Massive star formation science opportunities with SOFIA

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(High-mass) clump evolution

G023.2056–0.3772 IRAC + 870 μm Contours

https://atlasgal.mpifr-bonn.mpg.de

G3CC 38
(l = 339.584, b = −0.127)

Morph. type: EC1

[DBS2003] 176
(l = 343.482, b = −0.042)

Morph. type: OC0

Morales+2013
Key MSF questions

Recent reviews: Motte+2018, Rosen+2020

- Fragmentation and mass assembly
- Accretion/Outflows/Jets
- Dynamics of inflow/infall
- Clump cooling
- Timescales
- Feedback processes
- Role of magnetic fields

Current concepts, e.g.

- Turbulent core model (McKee & Tan 2003), monolithic collapse
- Competitive accretion (Bonnell+1998)
- Global hierarchical collapse (Vazquez-Semadeni+2019)

→ Different kinematical signatures
Key MSF questions

- Fragmentation and mass assembly → ALMA/NOEMA
- Accretion/Outflows/Jets → Fischer talk: time variability / SOMA
- Dynamics of inflow/infall
- Clump cooling
- Timescales
- Feedback processes → Pabst talk, FEEDBACK
- Role of magnetic fields → Stephens talk, pilot legacy programs
FIR: Roadmap
W3 IRS5
Karska+2013

Fig. 1. Herschel-PACS continuum-normalized spectrum of W3 IRS5 at the central position. Lines of CO are shown in red, H$_2$C in blue, OH in light blue, CH in orange, and atoms and ions in green. Horizontal magenta lines show spectral regions zoomed in Figure C.1.
Unique spectroscopy in the FIR

- Only the FIR offers:
  - Dense cloud cooling: Access to major fine-structure cooling lines
  - Dense cloud kinematics: Access to absorption lines in front of dust
  - Dense cloud excitation: Access to high excitation of abundant and chemically (relatively) stable CO
  - Dense clouds chemistry: Access to hydrides as initial products of ISM chemistry → Neufeld Talk, HyGAL

Velocity resolved spectra crucial for dynamics, kinematics, excitation (optical depth effects)
Science case examples
(small selection with strong personal bias)

• Cooling budget separated into different components
• High-J CO to probe excitation/kinematics
• Infall/accretion onto protostars/clusters
• Timescales: chemical clocks
OI: from PACS to GREAT

Leurini+2015

Karska+2013
OI: from PACS to GREAT

Leurini+2015

Karska+2013
Cooling budget

- OI, CII, CO, OH, (H$_2$O)
- Census of cooling in a wide range of conditions
- High spectral resolution mandatory
  - to separate different physical components (e.g. outflow, envelope, different density regimes) and
  - to address optical depths effects
- SOFIA allows already important pathfinder and individual source studies but will for larger statistical samples more sensitivity and spatial coverages are needed.
- Range spectroscopy? Or many lines simultaneously with HIRMES like instrument.
- For dense regions, OI crucial! For excitation and in cases where OI 63$\mu$m is optically thick, OI 145$\mu$m necessary (potentially in combination with CII 157$\mu$m) → GREAT
CO SLEDs
e.g. HH46 (van Kempen+2010)

Fig. 2. CO line fluxes observed in the central PACS spaxel ($J_u > 10$) and with APEX ($J_u < 10$). Model fluxes are used to estimate the ratio of flux in a fictive PACS spaxel at the APEX wavelength and the observed APEX flux. Overplotted are predictions from a passively heated envelope (blue), a UV-heated cavity (green), and small-scale shocks in the cavity walls (red). The black line is the sum of the three. A cartoon of the different components is shown in the inset.
A. Karska et al. 2013: Far-infrared molecular lines from Low- to High-Mass Star Forming Regions observed with Herschel
CO SEDs

- CO chemically relative stable in warm gas
- Wide range of excitation can be covered → important cooling contribution
- For Galactic sources, high spectral resolution needed to separated line components arising from different exciting processes
- Again: range spec./many lines simultaneously
(High-mass) clump evolution

Infall is a fundamental process in SF!
Key questions SOFIA can address

- What are the infall speeds? Are free-fall velocities measured or is the infall slowed down?
- Which parts of the clouds take part in the infall? Is the infall local or global?
- What is the velocity profile of the infall?
- What are the corresponding timelines, hence in which evolutionary stages can infall be measured?
- What are the infall rates and can they be converted into accretion rates? Are the accretion rates high enough to overcome radiation pressure?
Infall in star forming regions

• New approach:
  - Employ absorption of THz lines in front of dust continuum as more straightforward tool (previously only studies in the cm towards evolved stages, HII regions and mm/submm blue-skewed selfabsorption)

• Determine infall rates on LOS
• Probe abundances in envelope
• Study infall through the evolution of star forming clumps
Search for infall

I: Blue-skewed profiles
   Needs excitation gradient, right tau
II: red-shifted absorption
   Needs high critical density, central continuum

- Evans 1999
Ammonia

- cm: Inversion lines
- FIR: Rotational lines, high $n_{\text{crit}}$
- overabundant in hot cores, apparently no depletion in cold sources

*Figure 1*  Energy level diagram of rotation-inversion states. $J$ is the total angular-momentum quantum number, and $K$ is the projected angular momentum along the molecular axis.
SOFIA results: Wyrowski+2012,2016

New data from 2016:

- 5 new redshifted absorption with shifts of 0.2 – 1.6 km/s with respect to $^{17}$O
- 1 source dominated by outflow (G5.89), several blue wings
- 2 sources with blue shifted absorption

Clumps in IRDCs

Fig 2. NH$_3$ 3$_{2}$–2$_{1}$ spectra of the observed sources. Results of Gaussian fits to the line profiles are overlaid in green. The systemic velocities of the sources, determined using $^{17}$O (3–2), are shown with dotted lines. W49N shows in addition at 30 km/s the NH$_3$ 3$_{1}$–2$_{1}$ from the other sideband.
Modeling: RATRAN + Outflow component

HCO$^+$ usually probing additional outflow component → RATRAN modification of Mottram+2013

Additional parameter:
- outflow widths/strength
- HCO$^+$ abundance
Modeling results
Wyrowski+2016

<table>
<thead>
<tr>
<th>Source</th>
<th>$R_{\text{out}}$ (pc)</th>
<th>$\alpha_n$</th>
<th>$n_{1\text{pc}}$ ($10^3\text{cm}^{-3}$)</th>
<th>$\delta v_t$ (km/s)</th>
<th>$f_{ff}$</th>
<th>$X(\text{NH}_3)$ $10^{-8}$</th>
<th>$X(\text{HCO}^+)$ $10^{-10}$</th>
<th>$\dot{M}$ ($10^{-3} M_\odot/\text{yr}$)</th>
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<tbody>
<tr>
<td>G34.26+0.2</td>
<td>0.8</td>
<td>-1.7</td>
<td>10</td>
<td>2.4</td>
<td>0.3</td>
<td>0.19</td>
<td>0.25</td>
<td>9</td>
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<tr>
<td>G327.29-0.6</td>
<td>2.0</td>
<td>-1.9</td>
<td>10</td>
<td>2.3</td>
<td>0.05</td>
<td>0.5</td>
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<tr>
<td>G351.58-0.4</td>
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<td>-1.9</td>
<td>15</td>
<td>1.5</td>
<td>0.1</td>
<td>1.5</td>
<td>0.2</td>
<td>16</td>
</tr>
<tr>
<td>G23.21-0.3</td>
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<td>-2.0</td>
<td>4.5</td>
<td>1.0</td>
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<td>1.5</td>
<td>0.5</td>
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<tr>
<td>G35.20-0.7</td>
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<td>-1.6</td>
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<td>0.03</td>
<td>0.35</td>
<td>0.3</td>
<td>0.3</td>
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<td>0.1</td>
<td>0.15</td>
<td>0.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

- Modeling of sources results in infall with fractions of free-fall of 3 – 30 %. Clump scale probed. To further constrain models, → measure larger spatial range
Different excitation traces
different $v$

- infall accelerating towards
inner part of clump

Future SOFIA opportunities:

- GS 572 GHz @ 90%
transmission (4GREAT)

- 1214 GHz (201-100, 211-110)
@ 65%

- 2355 GHz (4-3 lines) @ 63%
Search for large scale infall

- Extended dust continuum, ~0.5pc
- Infall localized or global?
- Infer 3D velocity pattern.
- Search for velocity gradients, rotation?
Potential probes of infall for future SOFIA studies

- **HNCO** (range in E)
- Possible from the ground, but only lower J lines

Neill+2014: SgrB2(N) with Herschel/HIFI
Potential probes of infall for future SOFIA studies

- HNCO (range in E)
- NH, NH$_2$ (HFS)
- H$_2$O (H$_2^{18}$O), warm gas filter
- H$_2$S, o/p ratio
- H$_2$D$^+$, OD cold gas
- H$_2$, 28μm, cold gas
Karska+2013: W3IRS5

Still lots of discovery space, e.g.:

- OH, 65μm doublet
- Relatively close to OI
- $E_{\text{lower}} = 290 \text{ K}$
- PACS: Massive star forming regions
H$_2$D$^+$ observations give an age of at least one million years for a cloud core forming Sun-like stars

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Work on HM clumps ongoing. APEX: Giannetti+2019, Modelling e.g. Körtgen+2017. See also D$_2$H$^+$ (Harju+2017)
Probing the circumstellar disk in AFGL2136
Synergies between EXES/TEXES/CRIRES and ALMA
(Indriolo+2020)

- Hot disk emission from clumpy disk structure
- $\text{H}_2\text{O}$: 500-800K
- $\tau_l(\lambda)$
- + other molecules (CO, HCN, $\text{NH}_3$, HF, $\text{C}_2\text{H}_2$) and unidentified lines

![Graph showing example fits to water lines and all data separated by instrument/telescope](image_url)
EXES rovib. CS (Barr+2017)

- AFGL2591: Base of outflow in hot core (130AU, 0.04")
Spectroscopy towards statistically significant samples

- GMCs sizes on sky often within sqdeg → no adjustment of flight direction needed
- Increase efficiency for rapid observations of many targets within sqdeg
- e.g.: 40 cores in CygX in HR mode with HIRMES-like instrument in many lines. Also EXES/4GREAT projects would benefit
- While a lot can be learnt from individual sources, large samples allow to average out random traits and facilitate comparison to simulations
Summary

• HMSF studies with SOFIA, key requirements:
  – High spectral resolution to probe kinematics and deal with optical depths effects
  – Range of lines to probe different scales and evolutionary stages
  – Significant samples to probe large parameter space

• In general
  – increase sensitivity, efficiency
  – Explore new frequency ranges