The O budget in low-mass protostars:
The NGC1333-IRAS4A R1 shock observed in [O I] 63 μm with SOFIA-GREAT

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Low-mass YSO evolution

Class 0

Class I

Class II

Jet / wind present at all evolutionary stages

Arce & Sargent (2006)
H$_2$O chemistry: three routes
Shock chemistry 101

$V_{\text{shock}} \sim \text{few km/s}$

Volatile Oxygen budget

$H_2O_{\text{ice}}$

$H_2O_{\text{gas}}$

$\text{CO}$

$O$
Shock chemistry 101

$V_{\text{shock}} \sim \text{few}$ km/s

Volatile Oxygen budget

- $\text{H}_2\text{O}_{\text{ice}}$
- $\text{H}_2\text{O}_{\text{gas}}$
- CO

$T (K)$

10$^1$ 10$^2$ 10$^3$ 10$^4$ 10$^5$

3 km/s
Shock chemistry 101

\[ T (K) \]

\[ \nu_{\text{shock}} \sim \text{few} \quad 10 \quad 30 \quad 100 \text{ km/s} \]

Volatile Oxygen budget

- \( H_2O_{\text{ice}} \)
- \( H_2O_{\text{gas}} \)
- \( \text{CO} \)
- \( \text{O} \)

10 km/s
Shock chemistry 101

$T (K)$

$V_{\text{shock}} \sim \text{few} \quad 10 \quad 30 \quad 100 \text{ km/s}$

Volatile Oxygen budget

- $\text{H}_2\text{O}_{\text{ice}}$
- $\text{H}_2\text{O}_{\text{gas}}$
- CO
- O

$V_{\text{shock}}$ scale:
- 0 km/s
- 25 km/s
- 50 km/s
- 75 km/s
- 100 km/s

$T_{\text{shock}}$ scale:
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$
Shock chemistry 101

$V_{\text{shock}} \sim \text{few} \quad 10 \quad 30 \quad 100 \text{ km/s}$

Volatile Oxygen budget

$\text{H}_2\text{O}_{\text{ice}} \quad \text{H}_2\text{O}_{\text{gas}} \quad \text{CO} \quad \text{O}$
Kristensen et al. (2010, 2012), Mottram et al. (2014)
Dissecting a profile

- One profile: lots of H$_2$O moving!
- Bulk of emission in three components
- Velocity resolution allows for decomposition

Kristensen et al. (2012), Mottram et al. (2014)
Physical components

Cavity shocks

- Class 0
- Spot shocks
- Cavity shocks (broad)

Absorbing envelope


Protostellar wind

Panoglou et al. (2012)

Wart et al. (2016)

\( v (\text{km/s}) \)

\( \text{height} \ z (\text{AU}) \)

\( r_{\theta} (\text{AU}) \)

\( 12.8 \text{ AU} \)

X0

60°
Evolutionary scheme

- **Class 0**: H$_2$O tightly linked to outflow, infall, molecular jet, profiles are the broadest + brightest

- **Class I**: envelope opens, outflow force decreases, expansion, profiles decrease in width + intensity

(Visser et al. 2012, Kristensen et al. 2012, Mottram et al. 2014)
Quest for $\text{H}_2\text{O}$ abundance

- **Step I:** determine excitation conditions, particularly $N(\text{H}_2\text{O})$
- **Step II:** Choose appropriate reference frame to get $N(\text{H}_2)$
- **Step III:** Calculate $x(\text{H}_2\text{O}) = N(\text{H}_2\text{O}) / N(\text{H}_2)$
Profile shape vs. excitation

- Similarity in profile shapes independent of excitation (different at outflow positions)

- Excitation conditions constant with \( v \) in each component

Kristensen et al. (2010)
Mottram et al. (2014)
**H$_2$O: subthermally excited**

- RADEX excitation analysis
- Conclusion: small emitting area ($10^2$ AU), high temperature ($\sim$ 300 K), high column density ($\sim 10^{18}$ cm$^{-2}$), high density ($10^5$-10$^8$ cm$^{-3}$)

*Motttram et al. (2014)*
Surprisingly low $X(\text{H}_2\text{O})$: 
$\sim 10-100$ times “too little”? 

- Where is the oxygen?

Kristensen et al. 2012, 2017b, 
Santangelo et al. 2013, 2014, 
Tafalla et al. 2013, 
Neufeld et al. 2014
HH46

Kristensen et al. 2012; van Kempen, Kristensen et al. (2010)
Herschel-PACS: FIR inventory

Herczeg et al. (2012)
FIR line cooling budget

FIR cooling dominated by O-species
Cooling not chemistry!

Karska et al. 2013, in prep., Podio et al. 2013
• Velocity resolution: identifying physical components

Kristensen et al. (2012), Mottram et al. (2014)
[O I] emission lights up at shock spots - but where does [O I] emission come from?
Enter SOFIA-GREAT!

• [O I] 63 µm detected at R1 position

• *Only* seen in high-velocity component!

• HV component also seen in CO 16-15 (GREAT) and H$_2$O (HIFI)

Kristensen et al. 2017a
Excitation ->
Oxygen budget

**Recipe:**
Assume excitation from H$_2$O
Apply to CO, < OH, and O
Get $N$(CO), $N$(OH), $N$(O)
Assume $X$(O)$_{\text{volatile}}$ = 3 $10^{-4}$
Calculate $X$(M)

**X(H$_2$O)** $\sim$ 3 $10^{-5}$
**X(CO)** $\sim$ 2 $10^{-4}$
**X(OH)** < 2 $10^{-5}$
**X(O)** $\sim$ 5 $10^{-5}$
Low $X(O)$ at high $v$: what does it mean?

- Atomic O is $\sim 15\%$ of total O budget at high $v$, $\sim 85\%$ molecular and primarily CO

- Volatile C/O ratio $\sim 0.7$

- Do the youngest sources host atomic/ionic jets? Why so much molecular material? Reformation, or molecular from the start? Implications for outflow energetics? mass loss rates and infall rates? *One spectrum, one paper, many new questions!*
What have we learnt?

• **Lesson I:** SOFIA-GREAT is delivering beautiful [O I] 63 μm spectra!

• **Lesson II:** Toward one shock position, [O I] traces only the high-velocity component and the bulk of O is in molecular form

• **Lesson III:** Systematic surveys are needed: do lessons from one source apply elsewhere?  
  (Accepted C5 proposal: two new spectra not yet delivered, two more papers?)