SUPERWINDS FROM MASSIVE STAR-FORMING CLUMPS AT Z~2

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see Genzel et al. 2011:
arXiv: 1011.5360
Newman et al. in prep.
Understanding high-z SF

Forster Schreiber+11
BPT diagram with high-z galaxies

Kauffmann et al. 2003, Shapley et al. 2005, Erb et al. 2006

Starbursts

AGN

HII

Increase in SFR, sSFR, U and $n_e$ (Brinchmann+08 and Liu+08)

$\frac{[OIII]}{H\beta}$

$\frac{[NII]}{H\alpha}$
Observations

• SINFONI/VLT IFU K-band spectroscopy with AO
  – 0.2” FWHM ~ 1.7 kpc
  – $T_{\text{int}} = 2$-18h
  – 0.05”/px

• J- and H-band with natural seeing
  – 0.6” FWHM ~ 5 kpc
  – $T_{\text{int}} = 2$h
  – 0.05”/px

• Selection:
  – ZC, D3a: rest-frame optically selected, with BzK color
  – BX: rest-frame UV selected, BX color

• H$_\alpha$-bright, ~ 1 kpc clumps

• SFR and $\Sigma_{\text{gas}}$ from $L_{\text{H}\alpha}$
SFR$_{\text{H} \alpha} = 290 \ M_\odot/\text{yr}$

$M_* = 4.2 \times 10^{10} \ M_\odot$

$f_{\text{gas}} = 0.75$

$v/\sigma = 3.5$

$R_{\text{FWHM}} = 6.5 \ \text{kpc}$

**Mancini+11, Wuyts+11**
Superwinds

Marble 05

NGC 3079.

HST + CXO. Veilleux+05

At High-z:
- Winds are ubiquitous
- Not spatially resolved
Broad Hα emission from winds

Clump A

Wind B

Clump C
Outflow rates for clumps

- Outflow of gas into solid angle $\Omega$
  - case B photoionization with $T = 10^4$ K
    \[
    L_{H\alpha,br} \approx \gamma_{H\alpha} n_e n_p dV \\
    M_{H^+} \approx \mu n_p dV \approx \mu L_{H\alpha} / \gamma_{H\alpha} n_e \\
    \dot{M}_{H^+} \approx M_{H^+} v_{\text{wind}} / R_{\text{out}}
    \]

- Warm ionized component only, neglecting hot ionized gas (x-rays), molecular and atomic gas

- Outflow rates for individual clumps:
  
  \[10 - 200 \, M_\odot/\text{yr} \sim 1-8 \times \text{SFR}\]

  \[\text{vs. } \dot{M}_{\text{out}} \geq \text{SFR} \, (\text{Steidel+10, Pettini+00, Weiner+09})\]
Can clumps inspiral to form bulge?

• $t_{\text{expulsion}} \sim f_{\text{corr}} * M_{\text{clump,mol}} / \dot{M}_{\text{out}} \sim 150-1500$ Myr

• $t_{\text{migration}} \sim (v_c/\sigma)^2 t_{\text{dyn}} < 0.5$ Gyr (Noguchi 99, Immeli+04)

Simulations: (Elmegreen+09, Ceverino+08) find long lived clumps, (Oppenheimer and Dave 06 and S. Genel+10) find clumps disrupted in 50-100 Myr

Observations: Forster Schreiber+11, Wuyts+09, Elmegreen+09
Shocks in (U)LIRG winds

- Caused by AGN, tidal torques, SF
- Shocked regions characterized by $\frac{[\text{NII}]}{\text{H}\alpha} > 0.5$ & $\frac{[\text{SII}]}{\text{H}\alpha} > 0.3$

Monreal-Ibero+10
ZC406690 line maps

Log\[H\alpha_{\text{narrow}}\]

Log\[H\alpha_{\text{broad}}\]

log\[\text{NII}\]

[NII/H\alpha]
BPT with SINS/Lucifer

Buschkamp, Kurk et al. in prep
Summary

• SF in z\sim 2 SFGs occurs in \sim 1 kpc clumps outside the center, which are more similar to starbursting regions than normal H\text{II} regions.

• Winds with \Delta v \sim 100s km/s and \dot{M}_{\text{out}} \sim 1-8 \times \text{SFR} originate from clumps.

• Some clumps disrupted by winds \sim 100 \text{ Myr}

• Broad region corresponds to increased \text{[NII]}/\text{H}\alpha and \text{[SII]}/\text{H}\alpha

• Winds may contain shocks, partially contributing to high velocity dispersions
SII – maximizing S/N

Clump A

Clump B+C
Clump Timescale

• SED modeling
  \( t_{cl} \sim 100-300 \) Myr (Elmegreen+09, Maraston+10)

• Metallicity
  \( t_{metal} \sim 300-1000 \) Myr (Erb 08, closed and leaky box)

• EW
  \( t_{cl} \sim 30-800 \) Myr (Forster Schreiber+11)

• Exhaustion timescale
  \( t_{expulsion} \sim f_{corr} * M_{clump,mol}/M_{out} \sim 150-1500 \) Myr

• TS explosion
  \[ R_s = 12.8 \left( \frac{t_{exp}}{10^4} \right)^{2/5} \left( \frac{E_{51}}{n_0} \right)^{1/5} \text{ pc} \]
  \[ E = \dot{M}v_{out}^2 t_{exp} \varepsilon_f \]
  \( t_{TS} \sim 100-400 \) Myr
Outflow model continued...

\[
L_{H\alpha,0} = \gamma_{H\alpha}(T) \int \Omega R^2 n_e(R) n_p(R) dR,
\]

\[
M_{HII,He} = \mu \cdot \int \Omega R^2 n_p dR = \frac{\mu L_{H\alpha,0}}{\gamma_{H\alpha}(T) n_{eff}}, \text{ and}
\]

\[
\dot{M}_{out} = \Omega R^2 \mu n(R) v_{ex} = \zeta \cdot M_{HII,He} \cdot \frac{v_{ex}}{R_{out}}
\]

Genzel et al. 2011, Appendix B

- Model 1 (upper limit): \( n_{avg} \sim R^{-2}, n_{eff} \sim 100 \text{ cm}^{-3}, R_{out} \sim R_{HWHM} \)
- Model 2 (lower limit): \( n_{avg} \) and \( n_{local} \sim R^{-2}, n_{eff} \sim n_{in}(R_{in}) \times R_{in}/R_{out} \),
  \( R_{out} \sim R_{disk} \sim 10 \times R_{in}, n_{in} \sim n(SII), n_{cl\_vir}, n_{KS}, n_{gas\_GMC} \)
- \( \zeta \) (geometrical factor) \( \sim 1 \), constant expansion velocity
- Models vary by x4-5
Ostriker and Shetty (2011) Model

- \( P_{\text{kin}} = \rho_0 \sigma_z^2 \)
- \( P_{\text{weight}} = \pi G \Sigma^2 / 2 \)
- \( P_{\text{turb}} = f_p / 4 \rho_\star / m_\star \Sigma_{\text{SFR}} \)
- \( P_{\text{rad}} = \epsilon^* c_{\text{IR}} \Sigma \Sigma_{\text{SFR}} / 4 \)
- \( v_z = 2.3 \epsilon_{\text{eff}} G \Sigma^2 / \Sigma_{\text{SFR}} \)
ZC406690 Central Mass velocity field