Gas Outflows and Inflows in z < 1.5 Galaxies:

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Origin of Low-Ionization Gas in Winds?

MacLow et al. 89; Fujita+09
DeYoung & Heckman 2004
Heckman et al. 2000
Cooper et al. 2009
Demographics of Low-Ionization Outflows

- **Na I 5890,96 Absorption**
  - Sato+2009 measured Doppler shifts in 431 galaxies at 0.1 < z < 0.6
    - Found gas inflows and identified hosts as post-starburst systems
  - Chen+2011 made composite spectra of SDSS/DR7 galaxies
    - Outflows prevalent in massive galaxies with high SFR, A_V, SFRSD, M.

- **Mg II 2796, 2803 Absorption**
  - Dominate ion of Mg over wide range of physical conditions
  - Accessible in optical over 0.3 < z < 2.5
  - Intervening systems constrain spatial extent of outflows (*Bouche*+2006,2008; *Menard* 2009; *Kacprzak* +2008,2010; *Chen*+2010; *Nestor*+2010; *Bordoloi*+2011)
    - Interpretation of absorption trough complicated by emission filling

- **Near-UV Fe II Absorption (5-7 transitions)**
  - Cosmic abundance of Fe is similar to Mg
  - First and second ionization potentials of Fe are similar those of Mg
  - Some lines fluoresce strongly leaving ‘clean’ absorption troughs

- **Emission**
  - Scattered Mg II Emission
  - Optical emission-line radiation from shocked gas
Mg II 2796, 2803 Absorption in Galaxy Spectra

- Outflows are common
- Highest velocity gas is optically thick
- Mg II emission fills in absorption-line trough near v=0

See Also: Tremonti+2007; Rubin+2010a,b; Coil+2011; Prochaska+2011

Weiner+2009 -- Composite of 1496 z~1.4 Star-forming Galaxies

CLM & Bouche 2009 -- Velocity-dependent covering fraction
Outflow/Inflow Survey at $0.6 < z < 1.4$

Collaborators: Alice Shapley & Kathy Kornei (UCLA); Alison Coil (UCSD); Anna Pancoast (UCSB)

- Keck/LRISb spectra of 208 DEEP2 galaxies cover NUV (+FUV)
- Spectral Resolution ~ 120 to 185 km/s
Near-UV Spectra of z~1 Galaxies

Resonance Lines

Fe II

2344
2374
2382
2587
2600

Mg II

2796
2803

FeII* Fluorescence

2344
2374
2382
2587
2600

Fluorescence

2365
2396
2612
2626

z~1 Composite Spectrum

32010773 0.803921

22029066→0.785235
Origin of MgII Emission: Properties Inconsistent with HII Regions

- Spatial extent is at least 3.4” or 27 kpc
- Gas kinematics show the emission is not from the galactic disk.

MgII Emission

[OII] Emission
Physical Properties from Scattered Emission

- Optical Depth of Scattered Line (e.g., Murray+1999)
  \[ \tau = k \rho v_{\text{th}} |dv/dr|^{-1} \]

- Mg II emission \( r(\tau \sim 1) = 10 \text{ kpc} \)

- \( n(\text{Mg II}) \sim 5.6 \times 10^{-9} \text{ cm}^{-3} \) at \( b = 10 \text{ kpc} \)

- \( n(\text{H}) \sim 1.5 \times 10^{-4} \chi^{-1} (Z/Z_0)^{-1} \text{ cm}^{-3} \) at \( b = 10 \text{ kpc} \)

- Small Ionization correction (Murray + 2007)

- Mass loss rate (in low-ionization gas)
  \[ \frac{dM}{dt} = \rho(r_s) \Omega(r_s) r_s^2 v(r_s) \]
  \[ \sim 5 M_\odot/\text{yr} \sim \text{SFR} \]

See Also: Rubin+2010; Prochaska+2011
Properties of Mg II Emitters

- Show relatively bluer Fe II absorption
- Favor less reddened galaxies
- Stronger in lower mass galaxies

- Associated with outflow
- Scattered photons destroyed by dust
- Scattered halo fits within slit

Quider+2011; Martin+2011; Kornei+2011 (all in preparation)
Emission Filling

1. Curve-of-Growth
   - MgII $W(2308) > W(2796)$
   - FeII $W(2374) > W(2382)$

   $\log N_{\text{FeII}} (\text{cm}^{-2}) = 15.8, \ b = 70 \ \text{km/s}$

2. Pushes absorption bluer

3. Solution: Measure Doppler shifts from the most fluorescent lines, i.e., Fell 2374, 2587, 2344

CLM, Shapley, Kornei, Coil, Pancoast
Joint Fits to Five Clean FeII Lines
Which Galaxies Present Net Flows?

- Detection significance depends on SNR and velocity
- Detect (1-sigma) outflows in 51%
- 11 certain (3-sigma) inflows out of 208 ==> rare
Which Galaxies Have Outflows?
Which Galaxies Have Outflows?
Interstellar Absorption Reduces Doppler Shift

PRIOR

• Two velocity components
• Systemic component at $v=0$ has a Doppler parameter estimated from [OII] linewidth.
• Fit the maximum ISM absorption ($\tau$), and then fit the residual with a Doppler-shifted component.

RESULT

• Equivalent width of the “interstellar” absorption increases with $M_*$
• Attributed to larger line widths in more massive galaxies, although there may also be more ISM

CLM,+2011; Rubin+2011
Outflow Velocity vs. Stellar Mass

- 208 galaxies
  - 37 no absorption
  - 85 require outflow =>

- **Median velocity** is roughly constant with stellar mass

- Most (not all) of the rest consistent with low-ionization gas at v=0.

- Note that **Weiner+09 points** are terminal velocities, and the ISM has been subtracted out.
Outflow Velocities Increase with Surface Density of Young Stars

Outflow Velocity (km/s) vs. Star Formation Rate Surface Density (M☉ yr⁻¹ kpc⁻²)

Kathy Kornei
Poster 2.12
Does Low-Ionization Gas Escape?

Velocity dispersion from [OII] linewidth

CLM, Shapley, Kornei, Coil, Pancoast
Gas Inflows Detected

Systemic velocity defined by nebular emission.

Stellar absorption consistent with that redshift.
Gas Inflows Detected

Fe II Series Fitting
1-component:
\( v_{\text{FeII}} = 72 \text{ (19) km/s} \)
\( b = 122 \text{ (19) km/s} \)
2-components:
\( b_{\text{SYS}} = 109 \text{ km/s} \)
\( v_{\text{DOP}} = 191 \text{ (45) km/s} \)
\( b_{\text{DOP}} = 85 \text{ km/s} \)

MgII also redshifted
Another Gas Inflow

Fe II Series Fitting

1-component:
- \( v_{\text{Fe II}} = 61 \pm 11 \) km/s
- \( b = 95 \pm 9 \) km/s

2-components:
- \( b_{\text{SYS}} = 151 \) km/s
- \( v_{\text{DOP}} = 72 \pm 18 \) km/s
- \( b_{\text{DOP}} = 49 \pm 1 \) km/s

MgII also redshifted

Emission
Filling?
Do We Find Gas Inflow? Yes.

- Properties at \( z \sim 1.2 \)
  - \( V \sim 200 \text{ km/s} \) up to 400 km/s
  - \( \log N(\text{Fe II}) = 13.6 - 14.8 \)
  - \( N(\text{H}) \sim 1.3 - 20 \times 10^{18} \text{ cm}^{-2} (Z/Z_0)^{-1} \)
- Is it cosmological inflow?
- Not necessarily, but possibly…
  - Predict low \( Z/Z_0 < 10^{-2} \) (Kimm+2011; Fumagalli+2011), but…
  - Recycling could enrich infalling gas to 0.5 \( Z_0 \) by \( z=1 \) (Dave et al)
  - Predict velocity offset of 50 to 200 km/s (Stewart+2011)
- Not associated with post-starburst activity or mergers

Which Galaxies Have Inflows?
Which Galaxies Have Inflows?
Emission-Line Mapping of Starbursts

Soto + 2011a,b
Kinematics of Ionized Gas in z~0.1 Starbursts

Kurt Soto
+2011a,b

- Resolution \( \Delta v=60 \text{ km/s} \) shows asymmetric lines. Fit two velocity components.

- Look for relation between kinematics and excitation mechanism
Broad Emission
Excited by Shocks

- Detect broad emission in forbidden lines as well as recombination lines.
- Line ratios indicate shocks or AGN.
- Spatial extent of 3-5 kpc favors shocks.

Kurt Soto et al. 2011a,b
Local ULIRGs: High Velocity Dispersion Gas is Excited by Shocks

Kurt Soto + 2011a,b
Relation of Outflow Emission and Absorption

300 km/s
300 km/s
400 km/s
-430 km/s
-466 km/s
-392 km/s
-358 km/s

11 kpc


Soto + 2011a,b
Local Starbursts Mass-Loss Rates

- Implied mass of warm, ionized gas depends on volume filling factor, $f \sim 0.01$
- Timescale $\sim R / v$
- $\eta = \frac{dM/dt}{SFR}$
- Compare to mass carried by hot phase and by neutral gas

Kurt Soto + 2011a,b
Broad Component Detected in Integrated Spectra!

- Requires R~6000 and good SNR
- Requires coverage of Ha, [NII], [OI], [OIII], Hb
- Surveys for outflows across cosmic time with JWST
SUMMARY: Low-Ionization Out/Inflows

- Outflows are common (not ubiquitous) in galaxies at z~1
- Stronger ISM component in higher mass galaxies
- Outflow speed increases with M* but more strongly with SFRSD
- Extent of MgII emission and v of absorption indicate dM/dt ~ SFR
- Inflows found in ~5% percent of z~1 galaxies may be a mixture of recycled metals and cold streams.
- Need high-resolution hydro simulations of winds that address (1) relation of low-ionization outflow to hot wind, and (2) model absorption line trough shape
- Emission lines in R~6000 spectra offer another approach