Atomic gas in Protostellar outflows

SOFIA Tele-Talk
August 04, 2021

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A mysterious object in Orion

ORION

+ 3°

zoom in

Herbig-Haro object

HH111

~ 30''

Herbig 1951
Haro 1952

DSS colored
Herbig-Haro objects

- powered by an **outflow** from a **forming star**
  
  Schwartz 1975, 1978

- detected in various **emission lines**
  
  - optical: [SII], [NII], [OI], Hα
  - near-IR: [FeII], H₂
  - sub-mm/mm: CO, SiO

- shock-excited

  Schwartz 1977
  Hartigan+1995

Frank+2014
Bally 2016
Lee 2020
Ray & Ferreira 2020
The evolution of low-mass protostars

Class 0

Class I

Class II

Illustration: Karska 2014

Examples:
The evolution of low-mass protostars

**Illustration:**
Karska 2014

**Examples:**
- HH212
- HH111
- HH30

Class 0
- Prestellar Core
- 30,000 AU
- 10,000 AU
- 300 AU

Class I
- HH111
- [SII] blue, Hα orange
- [FeII] turquoise, H, red
- L ~ 0.1 pc
- L ~ 0.007 pc

Class II
- HH30
- L ~ 0.007 pc
- Optical R Band

coexisting gas components

near-IR H₂

L ... length of the shown outflow
Three challenges

Accretion/ejection mechanism?

Outflow evolution?

- **Class 0:**
  mainly molecular

- **Class I:**
  ?

- **Class II:**
  mainly atomic/ionic

Importance of FIR $[\text{OI}]$?

$\left\{ \begin{array}{l} [\text{OI}]_{63\mu m} \\ [\text{OI}]_{145\mu m} \end{array} \right\}$

Nisini+2015

- efficiency:
  \[ f = \frac{\dot{M}_{\text{out}}}{\dot{M}_{\text{acc}}} \]

- **X-wind vs. disk wind**

  Shu+2000, Ferreira+1997

Ellerbroek+2013, Watson+2016

Optical spectrum of HH111

Tsianganos 2010

Reipurth 1989a
The far-infrared [OI] lines

- **Collisional excitation**
  \[
  \text{O}(^3\text{P}_j) + \text{p} \xrightarrow{\text{collision}} \text{O}(^3\text{P}_{j'}) + \text{p}, \quad j > j'.
  \]

- **Radiative decay**
  \[
  \text{O}(^3\text{P}_1) \xrightarrow{\text{time}} \text{O}(^3\text{P}_2) + h\nu_{63\mu m}
  \]

- **Extinction negligible**
The OI line ratio is density sensitive

\[ \frac{[\text{OI}]_{63.0 \mu m}}{[\text{OI}]_{145.9 \mu m}} \]

\( \log_{10}(n_{\text{coll}}) \) vs. \( n_{\text{coll}} \) in \( \text{cm}^{-3} \)

Nisini+2015
[O\textsc{i}]63\textmu{}m is not observable from the ground!

Mostly Class 0 outflows have been mapped in [O\textsc{i}]!

Nisini+2015, Dionatos+2018, Dionatos & Güdel 2017

It became clear, that...

- bulk [O\textsc{i}] emission $\rightarrow$ shocks
- [O\textsc{i}] traces warm, atomic gas

What about more evolved Class I sources?

Herschel/PACS 2009-2013

Hollenbach & McKee 1989

Watson+2016

Alonso-Martinez+2017
PACS' twin instrument aboard SOFIA

**Telescope**

- Effective aperture: 2.5m

Young+2012, Krabbe+2013

**Instrument**

Field Imaging Far-Infrared Line Spectrometer

FIFI-LS

5x5 Integral Field Unit

**Wavelength Range**

- Resolving Power $R = \lambda/\Delta\lambda$
  - 51 – 200 µm

**Field of View Features**

- 30" x 30" (Blue)
- 60" x 60" (Red)
- 2x(16x25) Ge:Ga
Mitigating the Earth atmosphere

(1) Gaussian emission line
\[ \varphi(\lambda; b) = \frac{A}{\sqrt{2\pi}\sigma} \exp\left[ -\frac{1}{2} \left( \frac{\lambda - \mu}{\sigma} \right)^2 \right] + B \]

(2) Passage through atmosphere
\[ \varphi(\lambda; b) \cdot \tau(\lambda; a) \]

(3) Telescope + instrument
\[ y(\lambda_k; a, b, R) = S \left( [\varphi(\lambda; b) \cdot \tau(\lambda; a)] \ast \text{SIF}(\lambda; R) \right) \]
Atmospheric transmission

(1) Line signal

(2) Passage through atmosphere

(3) Convolved signal
FIFI-LS datacube

$\lambda_{\text{c}} = 63.18 \, \mu\text{m}$

pixel: $1''$

Levenberg-Marquardt algorithm

$$
\chi^2 = \sum_{k=1}^{N} \tau(\lambda_k; a) \cdot \left( \frac{\text{data}(\lambda_k) - y(\lambda_k; a, b, R)}{\epsilon(\lambda_k)} \right)^2
$$

Sperling+2020
RESULTS
First [OI] mappings of...

[Cep E][OI]63μm is not observable from the ground!

Class 0 outflows

HH1 [OI]63μm

HH212 [OI]63μm

Sperling+2021
First \([\text{OI}]\) mappings of...  

\textbf{HH111}  
\([\text{OI}]63\mu\text{m}\) is not observable from the ground!  

\textbf{HH34}  
\([\text{OI}]63\mu\text{m}\) is not observable from the ground!  

\textbf{HH26}  
\([\text{OI}]63\mu\text{m}\) is not observable from the ground!  

\textbf{SVS13}  
\([\text{OI}]63\mu\text{m}\) is not observable from the ground!  

\textbf{L1551}  
\([\text{OI}]63\mu\text{m}\) is not observable from the ground!
The spectacular HH111 jet

- shock excitation
- luminosity measurements

\[ L([\text{O I}]_{63}) \xrightarrow{?} \dot{M}_{\text{out}} \]
Mass-loss rates

Shock model (HM89)

Hollenbach 1985, Hollenbach & McKee 1989

In a nutshell...

- single dissociative wind shock of jump (J) type

- parameter range

  \[ v_s = 30 - 150 \text{ km s}^{-1} \]
  \[ n = 10^3 - 10^6 \text{ cm}^{-3} \]

- predictions

  a) \([\text{OI}]_{63\mu m}\) is the dominant cooling line

b) \( \frac{\dot{M}_{\text{out}}}{M_\odot \text{ yr}^{-1}} = 10^{-4} \cdot \left( \frac{L([\text{OI}]_{63})}{L_\odot} \right) \)
Is the HM89 model applicable?

- **multiple unresolved shocks**
  Dougados+2010, Nisini+2015

- **other emission lines?**
  e.g. [OI]145, [CII]157, [SII]25, [SiII]35, [FeII]26

**Issues**

1. Agreement of specific line ratios with HM89 predictions?
2. J-shock vs. C-shock?
3. [OI]63μm dominant cooling line?
4. Contamination by a Photodissociation region (PDR) or a disk?
5. A 30yr old model (new collisional coefficients, chemical networks...?)
Mass-loss rates – an alternative approach

jet luminosity  (Hartigan+1995)

\[
\left( \frac{\dot{M}_{\text{out}}}{M_\odot \text{yr}^{-1}} \right) = (3.3 - 6.7) \times 10^{-3} \cdot \left( \frac{v_t}{\text{km s}^{-1}} \right) \left( \frac{\theta''}{\theta} \right) \left( \frac{pc}{D} \right) \left( \frac{L([\text{O I}]_63)}{L_\odot} \right)
\]

Motivation?

jet geometry
Why the range of 3.3-6.7?

- fluid dynamics
- counting contributing atoms
- solving rate equations of OI

A critical assumption:
- $n_{\text{coll}}$ is close to the critical density

$D$ ... distance to the target
$\theta$ ... projected distance
$v_t$ ... component of the velocity on the plane of sky
$L([\text{O I}]_{63})$ ... [OI]63μm luminosity
## The outflow components I

<table>
<thead>
<tr>
<th>Target</th>
<th>Region</th>
<th>Class</th>
<th>$\dot{M}<em>{\text{out}}([\text{O I}])$ $10^{-7}$ $M</em>\odot$ yr$^{-1}$</th>
<th>$\dot{M}<em>{\text{out}}$ &amp; component $10^{-7}$ $M</em>\odot$ yr$^{-1}$</th>
<th>dominant component</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH1</td>
<td>VLA 1 knot A</td>
<td>0</td>
<td>$\lesssim 25.9 - 52.6$ $\lesssim 9.5 - 19.4$</td>
<td>$\sim 6$ in [Fe II] $\sim 4$ in [S II] $\sim 0.1$ in H$_2$</td>
<td>![Gold] = mainly atomic ![Red] = mainly molecular</td>
</tr>
<tr>
<td>HH212</td>
<td>knot A and B</td>
<td>0</td>
<td>$3.9 - 7.9$</td>
<td>$\sim 10$ in CO, SO, SiO $\leq 3$ in CO, SiO $\sim 1$ in H$_2$</td>
<td>![Gold] = mainly atomic ![Blue] = mainly molecular</td>
</tr>
<tr>
<td>Cep E</td>
<td>knot A jet</td>
<td>0</td>
<td>$\lesssim 22.4 - 45.5$ $\lesssim 7.2 - 14.7$</td>
<td>$\sim 200$ in CO</td>
<td>![Blue] = mainly molecular</td>
</tr>
<tr>
<td>L1551</td>
<td>IRS 5</td>
<td>I</td>
<td>$5.8 - 11.8$</td>
<td>$\sim 8.6$ in HI $\sim 1.7$ in [Fe II] $\sim 0.4$ in H$_2$</td>
<td>![Gold] = mainly atomic ![Red] = mainly molecular</td>
</tr>
</tbody>
</table>
## The outflow components II

<table>
<thead>
<tr>
<th>Target</th>
<th>Region</th>
<th>Class</th>
<th>$\dot{M}<em>{\text{out}}([\text{O I}])$ $10^{-7} M</em>\odot \text{yr}^{-1}$</th>
<th>$\dot{M}<em>{\text{out and component}}$ $10^{-7} M</em>\odot \text{yr}^{-1}$</th>
<th>dominant component</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH111</td>
<td>HH111IRS</td>
<td>I</td>
<td>26 – 53</td>
<td>4 in CO</td>
<td>![Atomic]</td>
</tr>
<tr>
<td></td>
<td>jet (knots F-O)</td>
<td></td>
<td>6 – 12</td>
<td>2 – 6 in [O I]$\lambda$6300</td>
<td></td>
</tr>
<tr>
<td>SVS13</td>
<td>SVS13A</td>
<td>I</td>
<td>25 – 51</td>
<td>30 in HI</td>
<td>![Molecular]</td>
</tr>
<tr>
<td></td>
<td>HH8-11</td>
<td></td>
<td>–</td>
<td>8.9 in[Fe II]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HH7</td>
<td></td>
<td>–</td>
<td>7.0 in H$_2$</td>
<td></td>
</tr>
<tr>
<td>HH34</td>
<td>HH34IRS</td>
<td>I</td>
<td>11 – 23</td>
<td>0.7 in [Fe II]</td>
<td>![Atomic]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.03 in H$_2$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~ 1.5 in[O I]$\lambda$6300</td>
<td></td>
</tr>
<tr>
<td>HH26</td>
<td>HH26A</td>
<td>I</td>
<td>–</td>
<td>0.2 – 0.5 in H$_2$</td>
<td>![Molecular]</td>
</tr>
</tbody>
</table>

= mainly atomic  
= mainly molecular
### Other fully mapped outflows

<table>
<thead>
<tr>
<th>Target</th>
<th>Class</th>
<th>$\dot{M}_{\text{out}}([\text{O I}])$</th>
<th>$\dot{M}_{\text{out}}$ &amp; component</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$10^{-7} , M_\odot , \text{yr}^{-1}$</td>
<td>$10^{-7} , M_\odot , \text{yr}^{-1}$</td>
</tr>
<tr>
<td>L1448</td>
<td>0</td>
<td>$1 - 2$</td>
<td>&gt; 100 in CO</td>
</tr>
<tr>
<td>IRAS4A</td>
<td>0</td>
<td>$0.3 - 1.0$</td>
<td>&gt; 70 in CO</td>
</tr>
<tr>
<td>HH46</td>
<td>I</td>
<td>$7 - 15$</td>
<td>15 - 28 in CO</td>
</tr>
<tr>
<td>BHR 71</td>
<td>0</td>
<td>$1 - 3$</td>
<td>&gt; 180 in CO</td>
</tr>
<tr>
<td>VLA 1623</td>
<td>0</td>
<td>$0.5 - 1$</td>
<td>16 - 160 in CO</td>
</tr>
<tr>
<td>HH211</td>
<td>0</td>
<td>$2.4 - 4.8$</td>
<td>7 - 28 in SiO, CO, SO</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~ 20 - 28 in H$_2$</td>
</tr>
<tr>
<td>IRAS 2A</td>
<td>0</td>
<td>$0.3 - 0.7$</td>
<td>6 in H$_2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt; 600 in CO</td>
</tr>
</tbody>
</table>

**Compilation**

Sperling+20

Nisini+2015

Dionatos & Güdel 2017

Dionatos+2018

Podio+2020

Lee 2020
Class 0: 7 out of 9

Class I: 4 out of 5

$\dot{M}(\text{OI})$, 

...underestimates the total mass-loss

...potentially traces the bulk mass-loss
Outflow efficiencies

- most outflows:
  \[ f \sim 0.01\text{-}0.5 \]
  → agreement with X-wind & disk wind

- many Class 0 outflows
  \[ f \lesssim 0.05 \]
  → take into account the molecular component!
Comparing with unresolved outflows

- WISH + DIGIT + WILL + GASPS surveys
  - single Herschel/PACS footprint
  - only outflows
  - 28 Class 0, 23 Class I, 21 Class II

Mottram+2017, Alonso-Martinez+2017

Consistent with my findings!

Evolutionary trend apparent!
Main conclusions

- my SOFIA observations support the notion that **protostellar outflows undergo an evolution**

- the bulk **mass-loss from Class 0 outflows** resides by tendency in a **molecular component**

- for more evolved **Class I outflows** the **[OI] emission line** tends to trace the **main component**

...but we need more data!
Upgrade of SOFIA instruments?
Future prospects?

SOFIA/FIFI-LS+
Most likely not sensitive enough!

SOFIA/HIRMES
No extensive mapping possible!

SOFIA/GREAT
No improvement in spatial resolution!
And what about JWST?

- **launch**: November 2021?
- **D ~ 6.5m**
- **\( \lambda = 0.6 \, \mu m - 28 \, \mu m \)**

**mid-IR lines**

[FeII], [SI], [SiII]...

no observations at FIR [OI] lines

Credit: NASA
The End