Metals: Another (Important) Mess?

Alice Shapley (UCLA)
Collaborators: Xin Liu, Alison Coil, Jarle Brinchmann, Chung-Pei Ma, Dawn Erb, Max Pettini, Chuck Steidel, Kevin Hainline
Overview and Motivation

• Importance of galaxy metallicities
• Methods for estimating galaxy metallicities
• Metals at high z (z~1-2): M-Z relation and emission-line ratios
• Causes of empirical offsets: ISM physical conditions
• Implications: M-Z evolution, feedback, IMF
Galaxy Metallicities

- Measured from HII regions and stars in star-forming galaxies (or cool ISM in DLAs), stars in early-types
- Gas phase oxygen abundance in star-forming galaxies
- Fundamental metric of galaxy formation process, reflects gas reprocessed by stars, metals returned to the ISM by SNe explosions
- Galaxies display universal correlations among Luminosity (L), Stellar mass (M), and metallicity (Z)
- Departures from closed-box expectations can reveal evidence for outflow/inflow, i.e. feedback
- Closed box:

\[ Z = y \times \ln \left( \frac{1}{\mu} \right) \]

\( Z = \text{metallicity}, y = \text{yield}, \mu = \text{gas fraction}=\frac{M_{\text{gas}}}{M_{\text{gas}} + M_{\ast}} \)
Feedback: Local Starbursts

- M82: Nearby starburst galaxy
- Red is $\text{H}\alpha$ emission from ionized gas above the plane of the galaxy.
- Outflow speed: $>500$ km/s.
- Outflows observed when $\Sigma_{\text{SFR}} > 0.1M_\odot/\text{yr/kpc}^2$ (Heckman et al. 2002).
- Ubiquitous in well-studied SF gals at high redshift.
- Crucial component of galaxy formation models?
M-Z Relation at z~0

• >50,000 local emission line measurements (2dF, Sloan), measure instantaneous O/H abundance in HII regions.

• M-Z possibly more fundamental than more traditional L-Z.

• Closed box model relates gas fraction and metallicity, according to the “effective” yield: $y_{\text{eff}} = Z/\ln(1/\mu)$

• SDSS sample revealed lower effective yield in lower mass galaxies.

• Importance of feedback (i.e. outflows)? But, evidence that $y_{\text{eff}}$ is high for some low-mass gals (Lee et al. 2006).

(Tremonti et al. 2004)
M-Z Relation at $z \sim 0$

- M-Z also estimated for luminosity-weighted stellar abundances (Bruzual and Charlot models used to interpret stellar absorption features)

- Stellar and gas-phase metallicity correlated, but with a lot of scatter

- M-Z relation for early-type galaxies demonstrated to form the basis of the observed color-magnitude and Mg-$\sigma$ relations

(Gallazzi et al. 2005)
**M-Z Relation at z~0**

- Models of galaxy formation including chemical abundances must reproduce normalization, slope and scatter of the M-Z relation as a function of redshift.

- *de Lucia* model, 3 versions: “retention” (circles); “ejection” (triangles), “wind” -- different parameterizations of fate of gas.

- *Tassis* et al. (2006) -- increasingly inefficient star formation at low masses

- *Finlator & Dave* (2007) -- more later....
Direct Abundance Determination

Use $[\text{OIII}] 4363/(5007,4959)$ to get $T_e$, $[\text{SII}]$ to get $n_e$.

Problem: 4363 weak, even in local low-$Z$ gals; star-forming gals are not very metal-poor--NO HOPE at high redshift (but see Hoyos et al. 2005).

Caveat: Temperature fluctuations.

$Z = 1/25 Z_{\text{sun}}$
Indirect: Bright Lines ($R_{23}$)

- High-Z branch: $R_{23}$ decreases as $Z$ increases
- Low-Z branch: $R_{23}$ decreases as $Z$ decreases
- Uncertainty in which branch $R_{23}$ corresponds to
- Systematic differences from direct method, $\sim$0.3 dex at high-Z end

(Kobulnicky et al. 1999)
Indirect: Bright Lines (N2)

- relationship between [NII]/Hα and O/H
- N is mixture of primary and secondary origin
- age, ionization, N/O effects, integ. spectra, DIG, AGN

(N2 = log([NII] 6584/Hα))

\[ 12 + \log(O/H) = 8.9 + 0.57 \times N2 \]

\( \sigma \approx 0.18 \), factor of 2.5 in O/H

(Pettini & Pagel 2004)
Indirect: Bright Lines (O3N2)

- at O/H greater than 0.25 solar O3N2 index is useful
- N2 increases as O3 decreases, so very sensitive to O/H

\[
O3N2 = \log\left(\frac{[[\text{OIII}]/H\beta]}{[[\text{NII}]/H\alpha]}\right)
\]

\[
12 + \log(O/H) = 8.73 - 0.32 \times O3N2
\]

\[\sigma \approx 0.14\]

(Pettini & Pagel 2004)
A Truly Scary Plot

- Different calibrations for the same 27000 SDSS DR4 emission-line galaxies.

- Choice of calibration has significant effect on slope, y-intercept, turnover of M-Z relation!!

- Relative metallicities better-constrained than absolute metallicities.

(Kewley & Ellison 2008)
Extragalactic Observations: Ensembles of HII regions

- Rather than individual HII regions, for galaxies at large distances, we obtain integrated emission-line spectra. Represent averages of ensemble of HII regions.

(Yang & Hester, HST/WFPC2)

(Tremonti et al. 2004)

(Erb et al. 2003)
Rest-frame Optical Spectra

Low redshift

- Emission-line set: [OII], Hβ, [OIII], Hα, [NII], [SII]

- At $z > 1.4$, [OII] moves past 9000Å

SDSS galaxy at $z=0.09$
Near-IR spectroscopy at $z \sim 2$

- $z \sim 2$ ideal for measuring several nebular lines in JHK bands
- Instruments: Keck/NIRSPEC and OSIRIS, VLT/ISAAC & SINFONI, Gemini/GNIRS
- Samples: UV-selected, near-IR selected, submm galaxies
• New sample of 87 star-forming galaxies at \( z \sim 2 \) with both \( M_\star \) and \([\text{NII}]/H\alpha\) (gas phase O/H) measurements; divide into 6 bins of \( M_\star \)

• Clear increase in \([\text{NII}]/H\alpha\) with increasing \( M_\star \) \( \rightarrow \) M-Z at \( z \sim 2 \)!!

• Estimate gas fractions from \( H\alpha \) SFR, determine how \( Z \) changes with \( \mu \)

• Shallow increase in \( Z \) with decrease of gas fraction, may indicate outflow from galaxies over the whole range in stellar masses, not just less massive ones!

(Erb et al. 2006a)
Among $K<20$ galaxies (brightest 10%), [SII] line ratio indicates high electron density. Inferred electron density is $\sim 1000$ cm$^{-3}$, this is higher than in local HII regions used to calibrate N2 vs. O/H relationship (Pettini et al. 2005).
z~2 Physical Conditions

- Well-defined sequence in [OIII]/Hβ vs. [NII]/Hα in local galaxies (SDSS) (star-formation vs. AGN)
- Four z~2 star-forming galaxies with O3 vs. N2 measurements are offset from this locus
- $n_e$, ionization parameter, ionizing spectrum (IMF, star-formation history)
- NB: $<\text{SFR}> \sim 30 \, M_\odot/yr$

(Erb et al. 2006a)
$z \sim 2$ Physical Conditions

- Cosmic Horseshoe ($z=2.38$)

- Clone ($z=2.00$)

(Hainline et al. 2009)

- Offsets also observed
- $n_e \sim 1000$ cm$^{-3}$
Near-IR spectroscopy at $z \sim 1-1.5$

- At $z \sim 1.3-1.4$, [NII]/H$\alpha$ in H-band, [OIII]/H$\beta$ in J-band
- At $z \sim 1$, [NII]/H$\alpha$ in J-band, [OIII]/H$\beta$ in NIRSPEC1 band
Near-IR spectroscopy at z~1-1.5

- DEEP2 redshift survey (University of California, Davis/Faber)
- 3 sq. degrees, 4 fields
- >40,000 redshifts, mostly at z=0.7-1.5, based on BRI selection criteria, down to $R_{AB}=24.1$
- Study properties and clustering of galaxies at z~1
- All DEEP2 star-forming galaxies have [OII] measurements
- Small sample (N=20) w/ Keck/NIRSPEC near-IR spectroscopy

(from Jeff Newman)
Near-IR spectroscopy at z~1-1.5

• Sample Keck/NIRSPEC near-IR spectra.

• At z~1, [OIII]/Hβ at ~1 µm, Hα/[NII] at ~1.3 µm. At z~1.4, [OIII]/Hβ at ~1.2 µm, Hα/[NII] at ~1.6 µm.

• <SFR>~10 M☉/yr

(z~1.4, from Liu et al. 2007)
• Well-defined sequence in [OIII]/Hβ vs. [NII]/Hα in local galaxies (SDSS) (star-formation vs. AGN)

• z~1-1.5 star-forming galaxies are offset from this locus

• Not all as extreme as z~2 sample, but still significantly offset on average. z~1.4 more offset than z~1 sample

(Liu et al. 2007)
What causes the offset?

- This offset in emission-line diagnostic ratios may have important implications.
  
  - First, as an indication of different physical conditions in HII regions at high z.
  
  - Second, as a source of systematic bias when using strong-line metallicity indicators that assume high-z galaxies are similar to low-z HII regions.
  
  - *Problem: very limited info at high z.*

(Liu et al. 2007, Erb et al. 2006a)
What causes the offset?

- Clues from SDSS:
  - Almost no objects in region between Kauffmann et al. (2003, dashed) & Kewley et al. (2001, dotted) curves. This is where most extreme offset high-z objects are.
  - But “almost no” still means ~100 for SDSS, DR4.

- We examine these offset objects, as possible analogs for high-z galaxies. Some show evidence for AGN (blue). Others don’t (red).

- Compare with “typical” SDSS galaxies with similar stellar mass (control sample).

(Liu et al. 2007)
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(Liu et al. 2007)
What causes the offset?

• Clues from SDSS:

  → Emission-line properties: strong-line metallicity indicators, O$_{32}$, n$_{e}$, EW(H$\alpha$)

  → Stellar population parameters (D$_{n}$(4000), H$\delta_{A}$, SFR/M$_{\star}$, G-R)

  → Structural parameters (concentration, size)

  → Environment (# of neighbors, bins from Kauffmann et al. 2004)

(Liu et al. 2007)
Properties of SDSS Offset Objects: Summary

- SDSS offset objects more compact, higher $\Sigma_{\text{SFR}}$, $\Sigma_*$, ionization parameter, $n_e$, $T_e$ -> HII region pressure than typical SDSS galaxies with similar stellar mass.

- Assuming pressure equilibrium between HII regions and ambient ISM, implies that the ISM pressure is higher than average in offset objects.

- This naturally follows if they have higher SFR surface densities (which they appear to have) (Thompson et al. 2005).

- Also: in simple model of Strömgren sphere, ionization parameter increases with increasing $n_e$ (as observed in integrated galaxy spectra).

(Liu et al. 2007)
Properties of SDSS Offset Objects: Summary

- On independent grounds, higher SFR surface density (higher SFR, smaller sizes), ISM pressure, $n_e$, ionization parameter, may be quite common at high redshift.

- HII region physical conditions may be systematically different for samples at $z>1$, compared with $z\sim 0$ samples used to calibrate e.g., [NII]/H$\alpha$. vs. O/H.

(Ferguson et al. 2004)
Future Observations

- More robust determinations of O/H will come from rest-frame optical spectra with the full set of strong lines.
- With [SII], we will estimate $n_e$. With [OII] and [OIII] we will measure ionization parameter.
- Need a statistical sample (Keck/MOSFIRE) !!!
Feedback/outflows

- Feedback = Large-scale outflows of mass, metals, energy, momentum from galaxies
- Enrichment and heating of IGM
- Enrichment and thermodynamics in ICM
- Problems in models of galaxy formation: faint-end LF slope, overcooling and angular momentum, origin of M-Z relation
- Both star-formation and AGN activity may contribute
- Proper understanding of feedback considered to be crucial to full theory of the evolution of both galaxies and the IGM
Simulations of Feedback

- Prescription: given typical resolution of cosmological simulations, need to parameterize wind outflow speed and mass-loading factor (outflow rate/SFR) to galaxy of given $v_c$.
- Base parameterizations on observations.
- One recent example: simulations by Dave, Oppenheimer, Finlator. Use $z\sim0$ observations from Martin (2005) to represent galaxies and IGM at $z\sim2-5$. Use $z\sim2$ M-Z observations as a constraint on feedback models.
Simulations of Feedback

- Finlator & Dave (2007) use momentum-driven prescription, compare with $z \sim 2$ M-Z relation (Erb et al. 2006a)

- Models with no winds, or constant $v_w$ don’t provide a good match to the data

- Slope and amplitude well-matched with best model, “momentum driven” wind. Is this meaningful given uncertainties in [NII]/H$\alpha$\rightarrow O/H?

- Maybe systematic bias at the level of 0.2-0.3 dex (high or low), due to systematic differences in HII region conditions, and application of locally-calibrated indicators. Affects slope and amplitude.
The IMF

• Form of IMF: crucial assumption in converting observations of light into inferences about stellar mass. Typically Salpeter or Chabrier assumed.

• Super star clusters in M82 may show evidence for top heavy IMF (McCready et al. 2003), same with clusters in Galactic center (Stolte et al. 2007).

• Durham models of submm galaxies include top-heavy IMF for burst mode (Baugh et al. would overproduce $z=0$ stellar mass density.

• As discussed this week, multiple recent independent lines of argument that IMF may have been different in the past, but IMF evolution is not too well motivated.

• Evidence that HII regions at high redshift have systematically different properties from those of local SF regions. If we can figure out how IMF depends on physical properties in ISM, then there might be a real physical basis for IMF variations at high $z$. 

The IMF

• van Dokkum (2008) shows evidence that evolution in M/L\(_B\) and U-V colors of massive cluster galaxies from z~0-1 is inconsistent with a standard Salpeter IMF near 1 M\(_\odot\)

• For rate of M/L\(_B\) evolution, color evolution is too slow. Cannot get consistent formation time based on M/L\(_B\) and U-V evolution, unless IMF is “top heavy” or “bottom light”

• Explains in terms of higher characteristic mass, at which IMF turns over at lower-mass end. Best-fit is for bottom-light IMF and z\(_{\text{form}}\) > 4

• Uses model of T\(_{\text{CMB}}\) evolution to explain higher minimum mass (Larson 1998)
The IMF

- Dave (2007) explores evolution of M*-SFR relation between z=0-2
- Finds that evolution (blue line) is much more rapid than semi-analytic models and hydrodynamic simulations predict out to z=2
- In the sense that, at z=2, galaxies M*/SFR is significantly smaller than Hubble time, inconsistent with small scatter in M*-SFR relation, and with the fact that majority of galaxies are included in sample.
- Also resolved if IMF is “bottom-light”, more high-mass relative to low-mass stars, i.e. SFR overestimated relative to M*
- Use model of $M_{\text{char}}$ evolving as $(1+z)^2$, but physical motivation is not clear. We have found evidence for systematic ISM differences, may provide ingredients for altered IMF.
Summary

• Rest-frame optical emission lines: in principle, a powerful probe of both the metallicities and physical conditions in distant galaxies.

• Evidence that these conditions were systematically different in star-forming galaxies at $z>1$: higher $n_e$, $T_e$, ISM pressure, ionization parameter, $\Sigma_{SFR}$. Given that empirical O/H indicators are only calibrated for local HII regions quiescently forming stars, O/H may be systematically over- or under-estimated at high-$z$. Additional complication to major metallicity calibration problem.

• Important related implications for the process of star formation, attempts to infer evolution in the M-Z relation, and constrain models of star-formation feedback.

• What is needed? More robust local calibration, understanding of how calibration varies with physical conditions, and accuracy required to distinguish among different feedback models. Molecular gas measurements. Understanding of local IMF in terms of measurable quantities at high $z$. 