Probing protostellar outflows in the far-infrared [OI] lines

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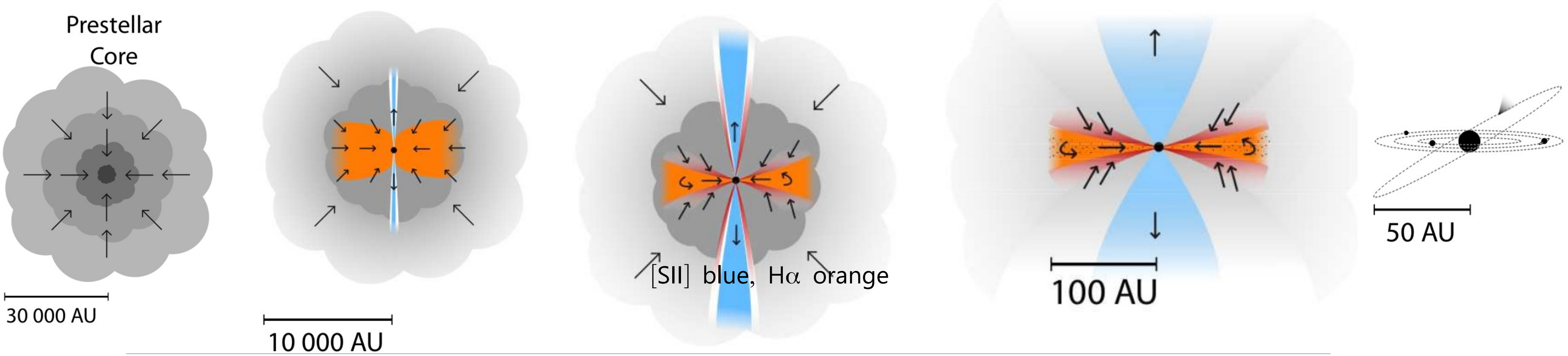
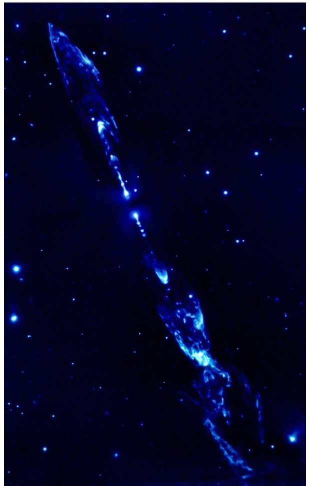
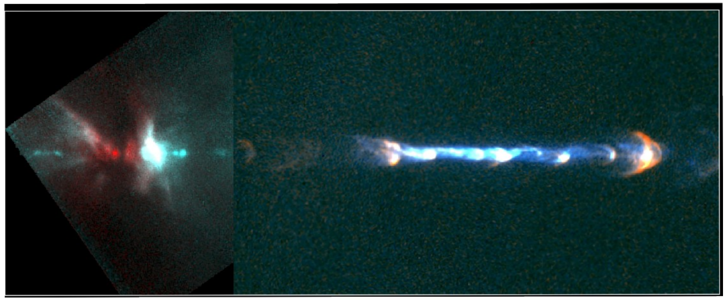
The evolution of low-mass protostars

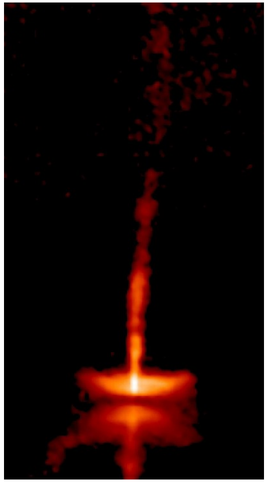


near-IR H_2





[FeII] - turquoise, [SII] – blue,
H_2 - red Hα - orange

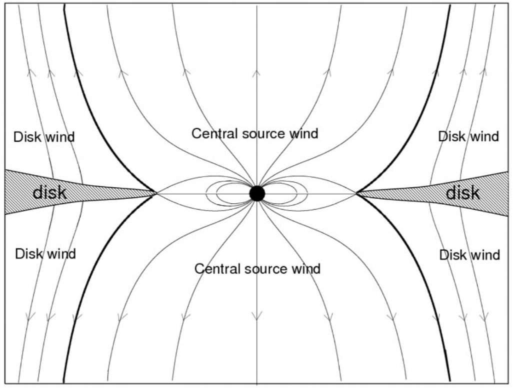


optical
R-band

Reipurth+1999
McCaughrean+2002
NASA, Watson+2008

Three open questions

Accretion/ejection mechanism



$$f = \frac{\dot{M}_{\rm out}}{\dot{M}_{\rm acc}}$$

X-wind vs. **disk wind**

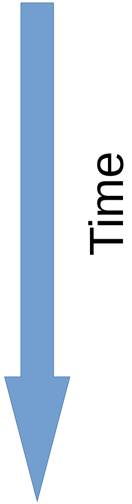
Shu+ 2000 Ferreira+1997

Outflow evolution

Class 0

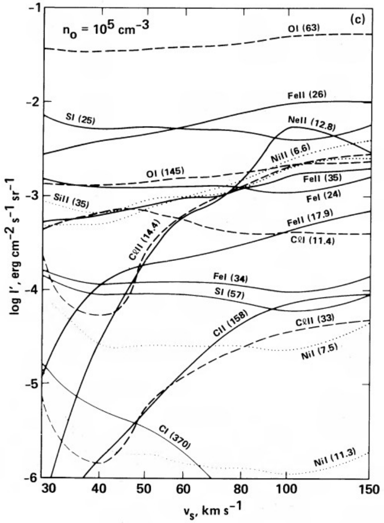
Class I

Class II



Ellerbroek+2013, Watson+2016

Importance of FIR [OI]



$$\left\{ \begin{array}{c} [\mathrm{O\,I}]_{63\mu\mathrm{m}} \\ [\mathrm{O\,I}]_{145\mu\mathrm{m}} \end{array} \right\}$$

Hollenbach & McKee 1989, Nisini+2015

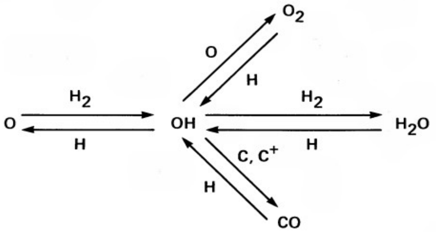
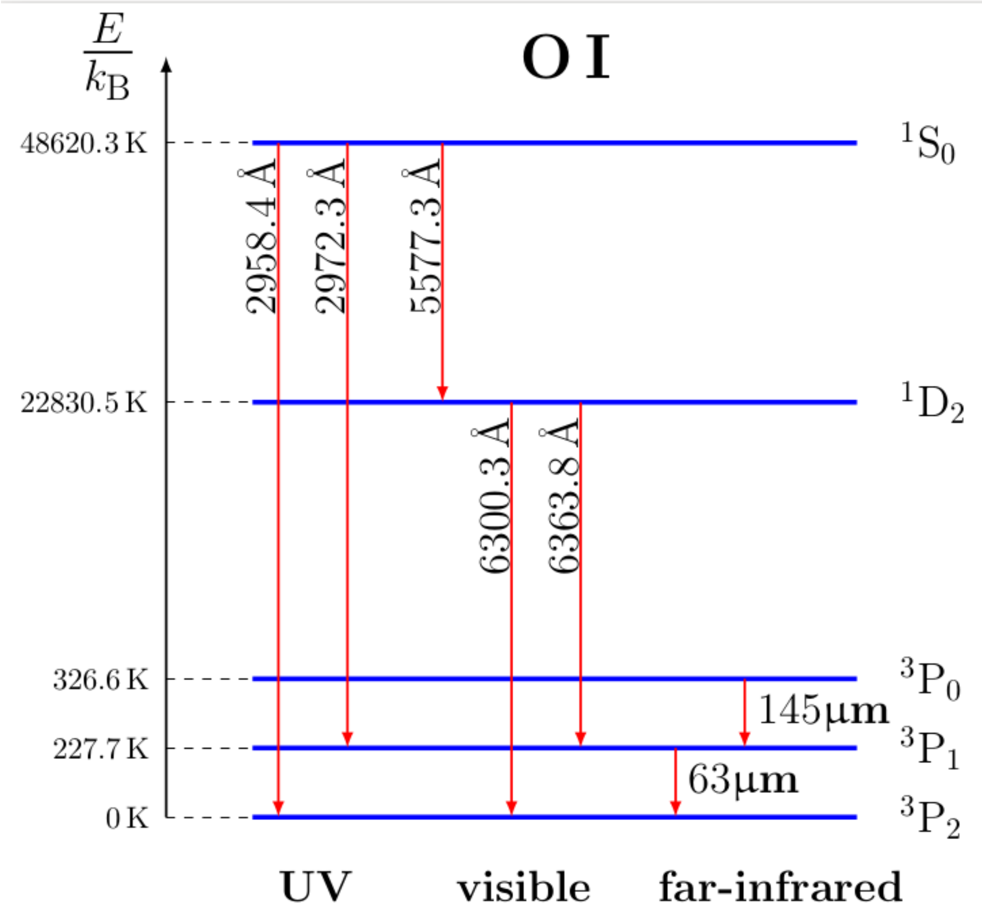


FIG. 2.—Fast neutral reactions with moderate activation energies or endothermicities dominate the oxygen chemistry in warm $T \gtrsim 300$ K postshock gas.

The far-infrared [OI] lines



collisional excitation:

$$O(^3P_j) + p \xrightarrow{\text{collision}} O(^3P_{j'}) + p, \qquad j > j'$$

radiative decay:

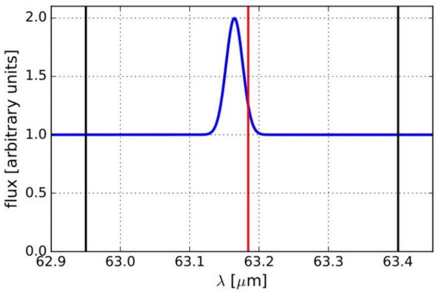
$$O(^3P_1) \xrightarrow{\text{time}} O(^3P_2) + h\nu_{63\mu m}$$

negligible extinction

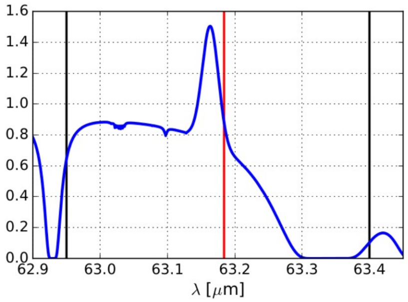
Osterbrock & Ferland 2006, Draine 2011

Signal path

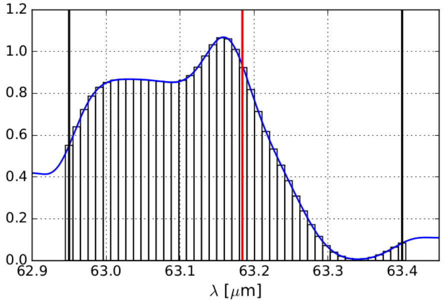
Line signal

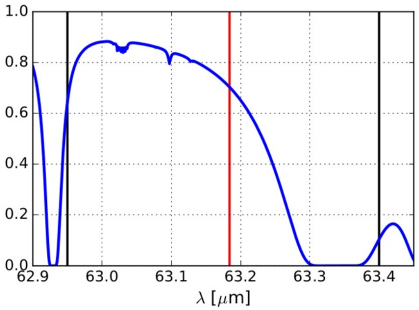


Passage through atmosphere

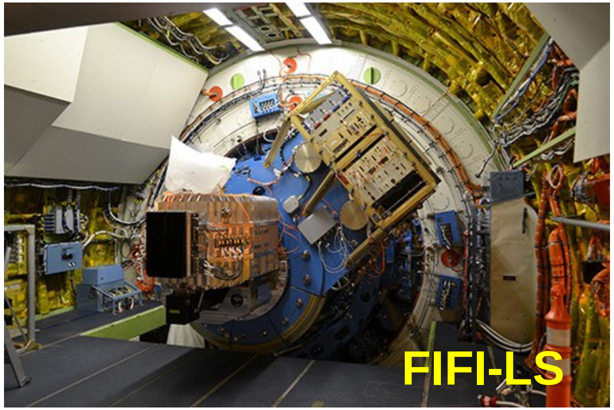


Convolved signal

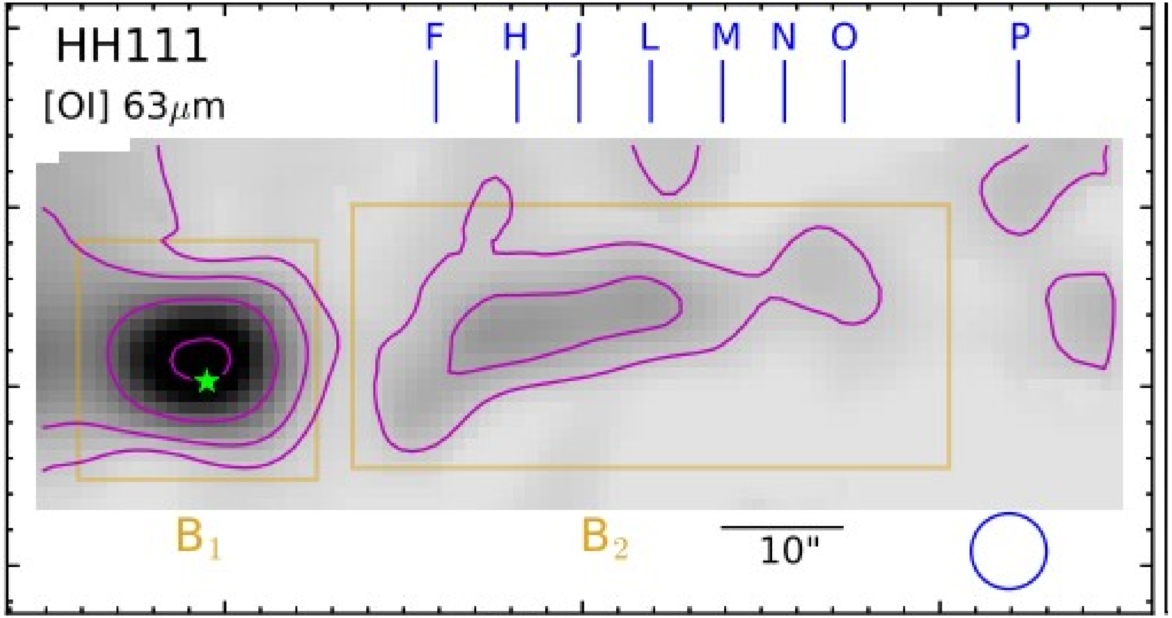


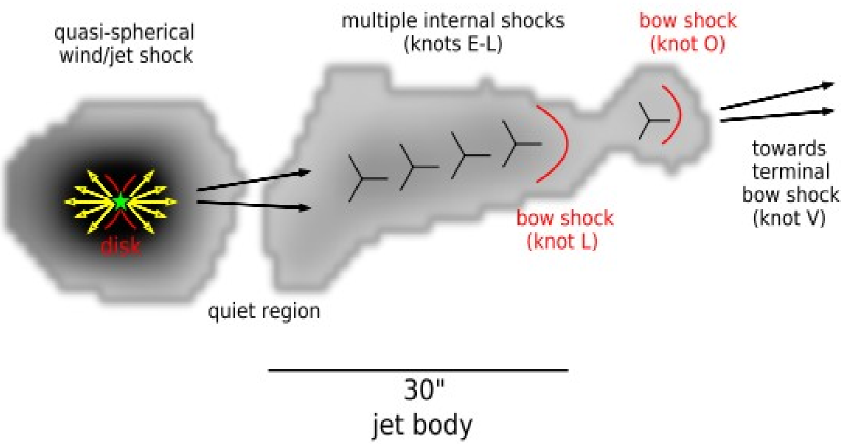


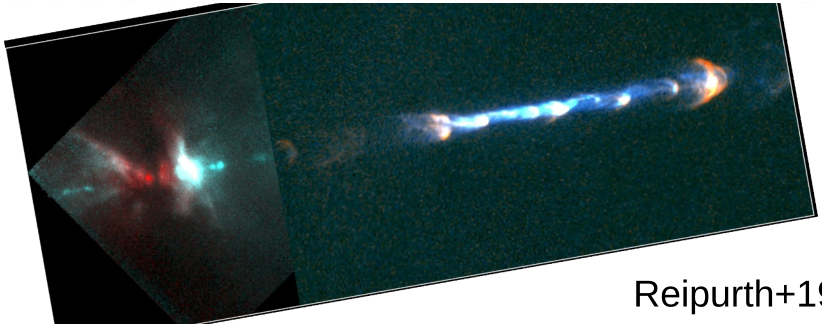
Atmospheric transmission



The spectacular HH111 jet



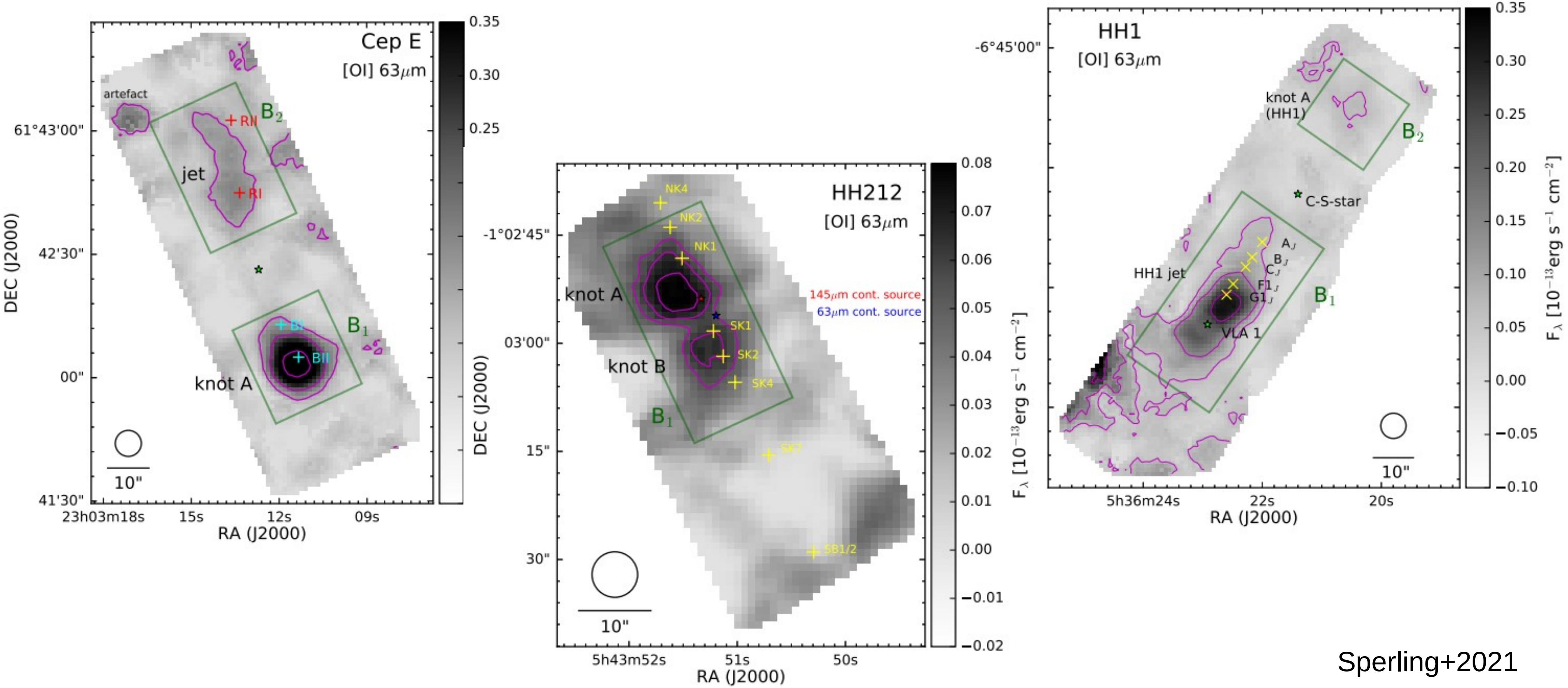




Reipurth+1999

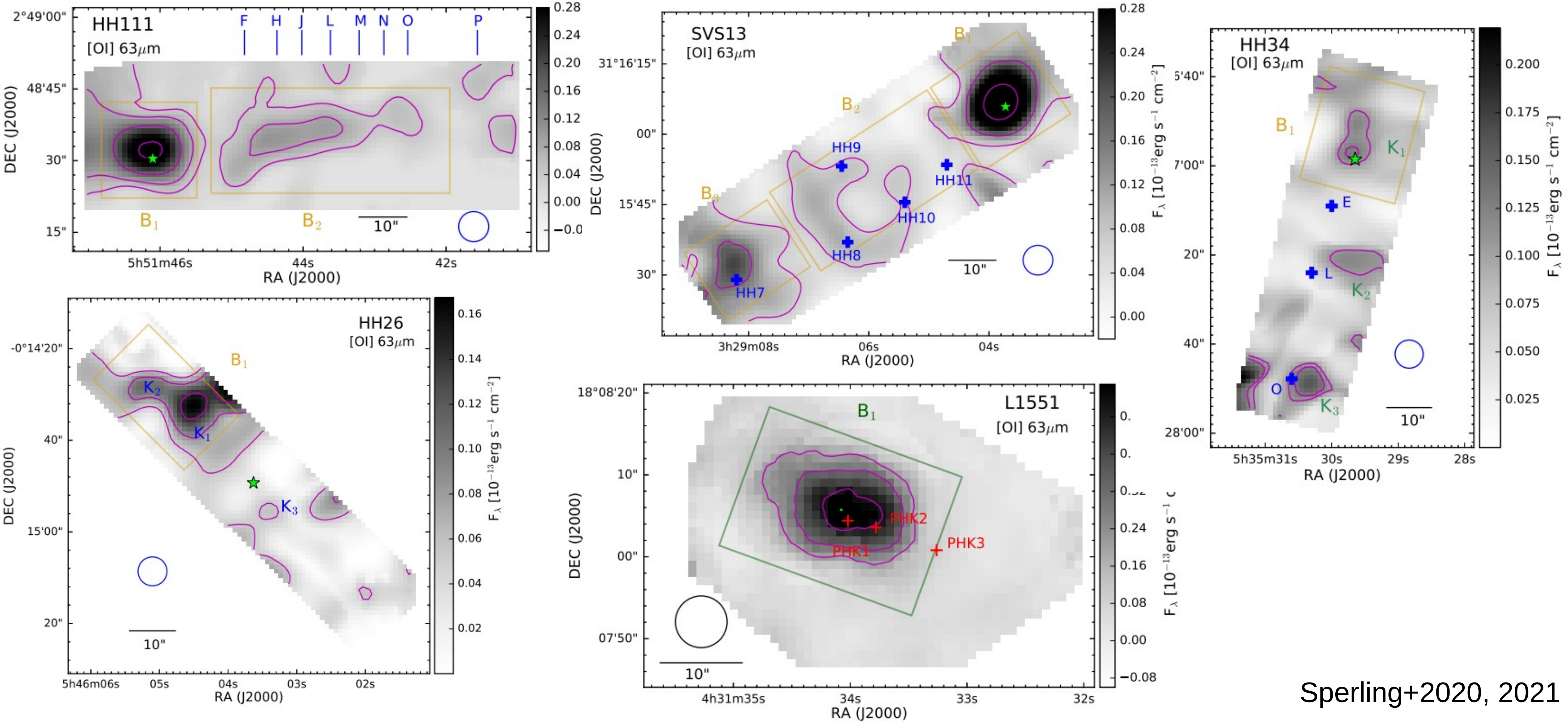
mass-loss rates derived from the [OI]63mum emission line maps.

First [OI] mappings of Class 0 outflows



Sperling+2021

First [OI] mappings of Class I outflows

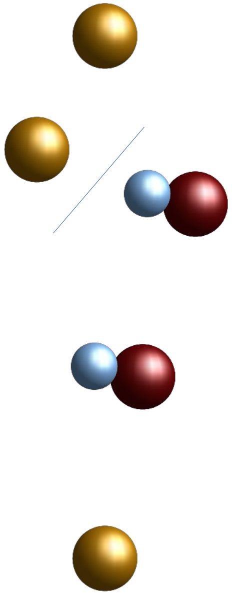


Sperling+2020, 2021

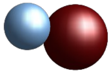
The outflow components

Target	Region	Class	$\dot{M}_{out}([O\,I])$ $10^{-7}\,M_\odot\,yr^{-1}$	$\dot{M}_{out}$ & component $10^{-7}\,M_\odot\,yr^{-1}$
HH1	VLA 1 knot A	**0**	$\lesssim 25.9 - 52.6$ $\lesssim 9.5 - 19.4$	~ 6 in [Fe II] ~ 4 in [S II] ~ 0.1 in H_2
HH212	knot A and B	**0**	$3.9 - 7.9$	~ 10 in CO, SO, SiO $\lesssim 3$ in CO, SiO ~ 1 in H_2
Cep E	knot A jet	**0**	$\lesssim 22.4 - 45.5$ $\lesssim 7.2 - 14.7$	~ 200 in CO
L1551	IRS 5	**I**	$5.8 - 11.8$	~ 8.6 in HI ~ 1.7 in [Fe II] ~ 0.4 in H_2

dominant component



 **= mainly atomic**

 **= mainly molecular**

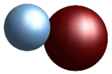
Sperling+2021

The outflow components

Target	Region	Class	$\dot{M}_{out}$([O I])	$\dot{M}_{out}$ & component
			$10^{-7}\,M_\odot\,yr^{-1}$	$10^{-7}\,M_\odot\,yr^{-1}$
HH111	HH111IRS	**I**	26 – 53	4 in CO
	jet (knots F-O)		6 – 12	2 – 6 in [O I]λ6300
SVS13	SVS13A	**I**	25 – 51	30 in HI
	HH8-11		–	8.9 in[Fe II]
	HH7		–	7.0 in H_2
HH34	HH34IRS	**I**	11 – 23	0.7 in [Fe II]
				0.03 in H_2
				~ 1.5 in[O I]λ6300
HH26	HH26A	**I**	–	0.2 – 0.5 in H_2

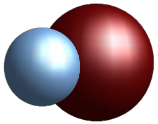
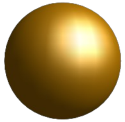
dominant component

 **= mainly atomic**

 **= mainly molecular**

Sperling+2020

Importance of [OI] outflow component

Class 0	7 out of 9 
Class I	4 out of 5 

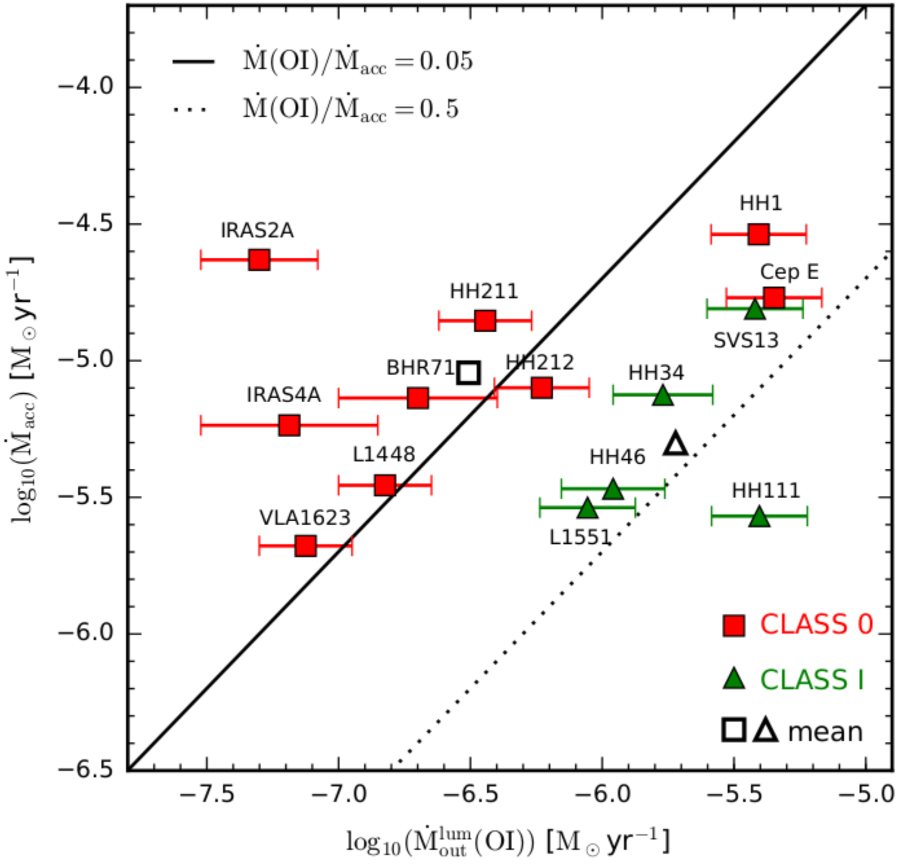
$\dot{M}(OI)$,

...underestimates the total mass-loss

...potentially traces the **bulk** mass-loss

Sperling+2021

Outflow efficiencies



- **most outflows:**

  f ~ 0.01-0.5

➔ agreement with X-wind & disk wind

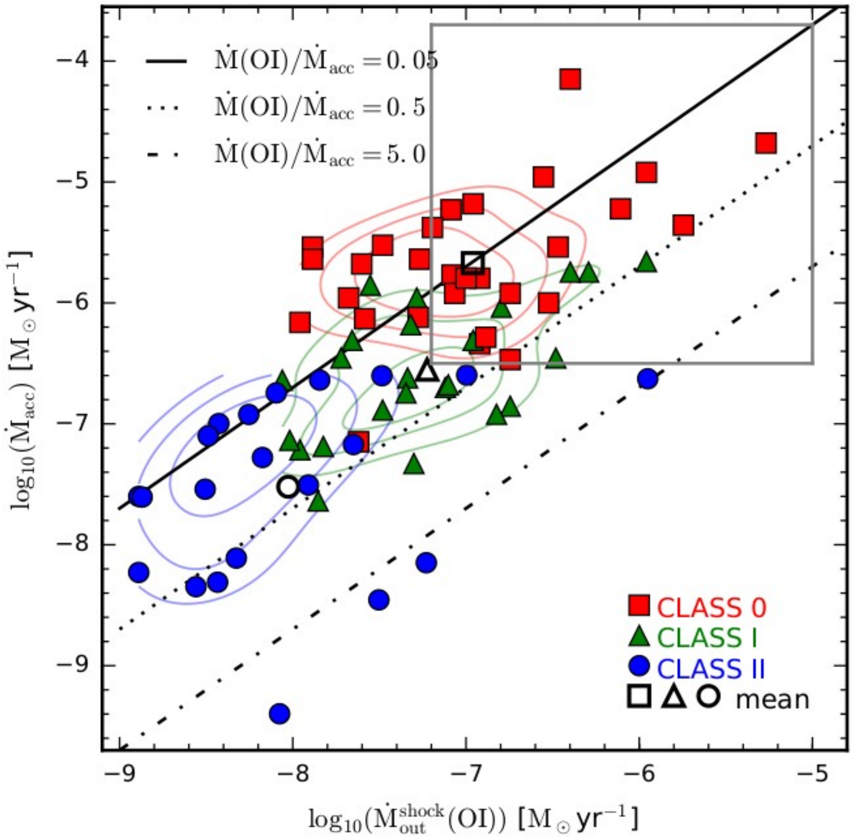
- **many Class 0 outflows**

  f <~ 0.05

➔ Must take into account the molecular component!

Sperling+2021

Comparison 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

Compilation Sperling+2021

Consistent!

Evolutionary trend apparent!

Summary

- Class 0/I outflows fully mapped in [OI] with SOFIA/FIFI-LS
- Determination of mass-loss rates and efficiencies
- Outflows initially mostly molecular, becoming more atomic with time