Precious Metals (or Lack Thereof) in SDSS Quasar Spectra

1. Title Slide
   - Aloha. Mahalo to the SOC and especially Gabor for the opportunity to present, as well as to y’all for the week of good science.
   - This talk will be in two parts: first, a summary of our metal-line surveys in SDSS DR7 quasar spectra and, second, recent results from surveys of Lyman-limit systems at redshift of 3.5, which tend to be low metallicity (hence the “lack thereof”). I’ll also intersperse work in various stages of progress.
   - A mahalo to my coast-to-coast-to-islands collaborators. “Non-students” in the first column and students otherwise (keep an eye out for some of these names in the future).
   - There’s more information and data products at igmabsorbers.info.

2. UH Hilo details

3. Quasar Absorption-Line Spectroscopy: Random Probe of Gaseous Structure
   - The observational technique for most of the work I will discuss is quasar absorption-line spectroscopy, whereby the background quasar continuum is attenuated by intervening gas clouds. The imprinted “chemical fingerprints” (i.e., absorption signatures) are spread out due to expansion of the universe. The intervening neutral hydrogen produces the Lya forest, which may also have absorption lines from metals. Metal lines that have rest wavelengths longer than Lya—like the ones I tend to study—are less blended.
   - My main point is that the foreground gas probed by the quasar sightline is random and reflects the cross-section and number density of the given structure. A quasar spectrum can sample low-density gas or high, pristine or polluted, canonical IGM or circumgalactic.
   - What one sees in any random quasar spectrum is also a function of signal-to-noise and resolution.

   - A focus on metal lines tends to be a focus on gas near galaxies, especially at SDSS resolution and signal-to-noise, because the galaxies have the stars that produce (or have produced) the metals.
   - Shown here are three snapshots from a cosmological hydrodynamic simulation. The top row shows only star particles and bottom, enriched gas, where red is solar.
   - The higher-metallicity gas is typically co-spatial with the stars (i.e., galaxies), but this circumgalactic medium has a larger cross-section than the optical/stellar component of the host galaxies.

5. Lifecycle of Gas & Metals
   - The gaseous structure of the universe gets polluted by a variety of feedback processes, both previous and on-going, as part of the cosmic chemical-enrichment cycle.
   - The CGM is the interface between what’s definitely the galaxy (e.g., optical part) and what’s definitely not the galaxy. It sees a lot of action from inflows, outflows, recycling, and what just hangs out. It tends to have components that are higher metallicity than the IGM and its derivatives (like inflows).
   - Remember that the processes and components of this cartoon are not going on in
every galaxy nor necessarily in any galaxy through all time. So the “random draw” one gets from quasar absorption-line spectroscopy is multiplexed random: of environments, of these processes/components, of epochs, etc.

- Hence, quasar absorption-line spectroscopy provides top-level constraints on the cumulative effect of stellar and galactic processes, in a range of environments and epochs.

6. Why CIV, MgII, & SiIV Doublets
- We have surveyed or are surveying for these particular ions as tracers of the cosmic chemical-enrichment cycle in the CGM because they are strong transitions of common metals that have been well studied over a range of epochs, with ground- and space-based facilities, with optical, IR, and UV spectrographs.
- They are also resonance-line doublets which means they are two lines with characteristic wavelength separation and correlated absorption (e.g., profiles, rest EW ratios). This means we could semi-automate the survey and hence plow through tens-of-thousands of quasar spectra.

7. Why SDSS
- SDSS DR7 provides over 100,000 quasar spectra, large subsets of which are suitable in quality and coverage for the targeted metal lines.
- Recall that quasar absorption-line spectroscopy randomly samples the universe as a function of cross-section and number density and that the CGM has a relatively small cross-section (compared to the IGM/Lya forest, though—as is one of my main points—larger than the host galaxies).
- So to get good statistics on CGM-probing absorption-line systems—some of the rarest structure—one needs a large haystack.
- For example, from our survey of 26,000 suitable DR7 quasar spectra, we detected almost 8,000 CIV systems 0.6 Å or stronger (where 0.6 Å is our 50%-complete limit). The frequency distribution—which is the number per rest equivalent-width bin, per co-moving path-length over which such a system could be detected—of these strong systems are an exponential that readily turns-over the power-law distribution of weaker systems from high-resolution and high-signal-to-noise surveys.
- We’re aiming to make a joint fit to these two datasets, not only in equivalent-width space but, hopefully, in column-density too. Then we can maybe forward model the parameterized distribution from a galaxy luminosity function or something.

8. Connecting SDSS Metals and CGM
- We asked whether there were enough galaxies for all the strong CIV systems to be tracing CGM, at least in the intermediate, SDSS redshift range, where we have good absorber statistics.
- From the CIV co-moving line density and the co-moving number (volume) density of UV-selected galaxies, which are star-forming and known to exhibit CIV absorption, we estimated the physical cross-section these >= 0.5 L* galaxies would have to have to give rise to the CIV systems we observe.

9. Connecting SDSS Metals and CGM
- The cross-section is reasonable, and if we convert it to radius, assuming a uniform disk geometry, it’s also reasonable, as measured by direct observations of quasar-absorber pairs.
- We assessed the necessary MgII-absorbing cross-section of B-band-selected (also star-forming, also >= 0.5 L*, also known to be associated with strong MgII absorption)
galaxies. (Here strong MgII was limited to the canonical 1 Å.)

10. Connecting SDSS Metals and CGM
- The necessary physical cross-section of the lowest-redshift systems are reasonable compared to what’s been observed directly, but at higher redshifts, it gets large. With all the caveats suitable to conclusions from such an exercise, we interpret this to mean either whatever processes produce the MgII-absorbing gas are more vigorous at higher redshifts (e.g., stronger star-formation-driven winds) and/or more galaxies contribute to the observed MgII line density, thus decreasing the average cross-section necessary.
- Also note how the overall evolution of the co-moving line densities of CIV and MgII differ (even, granted, they’re different rest equivalent widths). This led us to holistically examine a swath of common ions surveyed via quasar absorption-line spectroscopy.

11. [dN_ion/dX over redshift, bit-by-bit]
- The basic premise is that: though we target one specific ion for our surveys, we know that some, for example, strong CIV systems are also strong MgII absorbers. In other words, each ion has multiple absorber sub-populations that, together, yield the observed co-moving line density. Let’s step through some surveys of specific ions that are fairly comparable in spectra and/or methodology.
- MgII $W_r \geq 1$ Å: The strong MgII systems have this rise-and-fall shape that is likely at least partially due to evolution of the star-formation-rate density and, hence, rate of star-formation-driven winds.
- MgII $0.3$ Å $\leq W_r < 1$ Å: We have robust statistics of intermediate-redshift MgII in the weaker regime. It shows a different evolution than strong MgII (and if I were to include weaker SDSS MgII from e.g., Nestor et al., it’s all roughly flat). Perhaps this gas “just hangs out” or is constantly replenished (like condensations raining back onto the host galaxies).
- $\tau \geq 2$ HI: Optically thick neutral hydrogen absorbers including Lyman-limit systems, super-Lyman-limit systems (AKA sub-damped Lya absorbers), and DLAs. The overall evolution is what an increasingly ionized universe would produce.
- DLAs ($\log N_{\text{HI}} \geq 20.3$): DLAs are roughly 20% of the optically thick HI systems. They follow roughly the same trend. Strong MgII absorption has been used to pre-select for DLAs, but clearly, from a statistical standpoint, all of the strong MgII systems are not DLAs except perhaps at the highest redshift observed (where one might wonder how so much magnesium exists 1.3 Gyr after the Big Bang). This is an example of trying to holistically disentangle sub-populations.

12. [dN_ion/dX complete]
- Lastly, the strong CIV systems have a completely different evolution. It could be ionization (the others are low ions) and/or metallicity (perhaps the CGM is just “filling up” with carbon). But clearly every strong CIV system at $z \sim 2$ is not also a strong MgII system or DLA; they could all be weaker MgII and/or LLSs.
- We’re going to poke at this (including the SiIV catalog and whatever other ions we think we can fairly incorporate) with non-parametric clustering analysis to see if we can robustly identify absorber “classes.” And maybe we can link such absorber classes to actual galaxy types.

13. Future Works
- I’ve already mentioned the SDSS DR7 SiIV survey in the pipeline.
- We’re also shift-and-stacking in a variety of ways. It’s easy to implement and tough to interpret but informs us about the ensemble properties of the input samples. An
example study is strong-CIV-selected systems as a function of redshift and rest equivalent widths.

14. Stacking Analysis—Preliminary
- Here is a completeness-weighted median stack of almost 8,000 CIV systems, from blue to red. Note the change in vertical scale. Shown in gray is a single spectrum, with median CIV rest equivalent width from a spectrum with the median signal-to-noise ratio, for comparison.
- We can pick out absorption of other ions we've surveyed—CIV (input), MgII, SiIV—as well as other important ions: HI Lya, CII & CIII, and high ions like OVI & NV.

15. Evolution (or not) of Ensemble Absorber Properties—Preliminary
[Skip if short on time]
- If we divide the CIV systems by redshift and rest equivalent width, we can measure the equivalent widths in each composite spectrum for CIV 1548 (the line that defined the sample) and 1550. At a glance, we can see little to no evolution in 1548 (consistent with the frequency distributions) and, roughly, the same doublet ratio (1550:1548) at about 0.7 (moderately saturated and/or a lot of kinematic structure).

16. Evolution (or not) of Ensemble Absorber Properties—Preliminary
[Skip if short on time]
- And of course, we can examine many common transitions, to see what evolves and what doesn’t. What can be studied is a function of redshift because of rest wavelengths.

17. Evolution (or not) of Ensemble Absorber Properties—Preliminary
[Skip if short on time]
- The equivalent-width ratios are useful. Here is a classic: SiIV to CIV, which has been studied for a signature of HeII reionization (maybe talk to Gabor).

18. Evolution (or not) of Ensemble Absorber Properties—Preliminary
[Skip if short on time]
- Other ratios can perhaps inform about ionization state like SiII to SiIII or metallicity like OI to HI or abundance ratios like MgII (considered an alpha-element) to Fell.

19. Future Works
- There are many possibilities with stacking analysis, for example selection criterion.
- I mentioned using non-parametric clustering analysis to identify absorber “classes.” We can also apply stacking analysis to these automatically determined samples.
- We followed-up about 15 of the strongest CIV systems with MIKE on Magellan or the High Dispersion Spectrograph on Subaru. We are modeling these systems in detail to anchor some of the other analyses and help with interpretation (especially for stacking).

20. SDSS Discovery Spectra
[Skip if short on time]
- Here are velocity plots of four \( W_r >= 1 \) Å CIV systems with the snippets of spectra around other common lines available to SDSS (dependent on wavelength).

21. High-Resolution Follow-Up Spectra
[Skip if short on time]
- Here’s the MIKE spectra, ten-times better resolution (even binned a bit for display purposes). These systems are varied and interesting. I can flip back and forth.
- We’ll fit Voigt profiles and use CLOUDY modeling to constrain ionization corrections so we can assess physical conditions, such as metallicity.
22. $z_{sys} = 2.1167$, $W_r = 1.48$ Å—Preliminary
   [Skip if short on time]
   - This is a likely Lyman-limit system ($\log N_{HI} < 18.25$) that is perhaps super-solar (at least in one component), which is rare, as I will show later.

23. Future Works
   - As I mentioned before, we’re also fitting the joint CIV frequency distributions.

24. What about Metals Lack Thereof?
   - Here’s the second phase of the talk on the metallicity distribution of $z \sim 3.5$ Lyman-limit systems. Let me start by motivating our original working title “Do Cold Flows Exist?”

25. Sustaining Star Formation with Cold-Mode Accretion
   - Galaxies need gas to form stars as long as they do. Cold flows might be the way to get IGM fuel into the ISM. Simulations (even moving-mesh ones) show these flows are dense, cold, and inflowing (shown in brown).
   - We know galaxies eject gas. These outflows might have more diverse physical conditions: high or low density, cold or hot, and shape. (But they are moving away from the host galaxy.)

26. Metallicity of IGM Evolves (metals lost from ISM/CGM)
   - The outflows might be high density, like the expected cold flows, but they two ‘flows are expected to differ in metallicity.
   - Note the IGM is not zero metallicity (mark of previous outflows).
   - So metallicity is likely a good discriminator between inflowing and outflowing gas in the CGM.

27. Bimodal Metallicity of $z < 1$ (partial) Lyman-Limit Systems
   - Nicolas et al. has shown this metallicity bimodality at low redshift in partial and “total” Lyman-limit systems and will talk more about it shortly.
   - Our group followed-up $z \sim 3.5$ Lyman-limit systems (detected in SDSS) at higher resolution with MagE on Magellan and ESI on Keck to see if the metallicity distribution is also bimodal at higher redshift.

28. Metallicity of $z \sim 3.5$ Lyman-Limit Systems
   - Our study came in two waves via Cooper et al. (MagE; 17 systems) and Glidden et al. (ESI; 33). I’m happy to field questions later about details. But for now I’ll just say we constrained HI and metal-line column densities as best as possible. The uncertainties and limits were factored into 3- or 4-D MCMC analysis of CLOUDY models (4D: HI column, metallicity, ionization parameter, and [alpha/Al] abundance).
   - Here are the systems in the context of other strong HI systems at a range of epochs. The IGM measurements from Simcoe 2011 shown earlier are the blue points and gray shading as +/-1 and 2 sigma. There are several (conservative) upper limits; so several systems could be much lower metallicity.

29. $z \sim 3.5$ Lyman-Limit Systems: Bimodal Metallicity Distribution?
   - From the previous plot, with all the limits, it is not obvious whether the high-redshift LLS sample has a bimodal metallicity distribution. We used survival analysis to measure the cumulative distribution incorporating the censored data. We fit a bimodal metallicity distribution functions, using Rafelski et al. DLA and Simcoe IGM metallicities for the parent samples.
   - Following the Paul-Schechter axiom I learned at MIT: when the title is a question, the answer is always “No”: the best-fit bimodal distribution doesn’t reproduce the
observations.
- A unimodal distribution is a good representation of the observations, with mean metallicity is low, 0.2% solar.
- There are a few systems sampling the lowest-metallicity tail (see Fumagalli et al.) And it may be that our follow-up to \( W_r \geq 1 \) Å CIV systems will lead us to sample the highest-metallicity tail.

30. Future Works
- In the future, we’ll search for host galaxies to the LLSs where we have follow-up spectra, using Keck Cosmic Web Imager. We’ll assess properties of the galaxies but also the absorber-galaxy geometry \textit{a la} Bordoloi et al. and Kacprzak et al. (Remember those simulations I showed of cold-mode accretion.)

31. Main Points
- Here are your take-home messages.
- Strong absorbers trace the extended gaseous envelopes of galaxies. Since they are bigger than the host galaxy but heavily influenced by stellar and galactic properties, study of the CGM says a lot about galaxy evolution.
- The story of the various ions (or even strong vs weak of the same ion) are diverse and interesting stories, but they overlap.
- We need to look across species to flesh out our understanding of the properties and evolution of the CGM… and by extension, galaxies.
- Remember you can visit our website for more information (and a lot of data).
- Mahalo nui loa for your attention. Questions?