Astro2020 Science White Paper

The Chemical Enrichment History of the Universe

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:

Our understanding of the early formation and evolution of galaxies has advanced remarkably in recent decades. New observational techniques, surveys, and simulations have charted the surprisingly strong evolution in the distribution of gas content, star formation, and black hole accretion across the mass scale of galaxies and throughout much of cosmic time. Because of the extraordinary impact heavy elements have on the physical processes governing galaxy evolution, the next great challenge to advance our understanding of how galaxies form and evolve is uncovering the *chemical enrichment history of the Universe* — when and how metals formed in galaxies and began cycling through their halos. We highlight the current obstacles hampering attempts to measure the true abundance of metals in the gas within galaxies, and outline promising new methods to overcome them. We demonstrate the growing importance of *absolute* metal abundances in constraining modern accretion and outflow-driven galaxy formation models. And we describe a suite of observational methodologies capable of tracking absolute metal enrichment across cosmic time, free from the biases imposed by unknown temperature structure and dust obscuration. Together with traditional and recalibrated optical tracers, these methods include new UV gas abundance tools, bright-line infrared metal abundances based on some of the most luminous lines galaxies emit, and free-free continuum emission as a promising new metallicity normalization.

The Rise of Metals

Today, despite billions of years of accumulation, elements heavier than helium make up less than one-third of one percent of the mass of the Universe. And yet, this tiny contributor to the cosmic mass budget has an incredibly powerful impact. Due to the richness of their energy structures, the presence or absence of chemical species such as carbon, oxygen, and iron dramatically alter the efficiency with which light from stars and other radiation sources couples to gas. This sensitive dependence on metallicity leads to a wide range of transformations in the processes that govern how galaxies form and evolve, from the initial cooling and inflow of virialized gas, to its collapse into stars, to the feedback-driven outflows of enriched material, and the properties of the stars themselves.

Even tiny admixtures of metals fundamentally alter the physical processes controlling the conversion of gas into stars, driving a marked transition in the Universe from an early era dominated by massive and short-lived giants with masses $\gtrsim 100\,M_\odot$, to the current age of predominantly sub-solar stellar populations (e.g., Bromm & Yoshida, 2011). While the masses of forming stars attain their modern distribution at very low metal abundances, each star is indelibly marked by the composition of its natal gas. Stars formed from gas with lower initial metal content are hotter and more luminous, and with a diminished abundance of their principal coolants, the regions they ionize retain more heat. Metal-rich galactic outflows, driven by stellar and accretion-powered feedback, distribute heavy elements throughout the intergalactic medium such that the bulk of metals, even locally, exist *outside* galaxies (Peeples et al., 2014). These elements then alter the cooling of virializing gas and regulate the fresh fuel supply. The interplay between gas inflow and outflow, driving variations in the gas and metal content of galaxies, is now understood to be a fundamental process controlling galaxy evolution (e.g., Davé et al., 2011).

The strong physical impact of metal content on galaxy evolution is remarkably clear in the present day Universe, with many robust metal-driven physical processes uncovered, including the tight relations among a galaxy's gas-phase metallicity, stellar mass, luminosity, and star formation rate (e.g., Tremonti et al., 2004; Cresci et al., 2018), the relative abundance and physical properties of its dust content (e.g., Engelbracht et al., 2005; Sandstrom et al., 2010), the excitation conditions and structure of its molecular clouds (Bolatto et al., 2008), and the balance of heating and cooling in its neutral gas (Smith et al., 2017).

In the past decade, incredible progress has been made charting the rise and early evolution of galaxies in the Universe — the joint growth of stellar and central massive black hole mass (e.g., McConnell & Ma, 2013), the bi-modal separation of star formation into distinct *modes* with divergent gas consumption timescales ("main sequence" and "starburst"; e.g. Elbaz et al., 2011), and the accumulating reservoirs, production pathways, and physical conditions of gas and dust at early epochs (e.g., Michałowski, 2015; Decarli et al., 2016). **The next great challenge in understanding how galaxies form and evolve is uncovering the *chemical enrichment history of the Universe* —** learning both *when* and *how* heavy elements appeared within galaxies and cycled through their halos. Meeting this challenge will require new observational capabilities, sensitive new indicators carefully calibrated to track *absolute* metal abundance in gas, and robust modeling to fill in observational gaps and tie metal-sensitive tools into a single consistent framework.

The Role of Metal Abundance in Galaxy Formation Models

Galaxies grow in an evolving equilibrium between accretion from circum-galactic gas, star formation, and powerful galactic outflows. Understanding this so-called baryon cycle is a key challenge for galaxy formation models, which connects small scale processes such as supernovae and AGN to the distribution of gas in halos and the cosmic web. Metals provide a unique and direct tracer of baryon cycling processes. Generated inside stars, metals are seen distributed via galactic outflows into interstellar, circum-galactic, and intergalactic gas, and play a crucial role in gas cooling and star formation processes. Those same galactic outflows are also responsible for regulating star formation within galaxies. Hence the distribution of metals in the ISM, CGM, and IGM provides key constraints on galaxy formation processes.

A simple model for galaxy growth via baryon cycling (Finlator & Davé, 2008; Davé et al., 2012) suggests that inflows of relatively pristine gas fuel star formation, which in turn generates metals, some of which are expelled in outflows. Furthermore, winds can recycle back into galaxies (Oppenheimer et al., 2012), which provides additional enriched inflow and further diffuses the heavy metals across galaxies. Observations of cosmic metals are critical for constraining the key parameters governing this baryon cycling model: preventive feedback, ejective feedback, and wind recycling. The latest generation of galaxy formation simulations are able to reasonably reproduce the global stellar and gas properties of galaxies (e.g. Pillepich et al., 2018; Davé et al., 2019). Broadly, they also reproduce observations of metals in galaxies (e.g. Schaye et al., 2015; Davé et al., 2019) and the CGM (e.g. Ford et al., 2016). However, current constraints are relatively weak, owing to uncertainties in both supernova yields and in particular the abundance scale. Only by overcoming these challenges and obtaining consistent absolute abundance measurements can we fully exploit the metal distribution within and around galaxies as a constraint on galaxy formation models.

Metals expelled from galaxies end up in the CGM and IGM. Rest-UV absorption line surveys can probe metals along skewers through the CGM (e.g. Steidel et al., 2010; Tumlinson et al., 2013), but models are needed to holistically situate these absorbers within a cosmological baryon cycling context. Upcoming 30m telescopes will make CGM absorption line surveys routine at $z \sim 1$–3, when star formation and thus outflows were most active. Metal lines can also provide a treasure trove of information during the Epoch of Reionisation (EoR). ALMA can probe far-IR emission lines around the brightest $z \sim 6$ galaxies, and near-IR spectroscopy is beginning to detect metal absorbers out to $z \sim 7$, which likely arise in the CGM of EoR galaxies. Indeed, CGM metal lines are expected to trace EoR galaxies in the same mass range as *JWST* (Finlator et al., 2013), thus providing a remarkable opportunity to characterize the baryon cycle during the earliest epochs of galaxy assembly (see related whitepapers by N. Lehner and M. Peeples).

In summary, metals provide a unique tracer of the processes that govern galaxy assembly over cosmic time. A key linchpin of this understanding will be in *constraining the metal distribution within the ISM*, where new far-IR facilities can potentially extend back to the EoR. Combining this with advances from 30m telescopes and *JWST* will enable transformative progress in understanding how the baryon cycle shapes galaxies at a range of masses, epochs, and environments.

Current Status and Future Plans

Despite the rapid pace of new observational and theoretical insights, the absolute chemical enrichment history of the gas in galaxies remains elusive. Extensive studies of metal content in the nearby Universe reveal a $\sim 10\times$ increase in the metallicity of a typical galaxy between $z = 1$ and $z = 0$, but our knowledge of the evolution of galactic metal enrichment beyond $z \sim 1$ is as yet much more limited (e.g., Sanders et al., 2015; Strom et al., 2017). In part, this is purely an observational limitation — the typically-employed rest-frame optical indicators become challenging to observe from ground, as they redshift into infrared passbands. More significantly, the strong emission lines employed by current and planned abundance surveys retain the same decades-old systematic uncertainties impacting their conversion to underlying metal abundances. Figure. 1 illustrates this point dramatically. The celebrated relationship between stellar mass and metallicity in galaxies — which provides deep insights into the interplay between metal production in stars, metal-rich outflows, and pristine inflows of fresh material across a wide range of galaxy mass — suffers major systematic abundance uncertainties depending on the adopted calibration. This results in a nearly unbelievable situation. **We do not yet know whether the gas in the galaxies of today's Universe is predominantly super- or sub-solar in its heavy element abundance** (e.g., López-Sánchez et al., 2012).

Much of this gross ambiguity in the absolute abundance scale of the Universe arises from unknown *temperature structure* in ionized regions. Varying assumptions of thermal structure result in significantly different interpretations of the same observational inputs. The so-called *direct abundance method* attempts to address these issues by utilizing faint "auroral" lines (e.g. [O III]λ4363) to directly assess gas temperature. However, these lines are rarely detected and disappear altogether at higher metallicity. They also assume a homogeneous temperature throughout the nebula, whereas observations of HII regions reveal systematic temperature gradients and inhomogeneities (see Kewley, 2019 ARAA for a review). At high redshifts, observing optical auroral lines becomes even more challenging, as the lines move into near-IR windows with high terrestrial background. This major ambiguity among the prevailing optical abundance methodologies confounds attempts to track the evolving metal content of galaxies. These issues become particularly severe when attempting to piece together evolutionary trends with a patchwork of different calibrations, as is common.

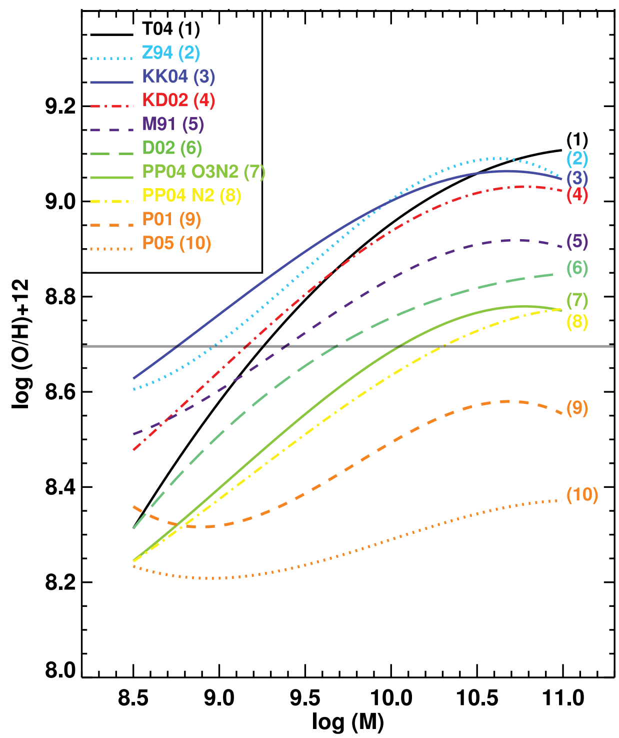

Figure 1: The central locus of the modern day mass-metallicity (MZ) relationship derived from $>10^4$ SDSS galaxies, using a variety of different strong line optical metallicity measures (colored lines). Abundances tied to photoionization models are highest, with empirically-tied calibrations lowest. The gray horizontal line shows the solar oxygen abundance[1], and demonstrates the current factor of $\sim$3–5$\times$ uncertainties in assessing gas phase metal abundance in the Universe. Adapted from Kewley & Ellison (2008).

Rest-frame UV and optical metallicity measures are also susceptible to dust extinction, leading to incorrect results and biases against dusty sources (e.g., Zahid et al., 2014). For tracking the Universe's enrichment history, this limitation is compounded by the fact that during the peak of star forming activity ($z\sim1$–3), most star formation occurred in dusty, luminous galaxies (e.g., Elbaz et al., 2018). Upcoming and planned facilities will extend the study of galaxy metal abundance to early epochs, but will necessarily be limited in scope in terms of numbers, luminosity/mass ranges, and available diagnostic tools. Spectroscopic surveys with *Euclid* and *WFIRST* will assess metallicity in galaxies to $z\sim4$ using traditional optical and new UV nebular line tracers (e.g. Byler et al., 2018). *JWST*, with its highly sensitive mid-infrared spectroscopic coverage, will probe galaxy metallicities using these same indicators at faint luminosities

[1] Assuming 12+log(O/H)$_\odot$=8.69 (Asplund et al., 2009)

Method Name	Observations	Features	z	Facilities
Strong UV	UV Strong (C,N,O), H/HeRec	Ionbal	2–7	Ground 8–30m, JWST
Direct Optical	Opt Strong+Weak (O,N), HRec	TempIns, Ionbal, ModInd	0–3	Ground 8–30m, JWST
Strong Optical	Opt Strong (O,N), HRec	Ionbal	0–8	Ground 4–30m, JWST
Direct FIR	FIR Strong (O), HRec/FF	TempIns, DustIns, ModInd	0–8	*FIRSurv*/ALMA, JWST/ngVLA
Modeled IR	IR Strong (O+N,Ne+S)	TempIns, DustIns	0–6	JWST, *FIRSurv*
Dust-Metals	IR Dust (PAH)	DustIns	0–6	JWST, *FIRSurv*

Strong=Strong Collisional Lines, **Weak**=Weak/Auroral Collisional Lines, **HRec**=Hydrogen Recombination Lines, **HeRec**=Helium Recomb. Lines, **FF**=Free-Free Continuum Emission, **Ionbal**=Directly measures Ionization Balance, **ModInd**=Independent of Photo-ionization Models, **TempIns**=Insensitive to Unknown Temperature Variations, **DustIns**=Insensitive to Moderate Dust Extinction, **FIRSurv**=A Space Far-Infrared Spectroscopic Survey Facility, **PAH**=Polycyclic Aromatic Hydrocarbon Bands and Band Ratios

Table 1: A suite of UV-FIR abundance measurements for the gas within galaxies applicable to studying the chemical enrichment history of the Universe. Key features, observational inputs and approximate observable redshift range for the associated facilities are included.

to higher redshifts over limited areas (Windhorst & Cohen, 2010). Moreover, *JWST* will be able to observe faint optical auroral lines to $z \sim 3$ in bright sources and determine direct metallicities to help validate strong-line calibrations at high redshifts, where ISM conditions may vary significantly. These missions will provide an important and powerful first glimpse of the relative trends of metal content in modest samples of galaxies across cosmic time.

Towards a Complete Metal Enrichment History of the Universe

There remain significant hurdles in our attempts to chart the rise of metals from the nearly pristine proto-galaxies driving the epoch of reionization to the massive and metal rich galaxies where most stars reside today. Maiolino & Mannucci (2019) present a recent and comprehensive review of metal abundance methodologies for stars and gas in galaxies as well as the CGM, and emphasize the need for unbiased absolute abundances in charting cosmic chemical evolution. Fulfilling this need requires a suite of tools that **1)** overcome temperature, ionization, and other sensitivities to target **absolute abundances** that relate to well-determined reference values like the solar oxygen abundance; **2)** are **inter-comparable**, using cross-calibration to control for, e.g., variability in relative abundances between atomic species that can result from differences in star formation history, etc.; and **3)** are insensitive to dust absorption by **penetrating** moderate to large **dust columns** or through self-assessing the impact of attenuation on the reliability of their results. Furthermore, while in the local universe at $Z \gtrsim 1/5\, Z_{\odot}$ a constant ~40% of metals are depleted onto dust grains, there is growing evidence of non-linearity in the dust-to-metal ratio at low abundance (e.g. Rémy-Ruyer et al., 2014; De Vis et al., 2019), so independent assessment of metal depletion through dust emission modeling will be important as well. Here we outline new methods which can meet these needs. Table 1 summarizes a suite of UV to FIR abundance tools applicable to cosmic enrichment.

Infrared Diagnostics: Since they arise from low-lying states that are readily excited in the ionized gas of galaxies, and are thus temperature-insensitive, the **far-infrared ground-state fine structure transitions** of the dominant ionized coolants can sidestep the long-standing impact of temperature uncertainty on gas metal-abundance measures. The fine structure ground-state levels of an ion like O^{++}, for example, *produce similar line emission for any gas temperature above a few 100K.*[2] This is an incredibly powerful property of the FIR lines, and is the key to their potential as metal abundance tracers (see, e.g., Croxall et al., 2013; Rigopoulou et al., 2018). Additionally, these infrared lines are typically among the most luminous, or even the brightest line a galaxy

[2] H II regions range in electron temperature from 5–20 kK.

emits. They are also unaffected by even substantial dust attenuation, and are increasingly accessible in the early Universe, where they redshift into submm bands. Their modest dependence on density which arises from reduced critical densities can be readily estimated using multiple IR lines (including [O III] 88/52 μm; see Croxall et al., 2013). ALMA has recently detected [O III] 88 μm emission in a handful of star-forming galaxies *directly in the era of reionization*, including in the earliest spectroscopically confirmed galaxy at $z = 9.1$ (Hashimoto et al., 2018). Yet the power of infrared metallicity diagnostics has remained largely untapped, since access to these wavelengths for studies of galaxies was only possible for relatively nearby sources with Spitzer and Herschel (e.g., Fernández-Ontiveros et al., 2016), and only a handful of massive or lensed galaxies have been characterized in ground-submm windows (e.g., Ferkinhoff et al., 2015; Lamarche et al., 2018).

Assessing Hydrogen: All methods for assessing gas metallicity aim to provide an absolute measure of metal abundance *relative* to hydrogen. Traditionally metal emission lines are compared to hydrogen recombination lines like Hα or Hβ. Although there are no similar strong hydrogen lines at long IR wavelengths, ionized gas does produce *free-free continuum emission*, observable in the radio, from non-recombination interactions between protons and electrons. The temperature sensitivities of the hydrogen lines and continuum are mild and similar, while their density dependencies are identical. Free-free emission therefore serves as an effective, extinction-free substitute for recombination lines to provide hydrogen normalization for abundance measures. X-ray abundance studies of $\sim 10^6$ K gas predominantly use free-free emission for this purpose (e.g., Mushotzky et al., 1996), and there are some pre-existing efforts to utilize radio free-free and infrared fine structure lines for abundance work in Galactic H II regions (e.g., Herter et al., 1981, 1982) and at higher redshift (e.g., Ferkinhoff et al., 2015; Lamarche et al., 2018). Since the energy density of the CMB scales as $(1 + z)^4$, synchrotron-generating cosmic ray particles are much more rapidly quenched by inverse Compton interactions with CMB photons in the early Universe, meaning that *thermal free-free continuum emission is expected to completely dominate over non-thermal emission* at early epochs (Murphy, 2009). Decomposed thermal radio detection is already underway in galaxies out to $z \sim 3$ (e.g., Murphy et al., 2017), and a future next-generation Very Large Array (ngVLA) will enable routine thermal continuum studies at much higher redshifts.

Dust as a Tracer of Enrichment: The discovery of large dust reservoirs ($\sim 10^8$ $M_\odot$) in some galaxies and quasar hosts just several hundred Myr after the Big Bang has challenged our theoretical understanding of early dust production in galaxies. The broad spectral dust features in the mid-infrared (3–30 μm) provide critical and unique information on dust origin, composition, and properties like grain size distribution. Dust can also play a direct role in charting the rise of metals in the Universe. Since dust grains are comprised of condensable species like C, Si, Fe, and O, dust is highly sensitive to the abundance of heavy elements. Studies of resolved dust emission permit indirect metallicity measurement via the powerful mid-infrared emission of the smallest dust grains — Polycyclic Aromatic Hydrocarbons (PAHs), which contribute up to 20% of the total infrared luminosity of star-forming galaxies (Smith et al., 2007). PAHs have a complex relationship with metal content in galaxies. However, the relevant physical processes (e.g. photo-destruction of PAHs in the harsher UV fields at low metallicity and inhibited formation in dense clouds with lower free carbon content) all drive a striking trend: the strength of PAH emission drops rapidly, then vanishes at metallicities approaching 1/10th the solar value (e.g., Sandstrom et al., 2012). *Spitzer* permitted a rough calibration of this trend, but *JWST* will complete this map between PAH fractional strength and band ratios to direct abundance measures in the nearby Universe. Due to their power, a sensitive background limited far-infrared space facility could enable PAH detection to $z \sim 6$ or above.

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