources or observe emitting gas with no point source in the aperture. Outflows are seen as blueshifted absorption in metal lines, or even as redshifted emission of resonantly scattered photons (e.g., Ly$\alpha$, Mg II, or C IV). Inflows are redshifted in absorption and blueshifted in resonantly-scattered emission. Multiplexed coverage of multiple species (HI, CII/III/IV, OVI, etc.) provide leverage on ionization and metallicity. Comparison of line profiles from species to species reveal the relative kinematics of the various phases. UV emission lines such as CIII] 1907,1909, OIII] 1661,1666, and He II 1640 emerge only at low metallicity (1/5-1/3 solar), signaling a transition in the ionizing spectrum produced by metal-poor star clusters (e.g., Berg et al. 2016; Berg et al. 2018; Senchyna et al. 2017). Lines like CIII] 1909/He II 1640 and CIV 1549/He II 1640 can help discriminate between photoionized gas versus gas that has been shock heated during the early development of an outflow (Jaskot & Ravindranath 2016). The presence of NV 1240 or Si IV 1393,1403 emission (Smith et al. 2016, Jaskot et al. 2017) might reveal the outflows driven by extremely young starbursts which may be suppressed and dominated by radiative rather than mechanical feedback (Jaskot et al. 2017). Correlating the stellar wind and Wolf-Rayet star signatures in the UV with stellar ages, metallicities, cluster mass, and other properties by isolating the individual clusters is one approach to get insight on the transition from radiative to mechanical feedback.

Lyman $\alpha$ is a powerful diagnostic with its own complexities. Resonance scattering in galactic outflows are known to affect the Ly$\alpha$ spectral profile, introducing velocity shifts and multiple asymmetric peaks to the line profile (e.g., Verhamme et al 2006). With spatially-resolved UV spectroscopy, this problem can be inverted and the spectral information used to infer the bulk properties of the scattering medium such as the velocity structure, hydrogen column density and clumpiness (Gronke 2017). Thus, if properly calibrated by observations like these, Ly$\alpha$ can potentially be used to obtain mass outflow rates and the fraction of ionizing radiation that escapes to the IGM. Because the Ly$\alpha$ line is often intrinsically bright, this can be done without the use of a background source to illuminate the gas, as is the case for down-the-barrel spectroscopy or QSO/galaxy pair studies. Moreover, the main constituent of gas flows is of course hydrogen, and because Ly$\alpha$ scatters at such low column densities, H I around galaxies can be illuminated and probed at levels that will not be possible with the next generation of radio telescopes.

**The Necessary Capabilities:** Astrophysical realities impose the basic requirements to make observational progress on these driving questions:

- the sources of the flows and the ionizing photons are small ($\lesssim 100$ pc) and clustered with each other, requiring spectroscopy of distinct sources down to $1 - 100$ pc scales.

- the sources are stochastically distributed across nearby galaxies ($\gtrsim 1 - 10$ kpc), making it necessary to cover them with wide fields ($\gtrsim 1'$) to capture variations with local conditions.
Figure 2: Several possible applications of a wide-field UV MOS or IFS capability. Each of these is a Hubble image with a $1' \times 1'$ 2D spectroscopic array overlaid. Shutters or IFUs slices at subarcsecond scales will provide unprecedentedly rich datasets to probe stars, gas, and radiation in these dynamic environments. At right, the small subregion of M83’s disk marked with the white box is zoomed to show the scale of the individual $0.1'' \times 0.2''$ shutters.

- the operative physical processes yield complex signatures encoded in emission and absorption line profiles that must be observed with adequate spectral resolution ($R \gtrsim 30,000$) and signal-to-noise ratio ($\gtrsim 20$) to support robust measurements.

- to obtain all these measurements, coverage of observed-frame UV wavelengths down to 1000 Å is essential: Ly$\alpha$ is at 1216 Å and the key O VI tracer of highly ionized gas falls at 1032 Å. For direct observations of the LyC ($< 912$ Å) in objects whose redshifts permit its detection, wavelength coverage as far down as 900 Å should be attempted.

- to take full advantage of the power of UV multiplexing, the single-aperture sensitivity should permit typical sources of interest (FUVmag $\lesssim 20$) to be observed in integrations of order $\sim 1 - 10$ hours, so that full UV-band wavelength coverage and tiling of the FOV across nearby galaxies can be done within the constraints of average GO-driven science programs. If single galaxies take $\gtrsim 100$ hours (as now with Hubble), practical constraints will severely limit the ability of the community to make the dramatic advances contemplated here.

**How to Do the Observations:** These basic requirements can be met with spatially resolved multi-object spectroscopy, similar to JWST’s NIRSpec Microshutter Arrays (MSAs), or with an integral field spectrograph (IFS). MOS or IFS provide nearly infinite flexibility to deliberately sample stars and clusters as sources of feedback as a function of their mass, age, metallicity, or other properties, or to avoid stars altogether and focus on gas and dust. Both have their advantages as implemented with currently available technology. MOS can operate over larger fields with a few hundred sources, but IFS are better for smaller areas when complete coverage of the field is needed (with no gaps from the shutter mask).

A wide-field MOS mode, perhaps derived from JWST’s MSAs, could provide millions of small ($\sim 0.1''$) shutters over arcminute fields. Each of the shutters is individually configurable, so arbitrary arrangements of hundreds of sources can be observed simultaneously. Apertures of $\sim 0.1$
arcsec correspond to $< 50$ pc out to 100 Mpc and $< 250$ pc out to $z \sim 0.1$. Figure 2 uses Hubble images of four nearby galaxy environments from the LMC’s 30 Doradus to the center of the Perseus cluster, with hypothetical $0.1'' \times 0.2''$ apertures shown to scale. A high-resolution image is needed to select and place the shutters, but pre-imaging through an all-open MSA suffices (cf. NIRSpec). MSAs also excel at a form of scientific multiplexing; the sheer amount of sky real estate allows a single observing program to cover many different kinds of sources, from stars to clusters to AGN. By changing configurations on the fly during a single visit, many distinct problems in the baryon cycle can be “resolved”.

UV IFS capability is optimal for fields where source locations are not known in advance and minimizing gaps between spatial elements is desired. Figure 3 shows the starburst merger Haro 11, the first confirmed LyC emitter. The $30''$ aperture of the FUSE spectrograph that first detected the LyC, shown to scale, would be closer to the size of the page than the galaxy (Leitet et al. 2011), so the LyC emission is still poorly localized. Of its three starburst knots in the HST image, one (C) is a Ly$\alpha$ source, two (B, C) host ULXs, and one (A) has extreme ionization parameter; knot A is the most likely origin of the LyC emission (Keenan et al. 2017). The COS aperture ($2.5''$) can isolate these knots from one another, but a higher spatial resolution IFS would be able to examine varying line fluxes and continuum emission (e.g. Ly$\alpha$, LyC, and C III] 1909) arising from within and between the various knots, resolving their individual sources and the transport of radiation along with differential reddening and other highly variable factors. With short-wavelength coverage, a UV MOS could even obtain a spatial map of LyC emission and determine its relationship to Ly$\alpha$ (e.g., Micheva et al. 2018). The presence and location of very massive stars ($> 100 M_{\odot}$) would be revealed by He II 1640 emission (Crowther et al. 2016), and the properties of their outflows – singly or, more likely, collectively – could be estimated from the P Cygni profiles of resonance lines of ionized metals (e.g., N V, C IV, Si IV).

**Complementarity:** Spatially-resolved UV spectroscopy can dissect the baryon cycle at unprecedented scales, complementing information from other wavelengths with unique constraints on mass, metallicity, ionization, and kinematics. The optical can map the starlight and the emission / absorption of low-ionization gas, while the IR can trace molecular gas and see through the dust. Radio wavelengths constrain the distribution of dense molecular gas. With foreseeable technological advances and the right kind of telescope, we can add unique UV-band diagnostics to these powerful probes of galactic evolution.
References
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