Star Formation Rates & Patterns in HII Regions in the Galaxy & Magellanic Clouds

Rosie Chen (MPIfR-Bonn)

Remy Indebetouw, Maria Messineo, You-Hua Chu, Karl Menten, Erik Muller, Sage-SMC team, GLOSTAR team
Motivation

• Connecting massive star formation
  -- how star formation is regulated? how gas is converted into stars?

• Relation b/w SFR & $\Sigma_{\text{Gas}}$
  -- tight @ kpc scale: Schmidt-Kennicutt law
  -- breaks down @ $\leq 0.3$ kpc (Schruba et al. 2010; Onodera et al. 2010)

  $\Sigma_{\text{SFR}} \sim (\Sigma_{\text{Gas}})^N$, $N=1.0-1.4$

  $\Sigma_{\text{SFR}}$ tracers: UV -- $<\text{SFR}>$ in last 100 Myr (Leitherer et al. 1995)
  H$\alpha$+24$\mu$m -- $<\text{SFR}>$ in last 10 Myr (Calzetti et al. 2007)

  GMC life time: $\sim 10$ or $>30$ Myr (Kawamura et al. 2009; Blitz et al. 2007)
  -- S-K relation $\Rightarrow$ <evolutionary stage> of GMC

Massive YSOs $\Rightarrow$ $<\text{SFR}>\sim 1$Myr, most direct way to connect MSF from GMC to kpc scales
Massive stars $\Rightarrow$ $<\text{SFR}>\sim 10$ Myr, feedback effect

Rosie Chen, MPIfR-Bonn

Lorentz Center, Feb 20, 2013
Resolved low-$Z_\odot$ MSF lab: LMC+SMC+Bridge

- Nearby, known distances $\Rightarrow$ YSOs can be resolved
- Reduced metallicity
  
<table>
<thead>
<tr>
<th></th>
<th>LMC</th>
<th>Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>kpc</td>
<td>50</td>
<td>55</td>
</tr>
<tr>
<td>$Z_\odot$</td>
<td>1/3</td>
<td>1/5-1/8</td>
</tr>
</tbody>
</table>
- Tidal environment
  $\Rightarrow$ Does $Z$ or interaction affect GMC/star formation?
- High sensitivity Spitzer surveys
  SAGE-LMC ($8^\circ \times 8^\circ \sim 7.2 \times 7.2$ kpc$^2$), S$^3$+SAGE-SMC ($10^\circ \times 6^\circ \sim 10 \times 6$ kpc$^2$)
  (Meixner+ 2006; Bolatto+ 2007; Gordon+ 2010)
Resolved low-$Z\odot$ MSF lab: LMC+$SMC+$Bridge

- Nearby, known distances:
- Reduced metallicity
  - LMC
    - kpc: 50
    - $Z\odot$: 1/3
  - Bridge
    - kpc: 55
    - $Z\odot$: 1/5-1/8
- Tidal environment
  - Does $Z$ or interaction affect GMC/star formation?
- High sensitivity Spitzer surveys
  - SAGE-LMC ($8^\circ\times8^\circ\sim7.2\times7.2$ kpc$^2$), $S^3+$SAGE
  - (Meixner+ 2006; Bolatto+ 2007; Gordon+ 2010)
MSF lab @ different environment: The Galaxy

- Nearest typical-size galaxy

- Mini-starbursts @ different environment
  
<table>
<thead>
<tr>
<th></th>
<th>W31</th>
<th>W43</th>
</tr>
</thead>
<tbody>
<tr>
<td>LL_{LYM}</td>
<td>2\times10^{50}</td>
<td>1\times10^{51}</td>
</tr>
<tr>
<td>Env</td>
<td>Inner galaxy</td>
<td>End of bar</td>
</tr>
</tbody>
</table>

- Multi-\lambda surveys of stars & gas:
  
  2MASS/UKIDSS, GLIMPSE+MIPSGAL, ATLASGAL, GRS etc.

- Problems: $A_V > 30$, ambiguity in $D_{kinematic}$
  
  $\Rightarrow R=3000$ SINFONI integral-field NIR H & K spectra
  $\Rightarrow D_{specphot}, V_{lsr} \leftrightarrow D_{trig.-para.}, V_{gas}$ from BeSSeL, ATLASGAL surveys
  
  in GLOSTAR (PI: Menten; a global view of star formation in the Milky Way)
Questions to be addressed

• What are MYSOs in Magellanic Clouds & M★ in Galaxy?  
  YSOs ≠ cores or protostars  
  Can extragalactic MYSOs be reliably identified?  
  What are their physical properties?  
  Can a census of M★ in Galactic HII regions be complete?

• Are massive stars formed in special conditions?  
  Are MYSO properties related to GMC properties?  
  What massive stars are formed @ different Galactic environment?

• What caused the tight correlation in S-K relation?  
  What are the evolutionary status & SFR of GMCs?

• Does MSF proceed in a universal fashion?  
  What is the effect of metallicity or galactic environment on MSF?
Identification of massive YSOs

Step 1:
Select YSO candidates w/ [8.0] vs [4.5]-[8.0] CMD:

[4.5]-[8.0] > 2.0
exclude normal stars & AGBs
(Groenewegen 2006)

[8.0] < 14 - ([4.5]-[8.0])
exclude galaxies (Harvey+ 2006),
low-mass (≤ 4M☉) YSOs

Step 2:
cull out contaminants w/ 1. multi-λ SED (0.35-70 μm)

IRS obs of 280 YSOs in LMC & 5 in Bridge
confirm our method w/ > 95% correct rate
(Seale+ 2009; Indebetouw+ in prep).

Rosie Chen, MPIfR-Bonn

Lorentz Center, Feb 20, 2013
Infer YSO properties using SED fits

- YSO properties inferred by comparing obs SEDs to model grids (Robitaille+ 2007).

- Radiative transfer models w/ dust distribution analogous to Class I/II/III for all masses (Robitaille+ 2006).

Validating SED Fits

- 20 YSOs associated w/ UCHII (Indebetouw+ 2004)
  - 80%: good agreement in $M_*$ from SED fits & ionizing fluxes
  - 20%: deficiency in models, uncertainty in $F_{24\mu m}$, radiation leakage
YSOs mostly found in GMCs in 2 HII complexes (350x450 pc\(^2\), 180x190 pc\(^2\))

YSO mass (M\(\odot\)): 4 - 45

GMCs show a wide range of YSO mass, clustering.
**YO S Properties v.s. GMC Properties**

<table>
<thead>
<tr>
<th></th>
<th>N159-E</th>
<th>N159-W</th>
<th>N159-S</th>
<th>N44-C</th>
<th>N44-S</th>
<th>N44-N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total $M_{YSO}$ ($M_\odot$)</td>
<td>440</td>
<td>1380</td>
<td>200</td>
<td>890</td>
<td>475</td>
<td>310</td>
</tr>
<tr>
<td>$M_{vir}$ ($10^4 M_\odot$)</td>
<td>17</td>
<td>16</td>
<td>36</td>
<td>37</td>
<td>210</td>
<td>...</td>
</tr>
<tr>
<td>$M_{vir}/M_{lum}$</td>
<td>0.8</td>
<td>0.6</td>
<td>0.9</td>
<td>0.8</td>
<td>1.4</td>
<td>...</td>
</tr>
<tr>
<td>$\Delta V$ (km/s)</td>
<td>7.6</td>
<td>5.7</td>
<td>7.7</td>
<td>7.2</td>
<td>15.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>

- $\Sigma M_{YSO}$ anti-correlates weakly w/ $M_{vir}/M_{lum}$ (Indebetouw+ 2008), $\Delta V$ $\Rightarrow$ small $E_{turb}$ $\Rightarrow$ large-volume collapse (Klessen+ 1998)

- $SFE_{YSO} = \Sigma M_{YSO}/M_{cloud} \approx 2 \times 10^{-4} - 9 \times 10^{-3}$
  $\approx 1-25 \times$ Pipe Nebula (Forbrich+ 2009)
YSO Properties in the Bridge

- 26 YSOs identified in the Bridge (in 2.9x1.3 kpc$^2$):
  $M_*: 4 - 10 M_\odot$ v.s. LMC -- $M_*: 4 - 45 M_\odot$

- YSOs sparsely distributed; little clustering of massive YSOs
- Scarce CO coverage; all 7 but 1 cloud has YSOs ⇒ SF starts quickly. 70% YSOs found in $N$(HI) > $8 \times 10^{20}$ cm$^{-2}$.
W31 -- 8 O-type stars: 4 new + 4 reported (Blum+ 2001)
loose cluster: O stars in 40"-diameter circle (~0.7 pc)

W43 -- 1 WN+4 O-type identified: 2 new + 3 reported (Blum+ 1999)
compact cluster: O stars in 8"-size circle (~0.24 pc)

⇒ O-star # increases, $M_{\text{cluster}}$ estimates increase

W31 -- $M_{\text{YSO}} \sim 10-30M\odot < M_\star \sim 60M\odot$ (Furness+ 2010; Chen+ in prep.)

W43 -- $M_{\text{YSO}} < 10M\odot$ $\ll M_\star \sim 60M\odot$

⇒ W31: on-going active MSF; W43: MSF decreases
• Massive YSOs preferentially found near ionized gas
  \[ \Rightarrow \text{energy feedback significant in MSF.} \]

• YSOs along superbubble rims: likely triggered by shell expansion.
  \[ \Rightarrow \text{Total } M_{\text{YSO}} \sim 0.1 \text{ Total } M_{\text{star}} \]; \[ \max(M_{\text{YSO}}) < \max(M_{\text{star}}) \]
  (Galactic & other LMC cases: Pomares+ 2009; Fleener+ 2010)
Resolved S-K relation in local SF regions

- $\Sigma_{H\alpha+24\mu m}$ vs $\Sigma_{YSO}$: $<\text{SFR}>$ in last 10 vs 1 Myr.

In GMCs w/ bright HII:
- $\Sigma_{H\alpha+24} \sim 0.2-3.0 \Sigma_{HI+H2}$
  $\Rightarrow$ depend on GMC evolutionary stage
- $\Sigma_{YSO}/\Sigma_{H\alpha+24} \sim 0.4-2.1$

$\Rightarrow$ SFR not const. in 10 Myr

- When averaging all GMCs in an HII complex $\geq 150$pc,
  $\Sigma_{H\alpha+24} \sim \Sigma_{HI+H2}$
- $\Sigma_{8\mu m} < 1/10 \Sigma_{Star}$ in W31 & W43 (Nguyen Luong+ 2010)
  $\Rightarrow$ PAHs easily destroyed by UV radiation.

Rosie Chen, MPIfR-Bonn

Lorentz Center, Feb 20, 2013
• $\Sigma_{H\alpha+24\mu m}$ vs $\Sigma_{YSO}$: 
  $\langle SFR \rangle$ in last 10 vs 1 Myr.

In GMCs w/o bright HII:
• $\Sigma_{H\alpha+24} \sim 0.02-0.1 \Sigma_{HI+H2}$
  $\Rightarrow$ $\Sigma_{H\alpha+24\mu m}$ requires
  fully sampled IMF, not applicable to poor, small
  clusters w/ low L/M.
• When averaging all GMCs in an HII complex $\geq 150$pc,
  $\Sigma_{H\alpha+24} \sim \Sigma_{HI+H2}$.
• $\geq 150$pc exception: LMC’s large (.5×1kpc$^2$) molecular
  ridge (Indebetouw+ 2008).

$\Rightarrow$ consider $SFR_{H\alpha+24}$ for different modes of MSF

Rosie Chen, MPIfR-Bonn  
Lorentz Center, Feb 20, 2013
Inefficiency of large-scale MSF @ low N(HI)

• $\Sigma_{\text{YSO}}$ in entire Bridge ($\sim 0.04 \Sigma_{\text{Gas}}^{1.4}$) $\ll \Sigma_{\text{YSO}}$ in Bridge GMCs

⇒ small fraction in Bridge forming GMCs/YSOs
⇒ threshold @ $Z,n$ to form $H_2$ (Krumholz+ 2009; Glover+ 2010)

• Low SFR$_{\text{FUV}}$ also seen in outer disks of galaxies (Bigiel+ 2010)

Rosie Chen, MPIfR-Bonn

Lorentz Center, Feb 20, 2013
SFEs across Z & galactic environments

- **SFE**: $\varepsilon = N(\text{YSO})/N[N(\text{HI})]$

- **N(\text{HI}) > 10 \times 10^{20} \text{ cm}^{-2}**: $\varepsilon_{\text{Bridge}} < 1/3 \varepsilon_{\text{LMC}}$  
  $\Rightarrow$ metallicity effect (Krumholz+ 2009)

- **N(\text{HI}) < 10 \times 10^{20} \text{ cm}^{-2}**: $\varepsilon_{\text{Bridge}} \sim \varepsilon_{\text{LMC}}$  
  $\Rightarrow$ tidal effect, e.g., colliding flows  
  (Heitsch+ 2006)

Rosie Chen, MPIfR-Bonn

Lorentz Center, Feb 20, 2013
High SFEs @ tidal environment

• 140+ hr Mopra CO survey of all 26 YSOs in the Bridge (PI: Chen): most unbiased GMC-YSO sample @ low-Z
• Except 7 previously reported, no new detection toward YSOs
  \[ M_{\text{cloud}} \leq 2-3 \times 10^3 M_\odot \Rightarrow \text{high SFE} \sim 1-3\% \]
  \Rightarrow \text{caveat: clouds & YSOs not always coincide (Muller+ 2013)}
• CO detections @ 10 pc from YSOs \Rightarrow \text{quick H}_2 \text{ dispersion @ YSOs}

Rosie Chen, MPIfR-Bonn
Conclusion

• What are massive YSOs in Magellanic Clouds?
  -- can be reliably identified w/ multi-λ SED+image examination
  Bridge: LMC
  -- YSO mass range (M☉): 4 - 10 4 - 45

• Do they form in special conditions?
  -- massive YSO formation may depend on GMC instability
  -- GMC w/ faint HII: Σ_{Gas} ≈ Σ_{YSO} ~ 10-50 Σ_{Hα+24μm}

• Is the S-K relation from <evolutionary stage> of GMCs?
  -- individual GMCs in an HII complex show different evolutionary stages;
    but follow S-K relation when averaging ≥150 pc scale.
  -- exceptions: LMC’s ridge (high Σ_{Gas}), Bridge (low Σ_{Gas})

• Does MSF proceed in a universal fashion?
  -- metallicity & tidal effects on MSF shown in the Bridge
  -- different cluster modes seen @ different Galactic environment