AGN Feedback: The Cold Gas Phase

S. Veilleux (U. Maryland, Joint Space-Science Institute)

(based on Tombesi, Meléndez, SV, et al. 2015, Nature)
Why Focus on the Cold Gas and Dust?

- Largely unexplored, until “recently” (≥ 2005 ARAA)
- Cold gas + dust = raw material for new stars
- Often is the energetically dominant phase of galactic winds
- Trends with AGN luminosities suggest that we are finally seeing quasar feedback in action.
NEUTRAL-GAS OUTFLOWS IN (U)LIRGS *(CIRCA 2010)*

*(Heckman+00; Rupke+02,05abc; Martin 05,06; Chen+10; Krug+10...)*

- **Detection rate:**
  - ~25% when \( SFR \sim 10 \, M_{\odot} \, \text{yr}^{-1} \)
  - ~75% when \( SFR > 100 \, M_{\odot} \, \text{yr}^{-1} \)

  *(Rupke, SV, & Sanders 2005a, b)*

- \( V_{out} \sim SFR^{0.2-0.3} \) (also \( \Sigma_{SFR} \))
  - \( p \)-driven winds: \( \sim SFR^{0.25} \) (e.g., Murray+05)

- \( V_{out} \sim V_{circ}^{0.8\pm0.2} \) (also \( V_{escape} \) and \( M^* \))

- \( \eta = (dM/dt) / SFR \sim 0.5 – 5 \)
  - \( \sim \sigma^{-1} ??? \) (e.g., Murray+05; Oppenheimer+10)

- \( f_{esc} \sim 5–20\% \) (if no halo drag)
  - pollute CGM (e.g., Steidel+10; Tumlinson+11; Stocke+13; Werk+13, 14...)

---

**Graphs:**

- Detection % = Opening Angle
- Changing geometry
- 1400 km/s
- Outflow!
IFS of neutral-gas outflows …

\[ \frac{dM}{dt} \geq (0.5 - 5.0) \text{ SFR} \]

\[ L_{\text{mech}} \geq \frac{dE_{\text{SB}}}{dt} \sim (0.2 - \text{few})\% L_{\text{BOL}}(\text{AGN}) \]

\[ \frac{dp}{dt} \geq 5 \frac{L_{\text{SB}}}{c} \text{ but } \geq 2 \frac{L_{\text{IR}}}{c} \]

\[ \rightarrow \text{AGN driving is important} \]
Sizes of Outflows from Resonant Na I Emission

(Rupke & SV 2015)

Type-2 Quasar / ULIRG F05189-2524

- Complementary to Na I D absorption
  (no need for background galaxy emission)
- Provide new constraints on sizes of local winds
  (cf. 100+ kpc Ly α halos; e.g., Steidel+ 2011; Matsuda+ 2012; Hayes+ 2013…)

Complementary to Na I D absorption
(no need for background galaxy emission)
Provide new constraints on sizes of local winds
(cf. 100+ kpc Ly α halos; e.g., Steidel+ 2011; Matsuda+ 2012; Hayes+ 2013…)
Massive Molecular Outflows in (U)LIRGs

(Fischer+2010; Sturm+ 2011; Gonzalez-Alfonso+2012ab; SV, Melendez+2013…)

- Herschel/PACS spectra: OH 65 / 79 / 119 um spectra
- P-Cygni profiles!
- Outflow: $|V_{out}|$ in excess of 1000 km s$^{-1}$
Massive Molecular Winds in 43 (U)LIRGs

\(\eta\) velocities
- \(\langle v_{50}\rangle\) (abs) \(\sim -200\) km s\(^{-1}\), \(\langle v_{84}\rangle\) (abs) \(\sim -500\) km s\(^{-1}\)
- \(\langle v_{\text{max}}\rangle\) (abs) \(\sim -925\) km s\(^{-1}\)

- Winds with \(v_{50}\) (abs) \(< -50\) km s\(^{-1}\) are detected in 70% of the 37 objects with OH 119 \(\mu\)m detection
  - \(\Rightarrow\) Wide-angle geometry (\(\sim 145^\circ\))

- Infall with \(v_{50}\) (abs) \(> +50\) km s\(^{-1}\) is detected in only 4 objects
  - \(\Rightarrow\) Rare or disky / filamentary geometry?

- \(|V_{\text{out}}|\) increases with \(L_{\text{AGN}}\) but not \(M_*\) or SFR (over \(\sim 1\) dex)

- \(\frac{dM}{dt} \sim 100 - 1000 \ M_{\text{sun}} \ \text{yr}^{-1} \sim (0.3 - 20) \ SFR\) (7 objects)

- \(\frac{dp}{dt} \sim (1 - 30) \ \frac{L_{\text{AGN}}}{c}\) (7 objects)

- \(\tau_{\text{depletion}} \sim \frac{M_{\text{gas}}}{(dM/dt)} \sim 10^7 - 10^8\ \text{yrs}\) (7 objects)
  - \(\Rightarrow\) remove “fuel” for new stars \(\Rightarrow\) quench star formation?
Spectral Imaging of Molecular Winds in ULIRGs

(H$_2$ 2.12 µm as a tracer of the cold molecular gas)

(Rupke & SV 2013b)

* Instrument: Keck OSIRIS IFU + AO + Laser (resolution ~ 0.09" ~ 100 pc)

* Results: v(H$_2$) ~ v(OH); H$_2$ wind size ~ 400 pc; H$_2$ opening angle = 100 ± 10 deg → consistent with Sturm+11

** Buried QSO: F08572+3915 NW **

T(H$_2$ wind) = 2400 K > T(disk) = 1500 K
Summary & TMT

Summary: Local (U)LIRGs and AGN
- Statistics: ~70% of local ULIRGs have OH winds (Θ ~145°) <10% among BAT AGN with lower L_{AGN}
- Kinematic trend with L_{AGN} suggests that the AGN is playing a dominant role in local galaxies when L_{AGN} ≥ 10^{11.8 ± 0.3} L_{sun}
- Energetics: dM/dt up to ~1000 M_{sun} yr^{-1}; L_{mech} up to ~10^{11} erg s^{-1} \ E_{mech} up to a few x 10^{56} ergs; \ dp/dt = (1 − 30) L_{AGN}/c  [ALMA]
- Na I D line emission \ → \ improved constraints on wind sizes / energetics

TMT = “Near-IR ALMA” [IRIS – IFU: ~0.8 – 2.5 μm]
- Census from z ~ 0.4 to ~ 3 (Na I D) → 7+ (UV low-ionization metal lines, H_{2} Lyman-Werner band, CO A-X bandhead)
- Θ ~ 0.01” and FOV ~ 1” @ z ~ 0.4 → 0.05 and 5 kpc
  @ z ~ 3.0 → 0.08 and 8 kpc
  @ z ~ 7.0 → 0.05 and 5 kpc