SOFIA follow-ups of ATLASGAL massive clumps

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Massive clump evolution
Infall is a fundamental process in SF!

G023.2056−0.3772 IRAC + 870 μm Contours

G3CC 38
($l = 339.584$, $b = -0.127$)

Morph. type: EC1

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

Morph. type: OC0

Morales+2013
Outline

- The ATLASGAL survey
- Molecular line follow-ups
- How to probe infall
- Previous ammonia results
- New ammonia observations
- The extended sample
- Comparing ammonia with other high density probes
- New modeling of profiles
- APEX-SOFIA synergies
Overview of the ATLASGAL Survey
Submillimetre Emission: Structure of the Dust

- APEX 870 μm continuum survey of the inner Galactic plane (300° < l < 60°, |b| < 1.5°)
- APEX: 12-m Single-dish Submillimetre Telescope located on the Chajnantor Plateau
- LABOCA: Large APEX BOIometer CAmera (MPIfR)
  - 295 elements at 870 μm
  - FoV = 11′, an angular resolution of ~19″ and sensitivity of ~60 mJy/beam

Complementary to Herschel/HiGAL & Pathfinder to ALMA MSF science
Overview of the ATLASGAL Survey
Submillimetre Emission: Structure of the Dust

10% of the Survey

Diffuse

Filaments

Compact Clumps
Molecular line follow ups

- Dust continuum is important but molecular line information is indispensable!
  - Effelsberg/Parkes NH$_3$ (Wienen+'12, '15):
    - Kinematic distances, temperatures
  - IRAM 30m/ATNF-Mopra/APEX (Wyrowski/Csengeri):
    - 3 & 0.85mm line surveys: Physical & chemical conditions (CO, Giannetti+2014)
  - Herschel/HIFI: 100 ATLASGAL sources currently observed in water lines → ATLASGAL water legacy (Wyrowski+; IRAS17233: Leurini+2014)
  - MALT90 (Jackson+2013): Mopra Galactic Plane Survey of high density regions. large program:
    - → about 2000 ATLASGAL clumps mapped at 3mm
  - SEDIGSM (Schuller+): APEX $^{13}$CO(2-1) survey of southern Galactic Plane
ATLASGAL @ SOFIA
concerted effort on several fronts

- Massive clumps selected in several GMCs (e.g. Wienen+2015)
- Observe multiple sources without changing flight directions
- Multi-semester project
- → statistical significant sample covering range of evolutionary stages

- Cooling budget: OI/CII (e.g. Leurini talk)
- High-J CO: (11-10)/(16-15)
- Ammonia infall study

Wienen+2015: HI+870μ+^{13}CO
SOFIA follow-ups (CO teaser)

G014.1944–0.1939 WISE + 870 μm Contours

Center: Longitude 14.193 Latitude −0.192

CO(16–15) luminosity ATLASGAL

ATLASGAL ○24 μm−dark ▲IRb

$L_{\text{CO(16–15)}} = 10^{-3.32} L_{\text{bol}}^{0.8}$

$L_{\text{CO(16–15)}}$ [K km s$^{-1}$ kpc$^{-2}$] vs $L$ [L$_\odot$]

AG13P66P18, AG14P19, AG14P63, AG351P77, AG351P16, AG351P25, AG351P44, AG351P58
Search for infall

I: Blue-skewed profiles
   Needs excitation gradient, right tau
II: red-shifted absorption
   Needs high critical density, central continuum
The story so far: Ammonia@1.8THz
Wyrowski+2012

- 3 absorption line detections in science verification
- All redshifted with respect to \( v_{\text{sys}} \)
- \( \tau \sim 1 \)

Table 2. Line parameters from Gaussian fits to the NH\(_3\) lines. Nominal fit errors are given in brackets. In addition, the velocity of C\(^{17}\)O (3–2) lines observed with the APEX telescope are given.

<table>
<thead>
<tr>
<th>Source</th>
<th>( T_{\text{peak}} ) (K)</th>
<th>( \Delta v ) (km s(^{-1}))</th>
<th>( \nu_{\text{LSR}} ) (km s(^{-1}))</th>
<th>( \nu_{\text{LSR}} ) (km s(^{-1}))</th>
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<tbody>
<tr>
<td>W43-MM1</td>
<td>-0.96 (0.22)</td>
<td>5.3 (0.8)</td>
<td>99.7 (0.4)</td>
<td>97.65 (0.06)</td>
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<tr>
<td>G31.41+0.31</td>
<td>-1.18 (0.29)</td>
<td>3.7 (0.8)</td>
<td>99.4 (0.4)</td>
<td>97.02 (0.04)</td>
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<tr>
<td>G34.26+0.15</td>
<td>-3.38 (0.56)</td>
<td>5.5 (0.6)</td>
<td>61.2 (0.3)</td>
<td>58.12 (0.03)</td>
</tr>
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</table>

Fig. 2. NH\(_3\) spectra of the observed sources. Results of Gaussian fits to the line are overlaid in green. The systemic velocities of the sources, determined using C\(^{17}\)O (3–2) are shown with dotted lines.
G34: comparison to VLA absorption

**Fig. 3.** G34.26+0.15 SOFIA NH$_3$ spectrum compared with the VLA NH$_3$ (2,2) spectrum taken from Gómez et al. (2000) which was integrated over the region which shows absorption. A two-component hyperfine fit to the (2,2) spectrum is shown in green.
Infall Results

- 3 clear detections of Ammonia line-of-sight infall consistent with results from cm-absorption and/or blue-skewed emission profiles

- More direct probe of infall that can be extended to earlier stages of SF without cm background continuum and cases where other species are depleted

- Infall rates of $3-10 \times 10^{-3} \, M_\odot/yr$ (if spherical)

- Next step: extend to more sources and stages, in particular earlier ones
SOFIA Observations

- GT and cycle 1 science flights

- GREAT:
  - L1, various lines
  - \( \text{NH}_3 \text{N}_2 \text{-2}_{2-} \quad 1810.379 \text{GHz} \) LSB
  - AFFTS/XFFTS:1.5/2.5 GHz
  - Chopped observations of 9 sources
Cycle I: a) continuation to Infrared dark clouds

Figure 2: IRDC G23.21-0.38: (a) ATLASGAL 870 $\mu$m dust continuum as contours on GLIMPSE 8 $\mu$m MIR emission in color, SOFIA beam in red. (b) APEX HNC (4–3) spectrum of this clump with systemic velocity indicated.
Cycle I: b) filling in further stages:

- **G35.20-0.74**: submm brightest, northern massive young stellar object, fulfilling Lumsden+ MSX color criteria

- **G327.3/G351.58**: hot cores/ultracompact HII regions with high luminosity (up to $2 \times 10^5 \, L_\odot$)
New SOFIA results: sample

König+2015

No/too weak SOFIA 1.8THz continuum ! → 572 GHz
New SOFIA results: continuum

Fig. 2. Comparison of GREAT continuum levels with PACS 160 μm flux densities with nominal 20% errors.

Fig. 3. Example of constraining the radial physical structure with the help of the ATLASGAL submm dust continuum radial profiles.
New SOFIA results: lines

Wyrowski et al.: Infall through the evolution of high-mass star forming clumps

Fig. 1. $NH_3$ $3_2 - 2_2$ spectra of the observed sources. Results of Gaussian fits to the line are overlaid in green. The systemic velocities sources, determined using $^{17}C\ O$ (3–2), are shown with dotted lines.

- 5 new redshifted absorption with shifts of 0.2 – 1.6 km/s with respect to $^{17}C\ O$
- 1 source dominated by outflow (G5.89), several blue wings
- 2 sources with blue shifted absorption
Complementary ground based data
How consistent are different probes?

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<th>hco+</th>
<th>hnc</th>
<th>cs</th>
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<tr>
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→ Ammonia and HCO\(^+\) (4-3) show best correspondence
Modeling

- Fit dust continuum (ATLASGAL) with density power law \( n \sim r^\alpha \), \( \alpha = 1.5 - 2.2 \)
- Temperature structure dictated by inner heating source (luminosities known from SED fits, König+2015)
- Adjust ammonia abundance and velocity structure in spherical RATRAN models
- Modelling of new sources results in infall with fractions of free-fall of 5 – 25 %. The ammonia abundance are in the range of \( 0.2 - 2 \times 10^{-8} \).
- But how consistent are models of \( \text{NH}_3 \) and \( \text{HCO}^+ \)?
New SOFIA modeling

Outflow component

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

Additional parameter:
- outflow widths/strength
- HCO$^+$ abundance
New SOFIA modeling

Outflow component

But many cases do not work with this simple geometry. Complicated outflows? Additional low density outer layer (Lopez-Sepulcre+2010)?

Also this clump shows consistent results!
Different excitation traces different $v$

SOFIA opportunities:

- GS 572 GHz @ 90% transmission
- 1214 GHz (201-100, 211-110) @ 65%
- 2355 GHz (4-3 lines) @ 63%
APEX-SOFIA synergies

- Mid vs. High J CO
- Blue-skewed self-absorbed high density probes vs. red-shifted absorption studies
- CO/CI cooling vs. CII/OI
- Complex molecules vs. hydrides
- Similar beamsizes in APEX submm windows and with SOFIA THz RX
- Imaging: CHAMP+/LASMA vs. UPGREAT
Summary & Outlook

- Infall on clump scales ubiquitous through wide range of evolutionary stages
- Ammonia and HCO\(^+\) (4-3) show best correspondence but HCO\(^+\) stronger affected by outflows
- Continue filling in stages (populating the M-L diagram)
- Study infall across clumps (upGREAT)
- Add additional lines to cover larger excitation range (new single pixel RXs)