The Rise of Metals across Time and Space, and High-Redshift Perspectives on SOFIA

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Also with Alberto Bolatto, Adam Leroy, Tucker Jones, Dan Marrone, Karin Sandstrom, Dan Stark, Ben Weiner
Sensitivity is the key limiting factor for real high-redshift work with SOFIA

- HAWC+ observations of rest-frame mid-IR in z~1 and z~4 lensed quasars
- Constrain buried AGN by detecting the hot dusty torus
- Both these targets have $L_{\text{IR}} \sim 10^{15} L_{\odot}$
- There just aren’t that many targets amenable to these observations!

J. Ma + 2018
z=1 lensed quasar

Leung + 2019
z=3.9 lensed quasar
High-z spectroscopy is virtually impossible without order-of-magnitude gains in raw sensitivity

- Even *Herschel* did fairly little far-IR spectroscopy

- Again concentrated on lensed starbursts & quasars, stacked spectra

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Zhang+2018
Stack of 45 SPIRE spectra towards dusty starbursts
ISM more dense than local starbursts

Wardlow+2017
Stack of 45 PACS spectra towards dusty starbursts
Consistent with solar metallicity ISM
Instead we must rely on *local analogs* of high-redshift systems

- Pick nearby galaxies with some property/properties similar to those seen at high redshift
- Typical choices: mass, UV/optical colors, optical nebular line strengths & ratios, ionizing radiation field strength, …
- Often these are motivated by puzzling / difficult observations from other facilities
Two Case Studies of High-z Applications of SOFIA Observations

Understanding unusual \([O III] / [C II]\) line ratios in the reionization epoch

Tracing the rise of metals with powerful extinction-immune metallicity indicators
ALMA Finds Bright \([\text{O III}]88\text{um}\) and Faint \([\text{C II}]158\text{um}\) at \(z > 6\)

- While \([\text{C II}]\) is typically the brightest far-IR line in nearby galaxies, the galaxies responsible for reionizing the universe show very weak \([\text{C II}]\), but very bright \([\text{O III}]88\text{um}\) instead.
  - This is true even in comparison to the dwarf galaxies observed by Herschel.

- The galaxies that reionized the universe were lower-mass, more metal-poor, and had harder UV radiation fields even than most nearby dwarf galaxies.
Establishing (one possible) local analog SOFIA sample

- Select local galaxies with (locally) extreme UV properties, very low stellar mass, and HST/COS spectra
- We want objects with ionizing spectra similar to the reionization era
- Cycle 7 program, PI: B. Weiner (analysis from new-PhD Peter Senchyna)
- FIFI-LS can observe [OIII]88um and [CII]158um simultaneously
Local objects with extreme [OIII]/[CII] ratios

- We find ubiquitously high [OIII]88 / [CII]158 ratios, with values & limits consistent with $z > 6$ reionization-era galaxies

Senchyna, Weiner, JS + in prep.
Local objects with extreme [OIII]/[CII] ratios

- We find ubiquitously high [OIII]88 / [CII]158 ratios, with values & limits consistent with z > 6 reionization-era galaxies
- All have very strong C III] emission in the UV
- Perhaps C⁺ is not the dominant ionization state of carbon?

FIFI-LS Targets

Senchyna, Weiner, JS + in prep.
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The Rise and of Metals Across Time and Space

- Galaxy metallicities are the end result of a huge range of physical processes:
  - Metal-poor inflow
  - Enrichment via star formation
  - Metal-enriched outflows

- Amazingly, there’s a tight mass-metallicity relation that evolves with redshift

- However…
Highly-obscured dusty galaxies dominate star formation in the universe at $z > \sim 1$.

90% (!!) of metals from stellar evolution don’t stay in the galaxies that produced them.

- **Total Obscured + Unobscured**
- **LIRGs ($L_{IR} > 10^{11} L_{\odot}$)**
- **ULIRGs ($L_{IR} > 10^{12} L_{\odot}$)**

**Total Universe SFR Density, $M_{\odot}/yr/Mpc^3$**

**Total Metals Produced**

- Metals in Stars
- Metals in Gas
- Metals in Dust

Casey+2014 compilation

Werk+2014, many others
How to measure galaxy metallicities

- Measure multiple spectral lines, of C/N/O etc.
- Relative line ratio depends on:
  - Temperature
  - Density
  - Ionization state
  - Elemental abundances
- Measure or assume 3 of these to get the other
How to measure galaxy metallicities

- There are many metallicity calibrations. How well do they agree?
  - … very poorly.
- Problems lie in:
  - Assumptions ($T_e$ in particular)
  - Dust along sightline

Kewley & Ellison 2008
Can we win in the far infrared?

- The far-IR has multiple advantages:
  - Temperature mostly irrelevant
  - Dust mostly irrelevant
  - Other parameters (e.g. density) easily constrained

Nagao+2011, Pereira-Santaella+2017
Developing Extinction-Free Metallicity Indicators

- We now have an indicator calibrated over \(~1\) dex in metallicity that relies *only* on far-IR fine structure lines.
- We recover a mass-metallicity relationship in agreement with SDSS work (independent check on the method).
- Only possible because FIFI-LS can get \([\text{O III}] 52\mu m\), unlike PACS.

See also T. Jones + 2020, arXiv:2006.02447 for a method using \([\text{O III}] 52\mu m\) with optical H-alpha or H-beta.
Tracking the dispersal of metals

- ~90% of all metals produced by stellar evolution don’t remain in the galaxies where they were produced.
- The get transported into the circumgalactic medium, primarily by metal-enriched galactic outflows.

**Problem:** Starbursts that drive these outflows are in heavily obscured regions.

**Solution:** Use our new far-IR metallicity diagnostics on spatially-resolved scales!
Tracking the dispersal of metals

- Are galactic winds really metal-enriched compared to their host galaxies?
- Combine new and archival FIFI-LS data to answer fundamental questions about the cycle of metals in and out of galaxies
- SPICA/Origins will do this across cosmic time

Preliminary Analysis — M82 [N III] 57um
Disk booming, [N III] detected out to ~300pc from disk!
“What the high-redshift community needs”
(a biased view)

- Sensitivity will always be key
  - Even ‘small’ ~2x gains let us access a more diverse and more distant set of (still-nearby) analogs — HIRMES-like sensitivity is very powerful
  - True far-IR high-z spectroscopy will require SPICA/Origins (~10x PACS sensitivity)

- Improved far-IR spectral resolution would be great
  - Enables dynamics / velocity-resolved observations. Need some middle-ground between FIFI±LS and upGREAT — HIRMES-like resolution supports many cases

- Need to encourage the community to be creative
  - “How can SOFIA make progress in my science area?” is a much harder question than “How can I make progress in my science area?”
  - High-z science is not a core strength of SOFIA. It is non-trivial to develop science programs that can compellingly address high-z science cases with SOFIA. Knowing that, how can we develop intuition and support creativity in the high-z community?
Conclusions

Large [OIII]/[CII] ratios at reionization can be found in the local universe. Possibly the result of very hard ionizing spectra.

- SOFIA can make valuable contributions to high-redshift science!
- Requires community effort and creativity to make the most of it

We now have a far-IR only metallicity indicator that can be used in dust-obscured systems. We can use this to trace metal enrichment on large scales.