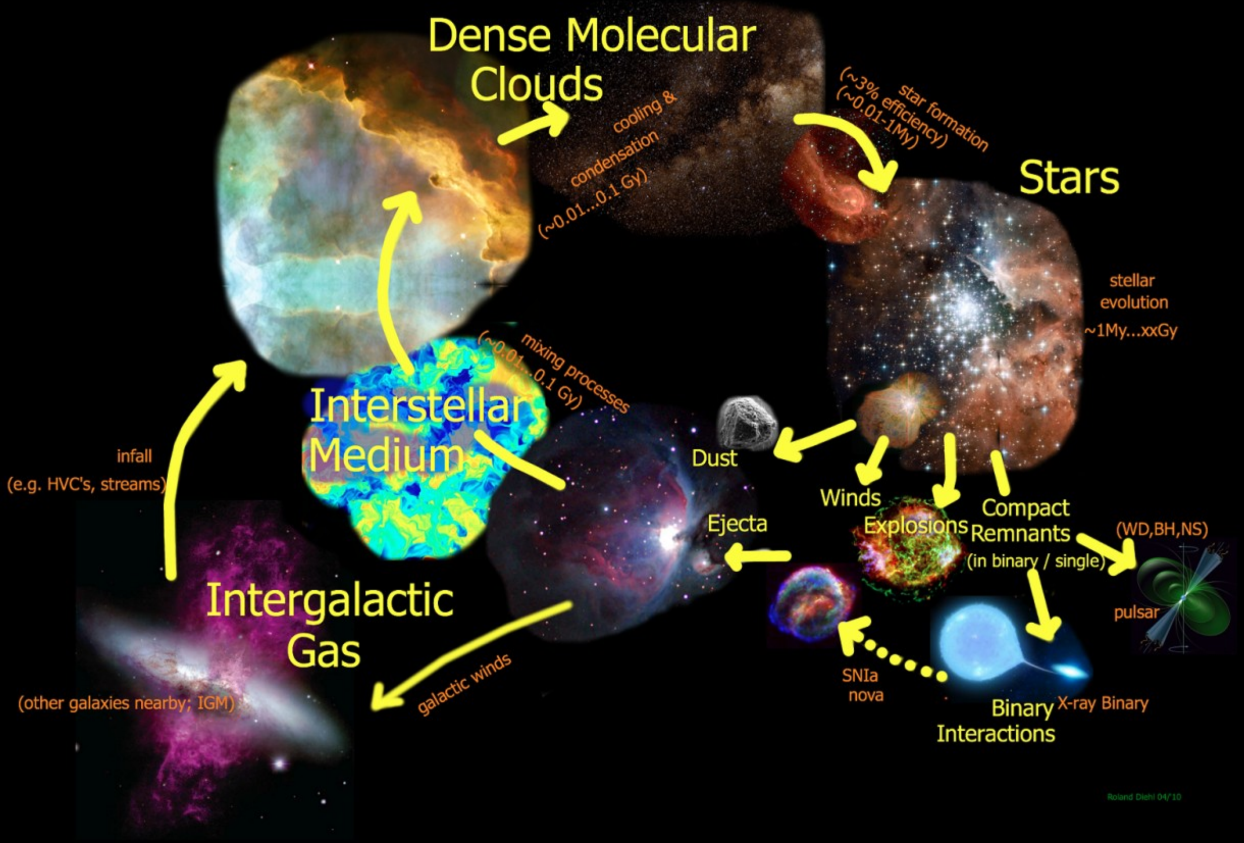
H_2 emission from non-stationary magnetized bow shock

by

Le Ngoc Tram

collaborating with

Lesaffre. P, Cabrit. S, Nhung. P, Gusdorf. A, Reach. B. W, Neufeld. D



Dense Molecular Clouds

cooling & condensation (~0.01...0.1 Gy)

star formation (~3% efficiency) (~0.01-1My)

Stars

stellar evolution ~1My...xxGy

Dust

Winds

Explosions

Compact Remnants (in binary / single)

(WD,BH,NS)

pulsar

Binary Interactions

X-ray Binary

SNIa nova

Ejecta

Interstellar Medium

mixing processes (~0.01...0.1 Gy)

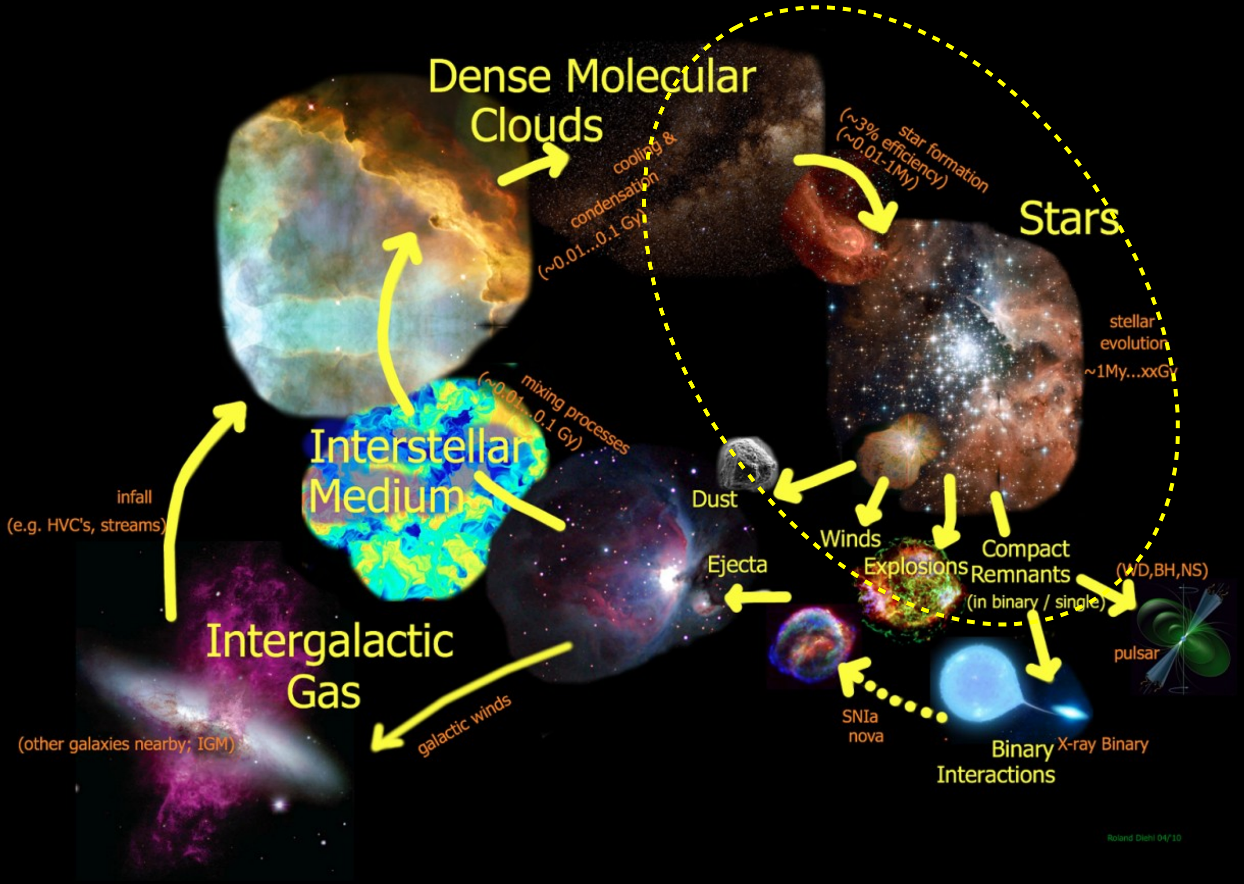
galactic winds

Intergalactic Gas

(other galaxies nearby; IGM)

infall (e.g. HVC's, streams)

Roland Diehl 04/'10



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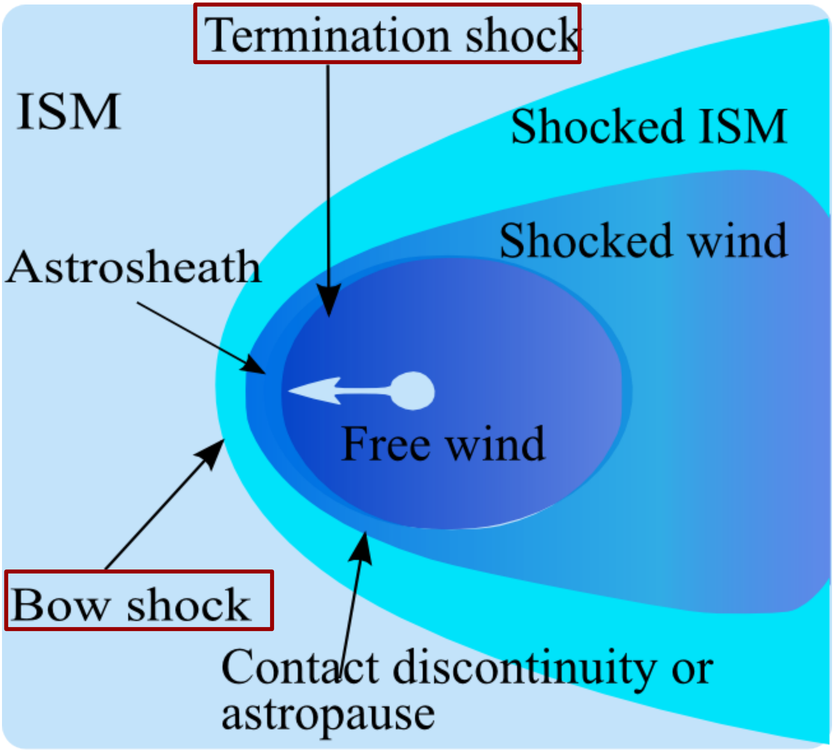
Roland Diehl 04/'10

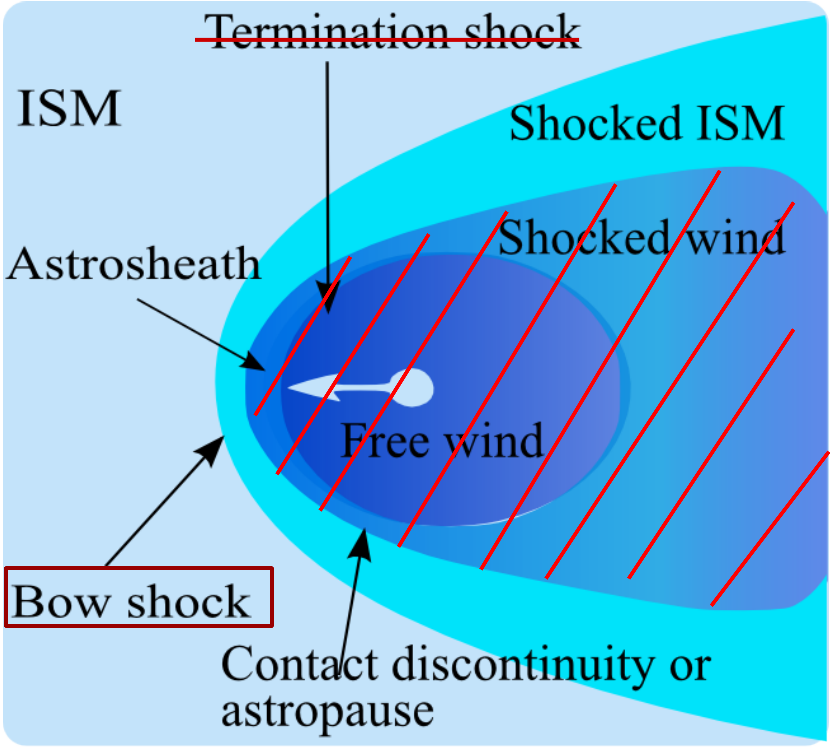
Interstellar shocks configuration



- **Bow shock (forward shock):** formed in the ambient materials.

- **Termination shock (reverse shock):** formed in the stellar wind/Jet materials.

Bow shock (forward shock)



- **Bow shock (forward shock):** formed in the ambient materials.

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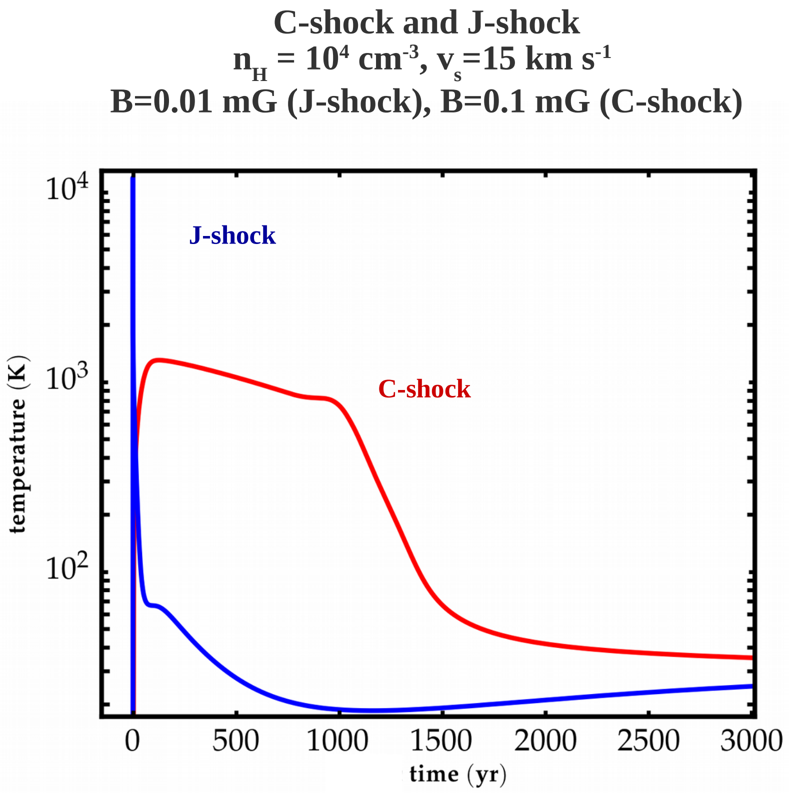
Contents

Stationary shock waves: J-shock and C-shock



- Absent/weak magnetic field
- Large Ionization fraction

J-shock $(v_s > v_{ims})$

- Strong magnetic field
- Small ionization fraction

C-shock $(v_s < v_{ims})$

➢ Magnetosonic speed in charged fluid

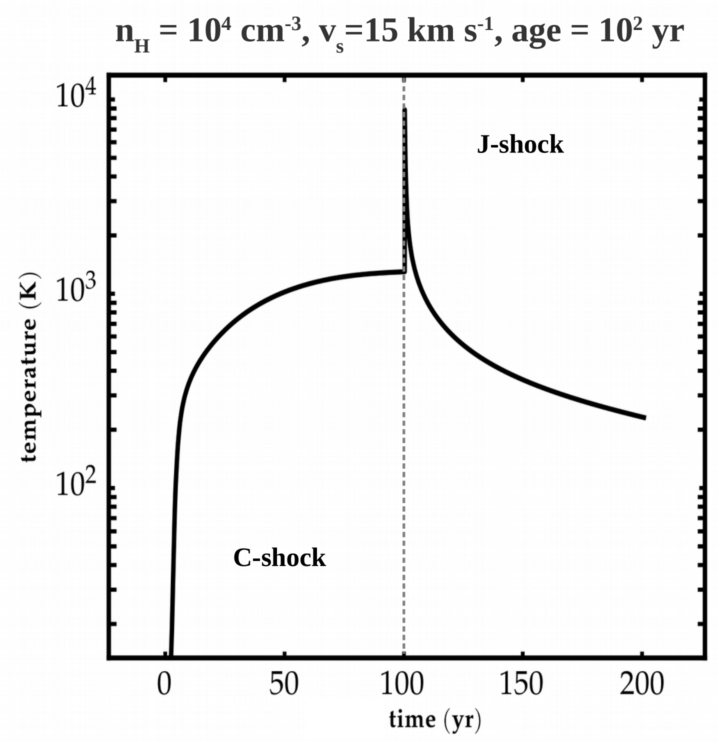
$$v_{ims} = \sqrt{v_{iA}^2 + c_s^2} \sim v_{iA} = \frac{B}{\sqrt{4\pi\rho_i}}$$

Young shock waves: CJ-shock

(Chièze et al., 1998; Lesaffre et al., 2004)

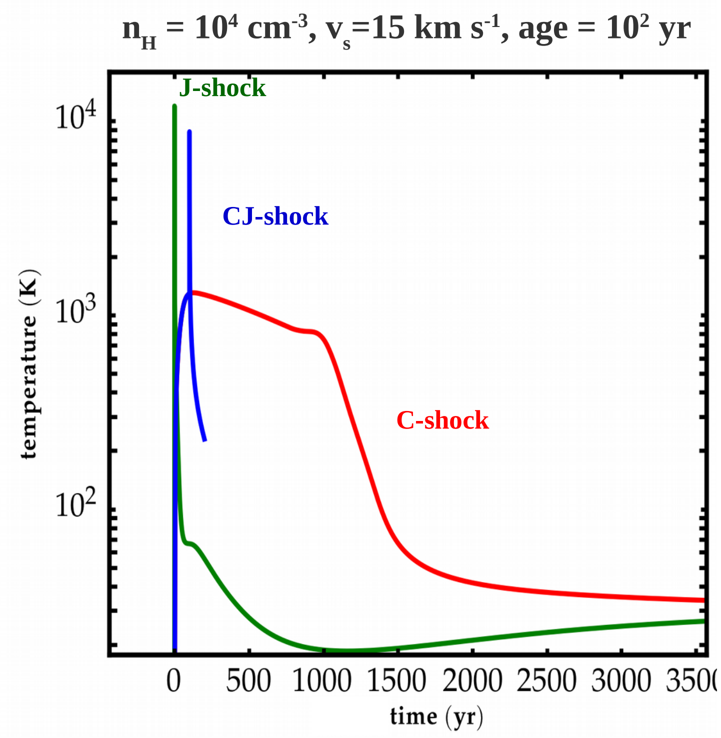
CJ-shock

$n_H = 10^4$ cm^{-3}, v_s=15 km s^{-1}, age = 10^2 yr



J-shock, C-shock and CJ-shock

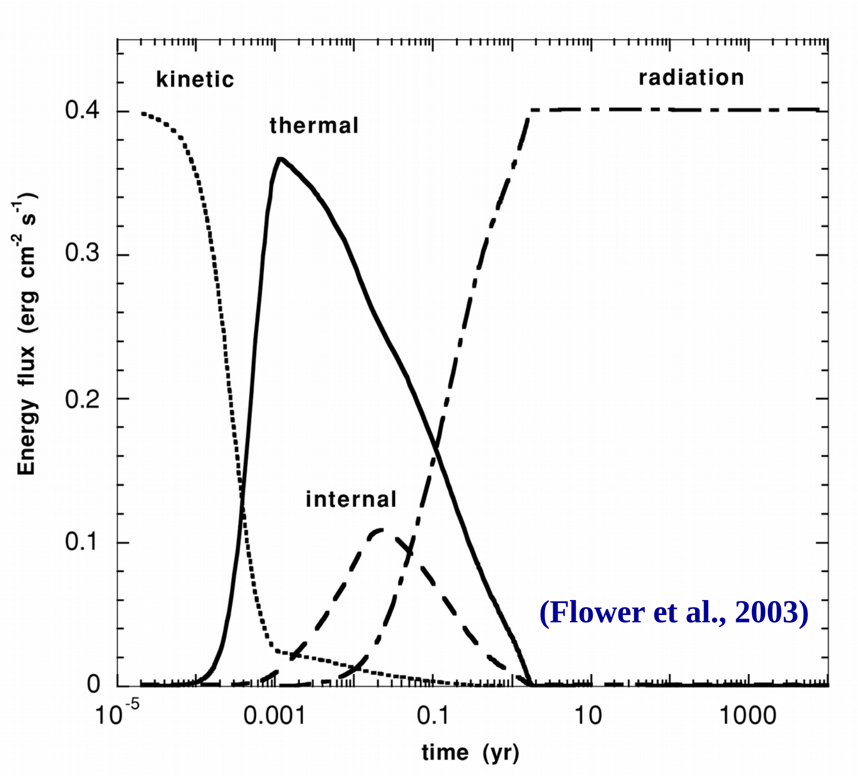
$n_H = 10^4$ cm^{-3}, v_s=15 km s^{-1}, age = 10^2 yr



Energy transfer through a shock

J-shock

$n_H = 10^5\ cm^{-3}$, v_s=15 km s^{-1}, B = 0



(Flower et al., 2003)

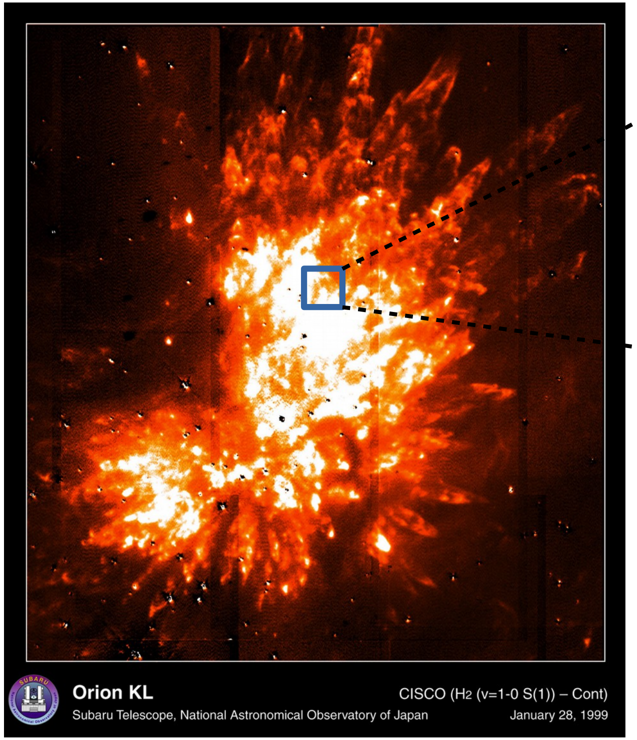
<u>During the shock</u>

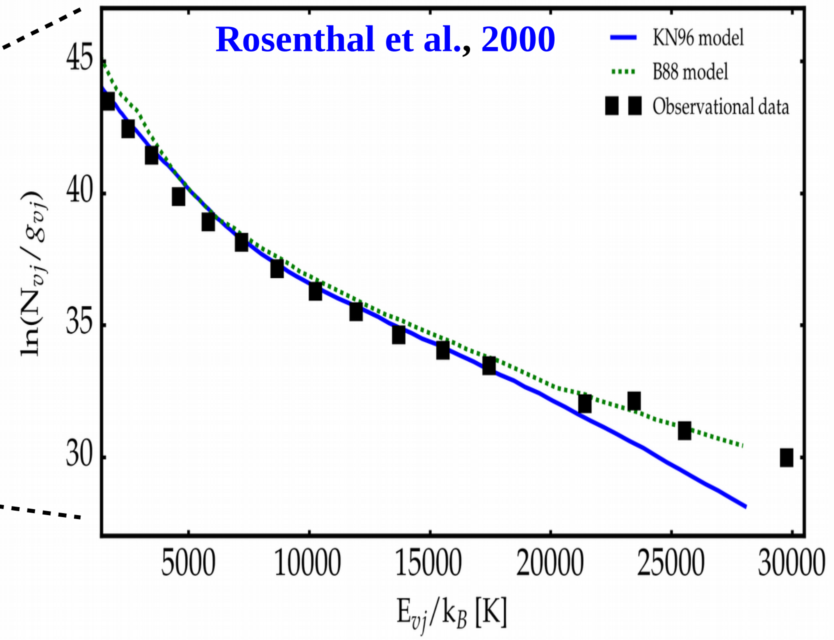
- Kinetic energy goes to thermal energy
- Thermal energy excites the molecular gas
- Molecular gas radiates through de-excitation

→ H_2 is one of the best shock tracers

1D shock models to interpret observations

Orion molecular cloud OMC-Peak1



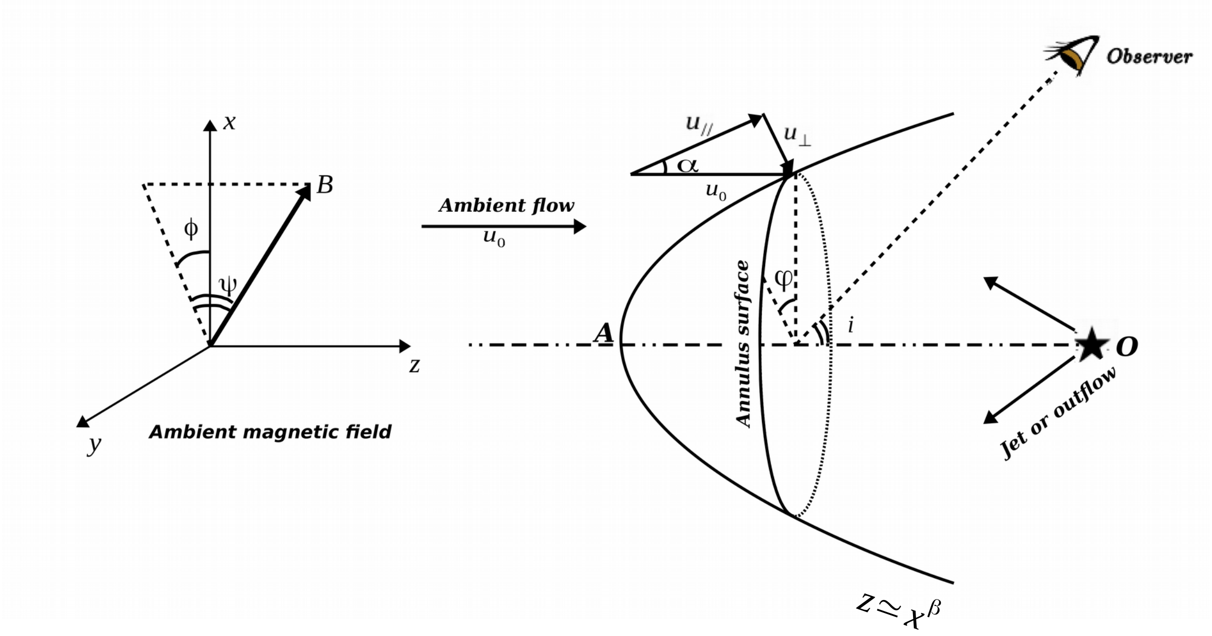

Rosenthal et al., 2000

<u>One single planar shock model cannot</u> reproduce observations

- ➢ good at **“low”** excitation energy (KN96)
- ➢ good at **“high”** excitation energy (B88)

3D shock model approximation

- Running 2D, 3D numerical MHD simulations: hard to do properly
- **Give a bow shape**, each surface element considered as an **independent** 1D shock model



First introduced by Smith et al.,1990

Validation of 3D shock model approximation

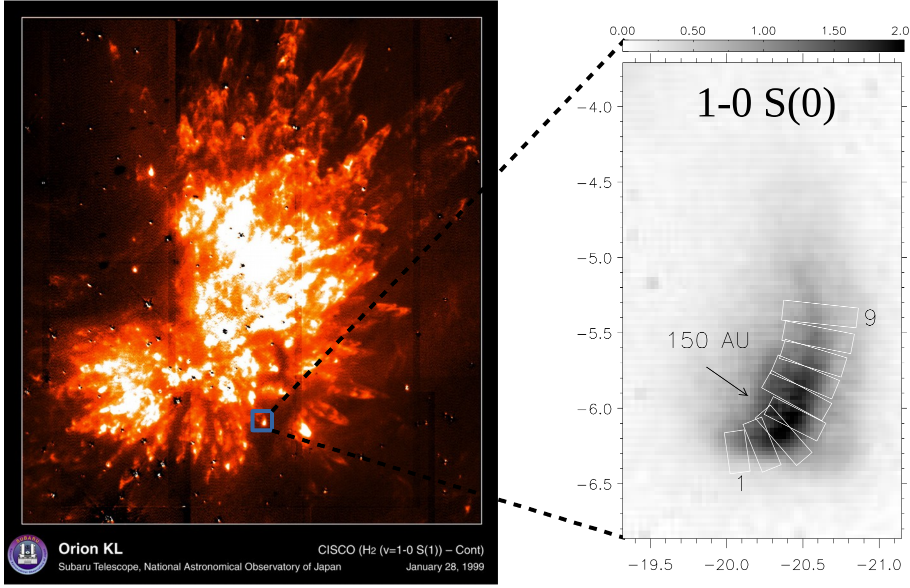
- Collection of steady-state C-shocks
- Non-equilibrium chemistry, ionization and cooling
- Bow shock shape: $z \simeq x^{\beta}$

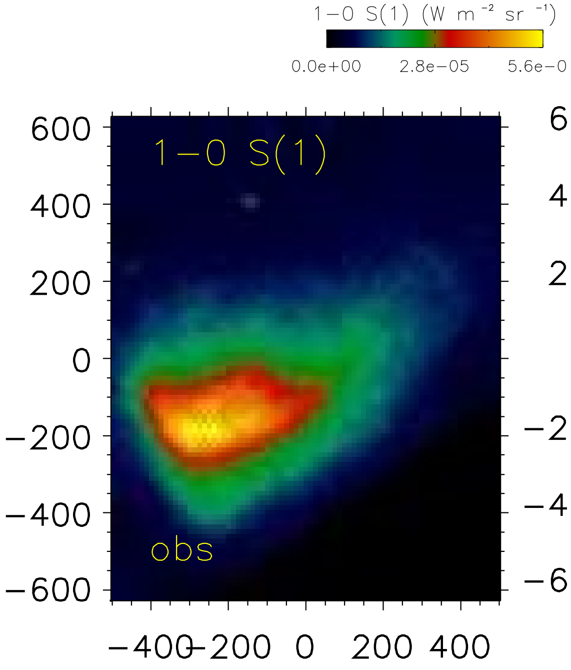
}

(1D Paris-Durham code)

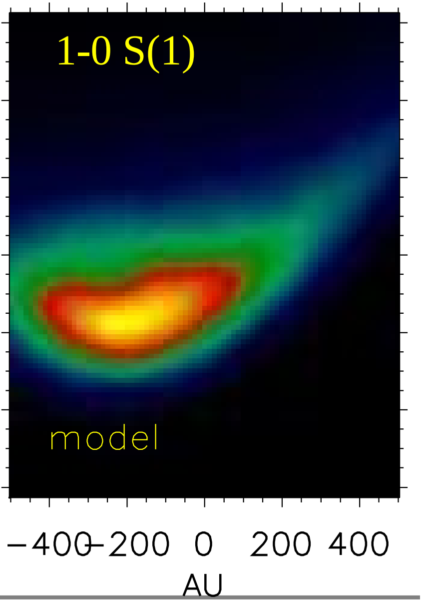
(Flower & Pineau des Forêts, 2015)

Kristensen et al., 2008





Gustafsson et al., 2010



3D shock model

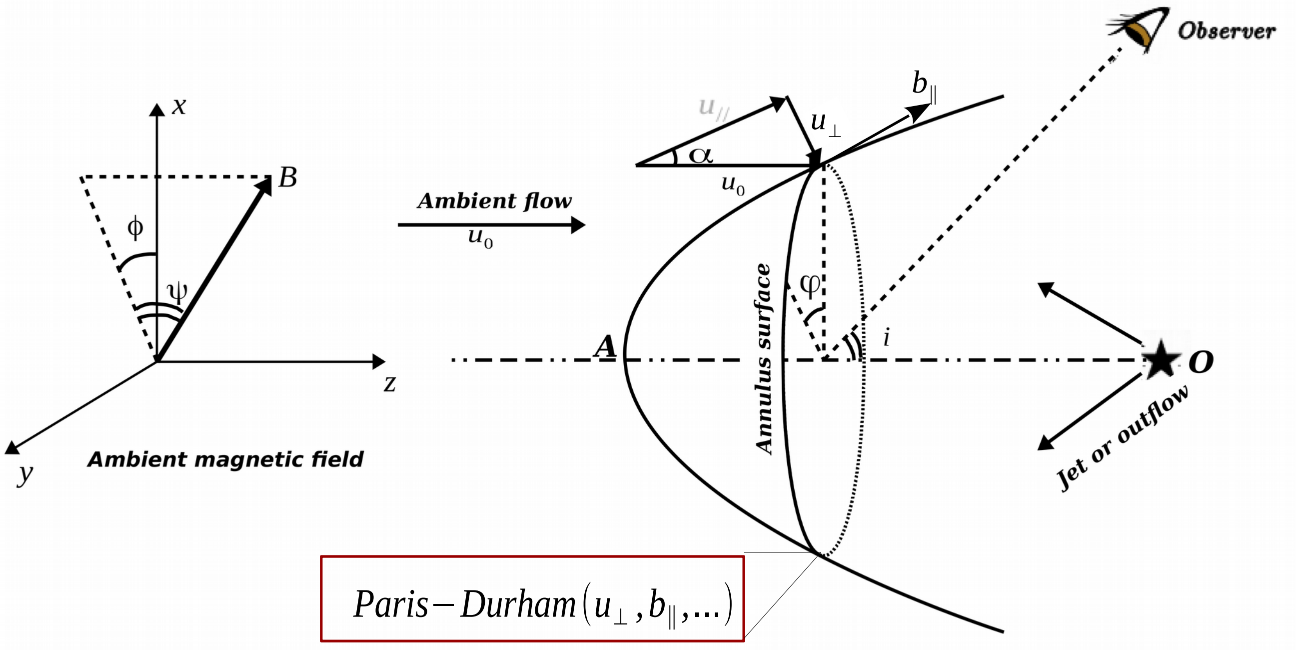
- Collection of steady-state C-shocks, **J-shocks and CJ-shocks**
- Non-equilibrium chemistry, ionization and cooling
- Distribution of 1D shock models, **arbitrary shape of shock**
- Integrated **H_2 excitation diagrams** and **H_2 line profiles**

}

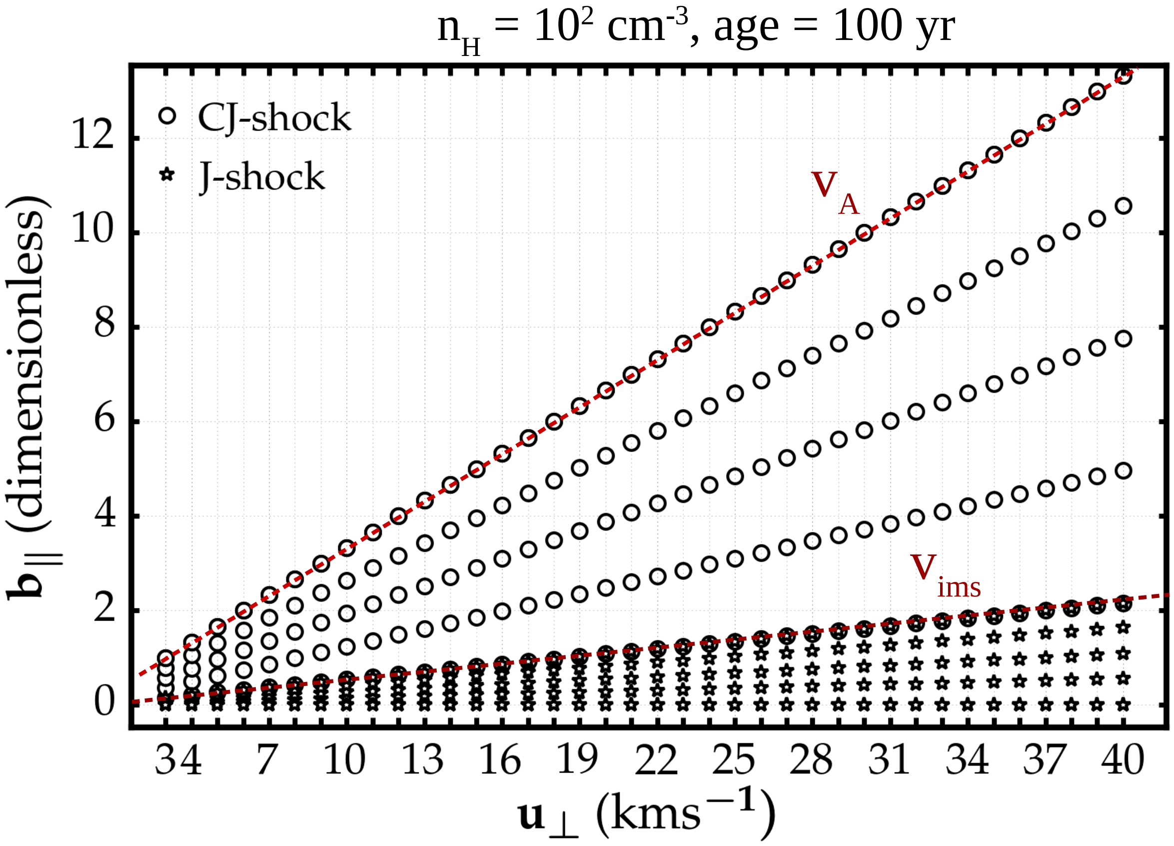
(1D Paris-Durham code)

(Flower & Pineau des Forêts, 2015)

parameters	descriptions
u_0	Terminal shock velocity
n_H	Number density
$b_0 = B(\mu G)/\sqrt{nH(cm^{-3})}$	Magnetization parameter
Shock age	Dynamical shock age
Ψ	Bfield inclination
β	Shock shape
i	Viewing angle



Grid of 1D planar Paris-Durham models

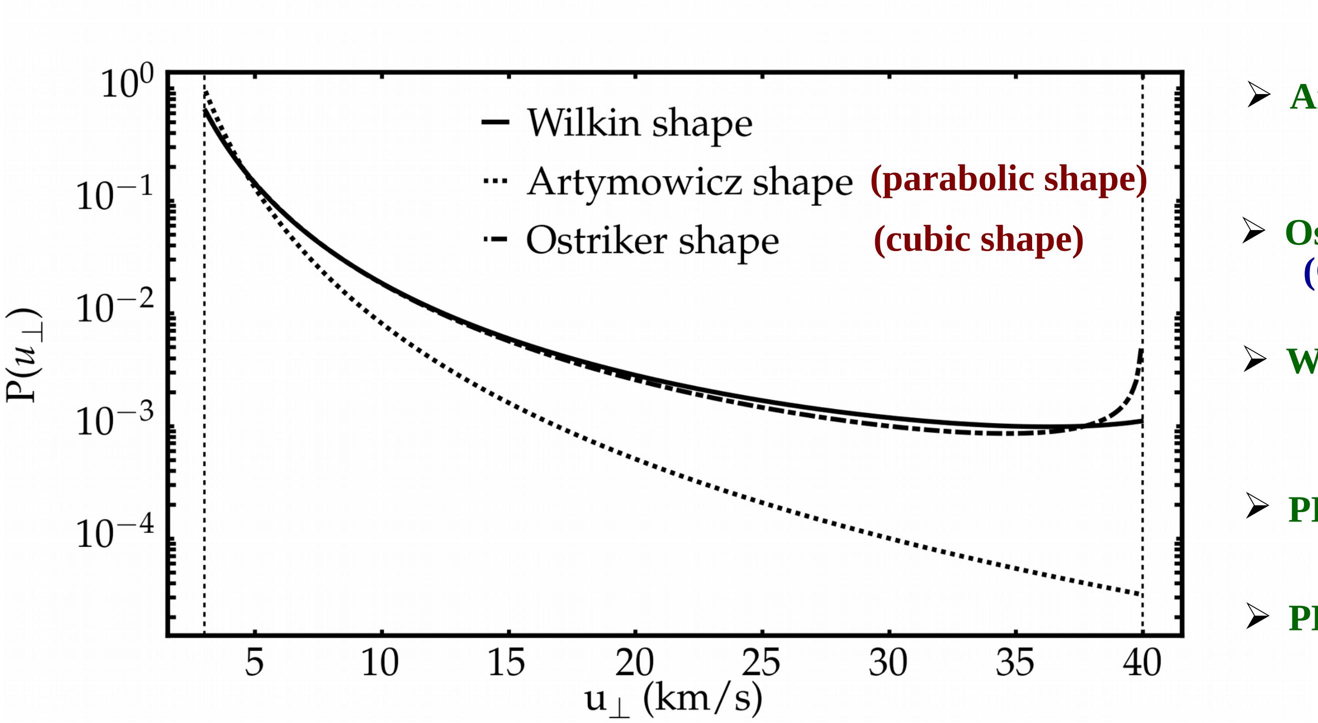


$n_H = 10^2$ cm^{-3}, age = 100 yr

$v_{m1} = 18.5$ kms^{-1} for $n_H = 10^2$ cm^{-3}

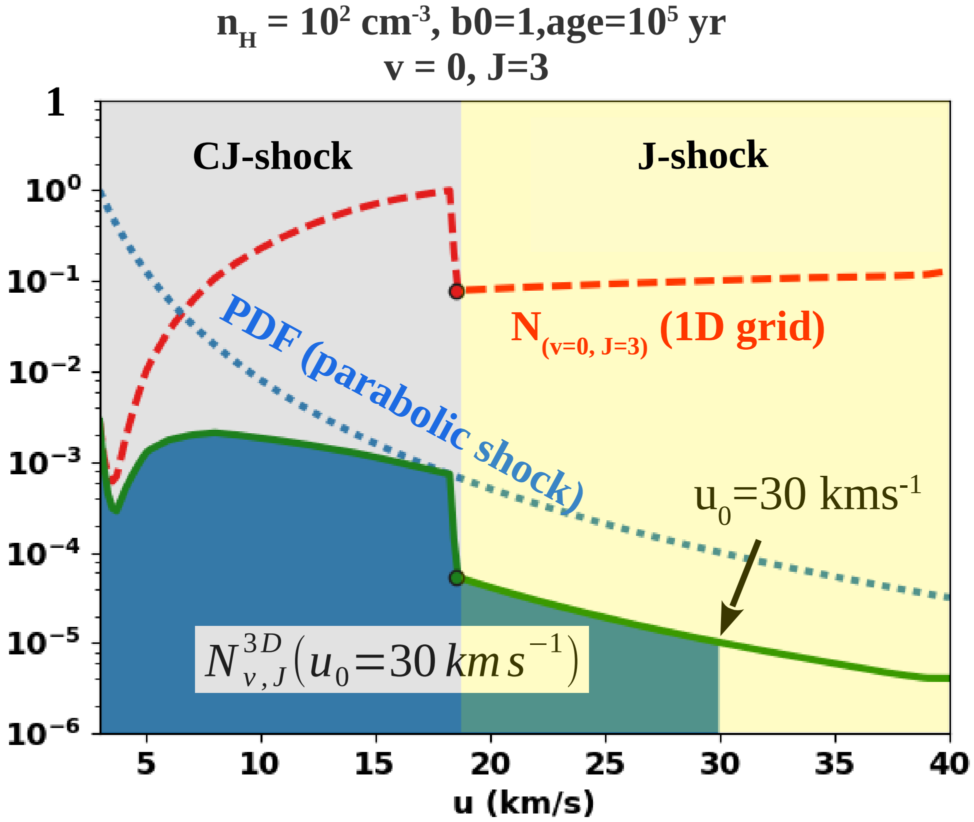
$v_{m1} = 19.2$ kms^{-1} for $n_H = 10^4$ cm^{-3}

Distribution of 1D shock model on working surface



- **Artymowicz: dust cloud – radiation interaction (Artymowicz and Clampin, 1997)**
- **Ostriker: Jet-driven shock (Ostriker et al., 2001)**
- **Wilkin: wind-cloud interaction (Wilkin., 1996)**
- **PDF is dominated by low shock velocities**
- **PDF(cubic) has a spike due to its flatness**

Population of H_2 excited levels

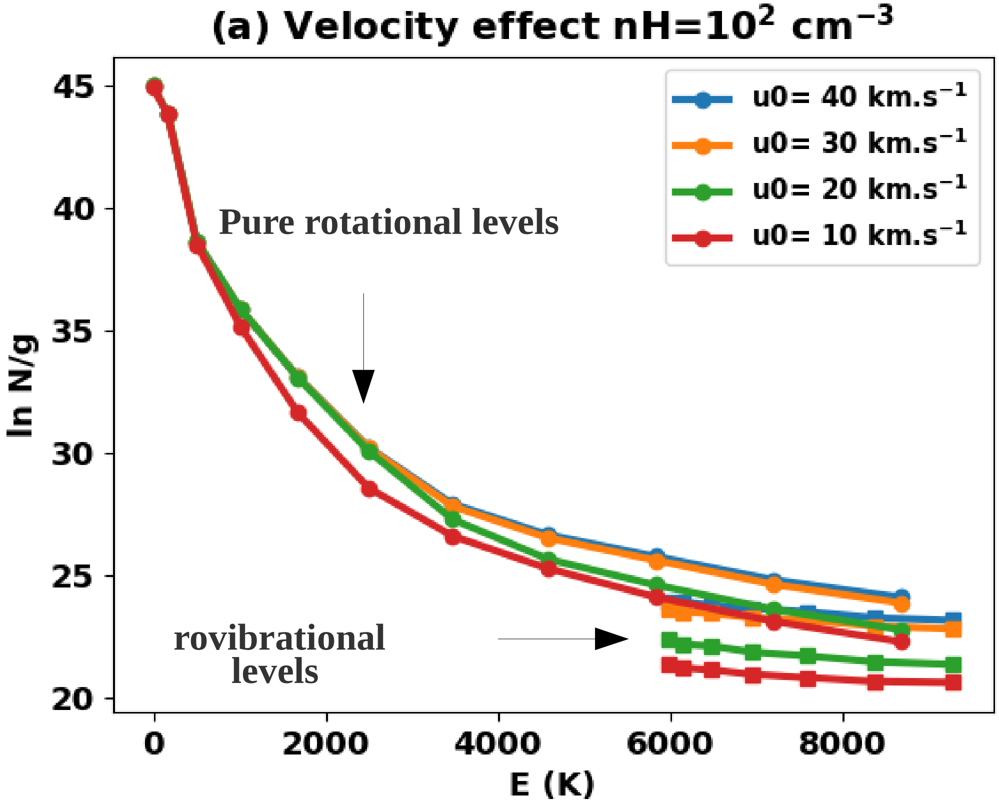


Column density of a (v,J) level in the bow

$$N^{3D}_{v,J}(u_0) \sim \int_{cs}^{u_0} PDF_{u_0}(u_\perp)\, N^{1D}_{v,J}(u_\perp, age, b_\parallel)\, du_\perp$$

- Population of H_2 excited level starts saturating at high terminal shock velocities.

Integrated H_2 excitation diagram of bow shocks


(a) Velocity effect nH=10^2 cm^{-3}

Pure rotational levels

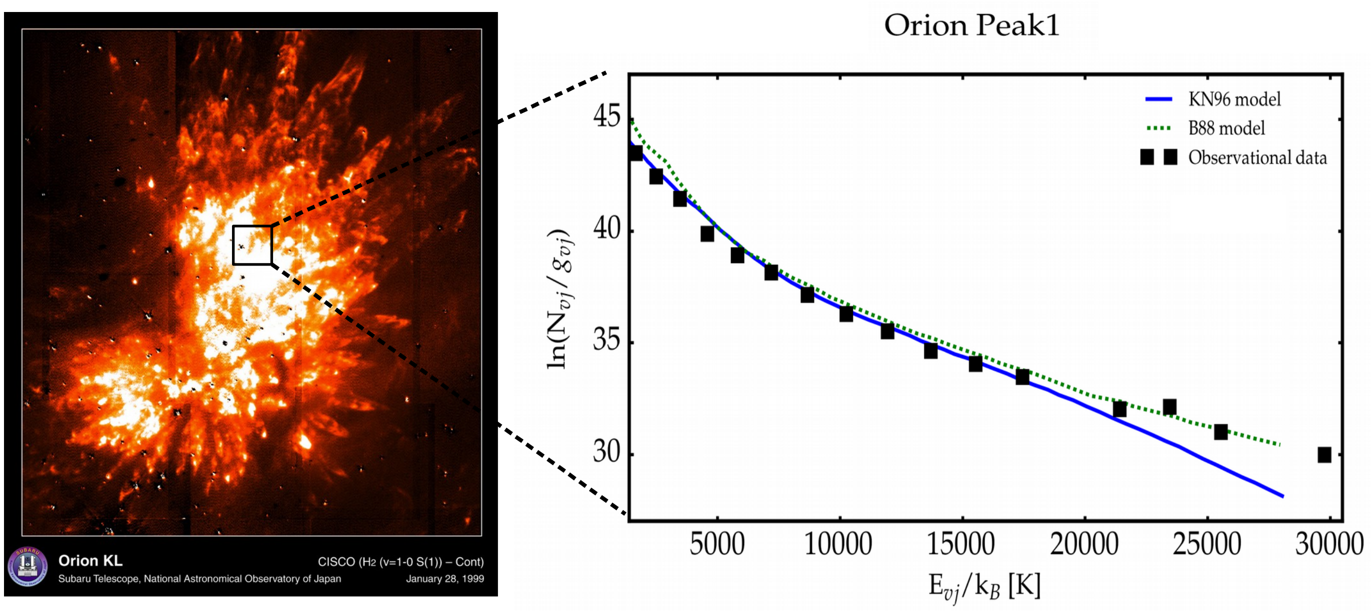
rovibrational levels

Tram et al., 2018

Contents

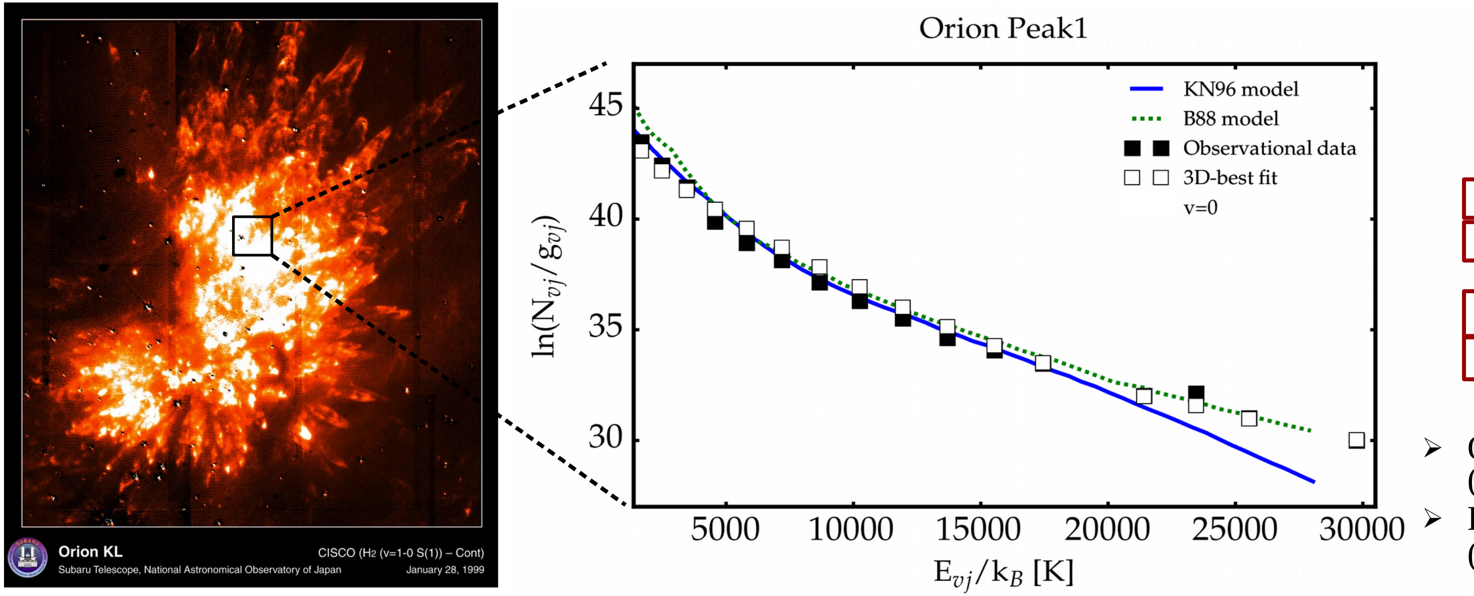
3D H_2 diagram to interpret observations

OMC – Peak 1



3D H_2 diagram to interpret observations

OMC – Peak 1



Parameter	Value
n_H	10^6 cm^{-3}
b_0	4.5 ± 0.9
u_0	≥ 30 km s^{-1}
Age	10^3 yr
ψ	$90^o \pm 30^o$
β	2.1 ± 0.2

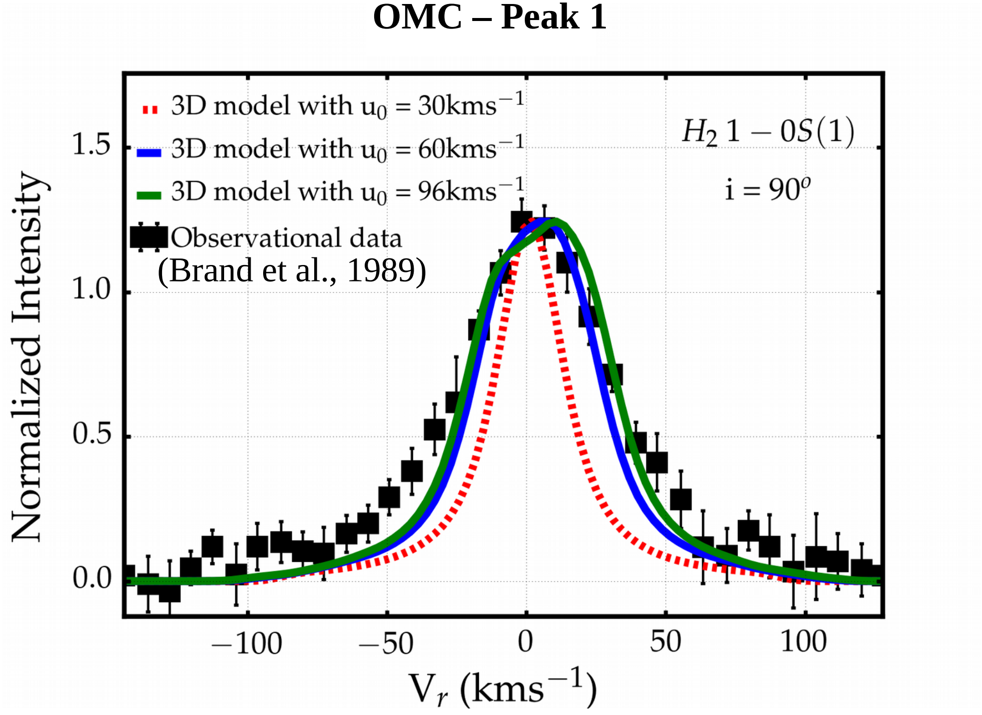
- OH observations: **B ~ 3 mG** (Norris,1984)
- Polarization observation: **B ~ 10 mG** (Chrysostomou et al.,1994)

Tram et al., 2018

H_2 line profile to interpret observations

Tram et al., 2018

OMC – Peak 1



- We constrain **u_0 ~ 100 km/s,** in good agreement with the proper motion of the bullet
- We constrain **i ~ 90^o**

Parameter	Value
n_H	10^6 cm^{-3}
b_0	4.5 ± 0.9
u_0	100 km s^{-1}
Age	10^3 yr
ψ	$90^o \pm 30^o$
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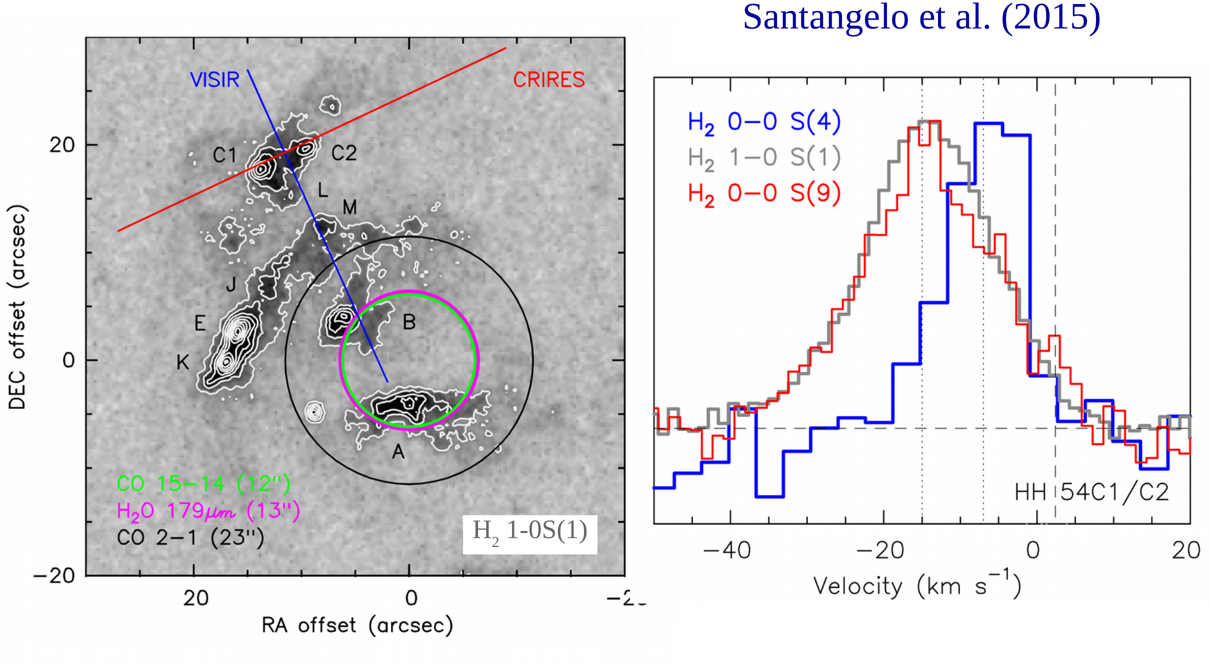
H_2 line profile to interpret observations

HH54 observations

Santangelo et al. (2015)



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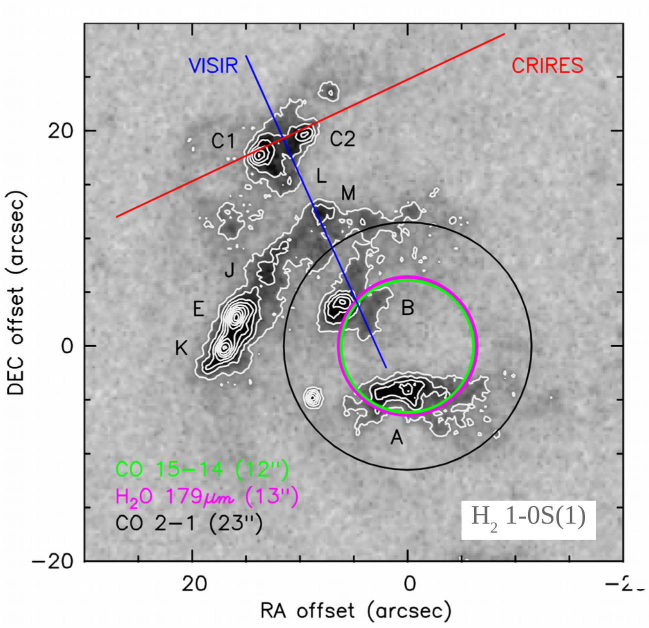

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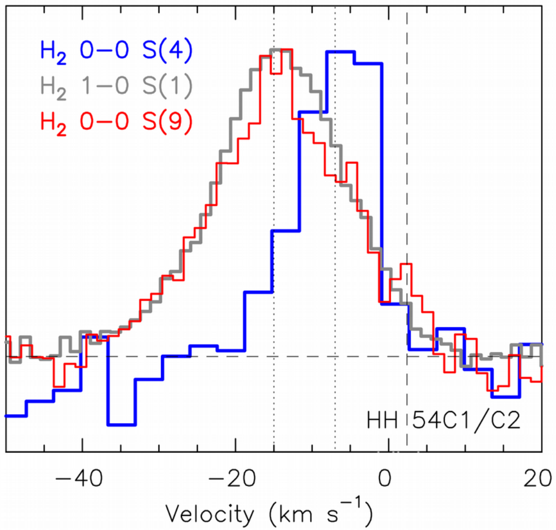


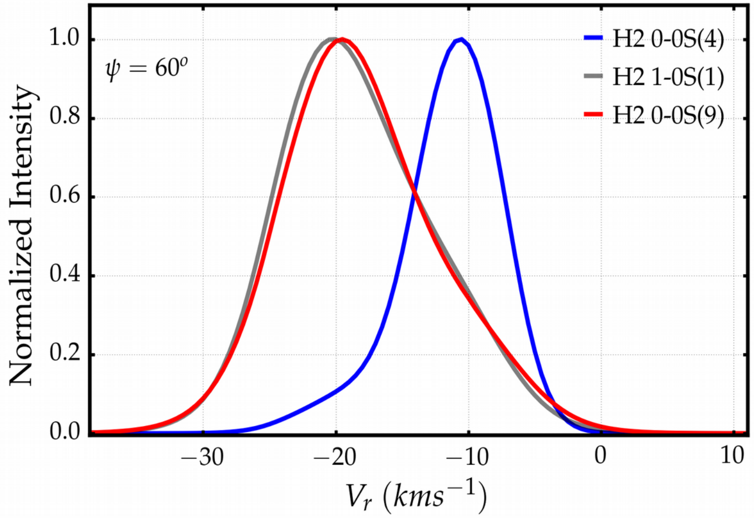
0-0S(4): E_{up} ~ 3500 K

1-0S(1): E_{up} ~ 6900 K

0-0S(9): E_{up} ~ 10261 K

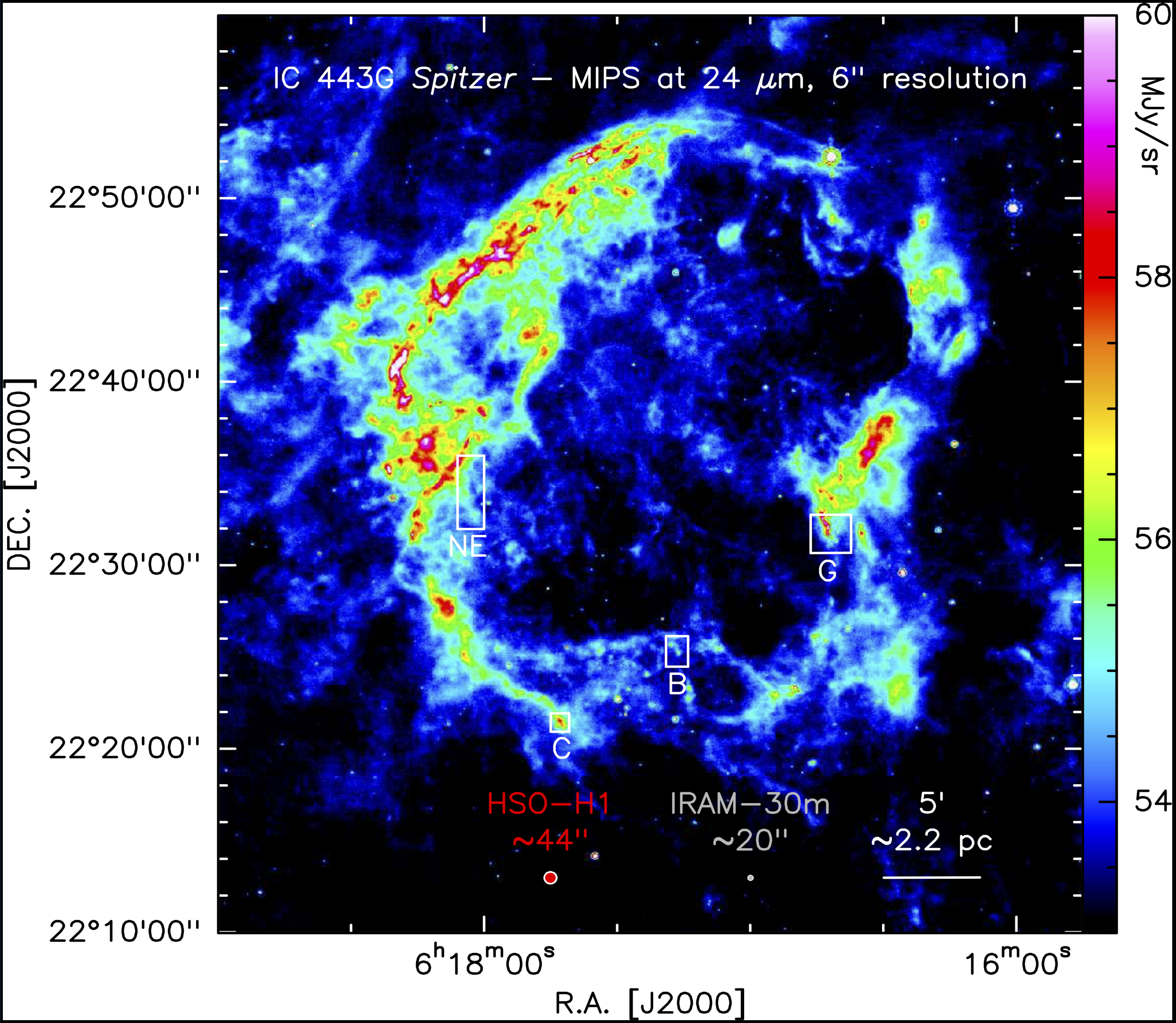
Bow shock

n_H = 10^4 cm^{-3}, u_0=20 km s^{-1}, age =10^2 yr, b_0 = 1, i=-60°



HH7 SOFIA/EXE (PI: Neufeld.D)

Contents



SNR IC443

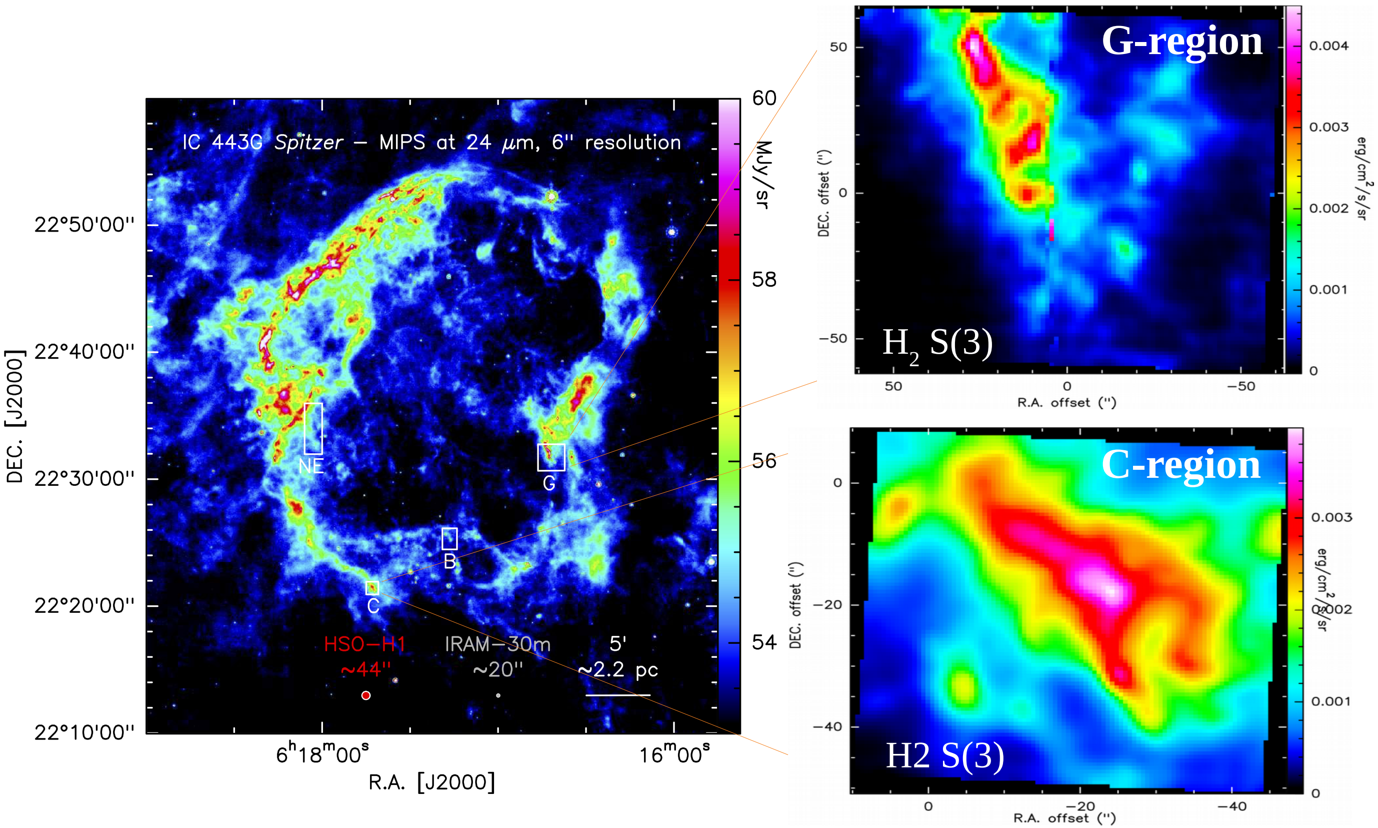
Position: ~ 1.5 kpc

Estimated age: 20,000 yr

Contains of many shocked regions:
8 clumps (A-H) via CO, HCO+ lines

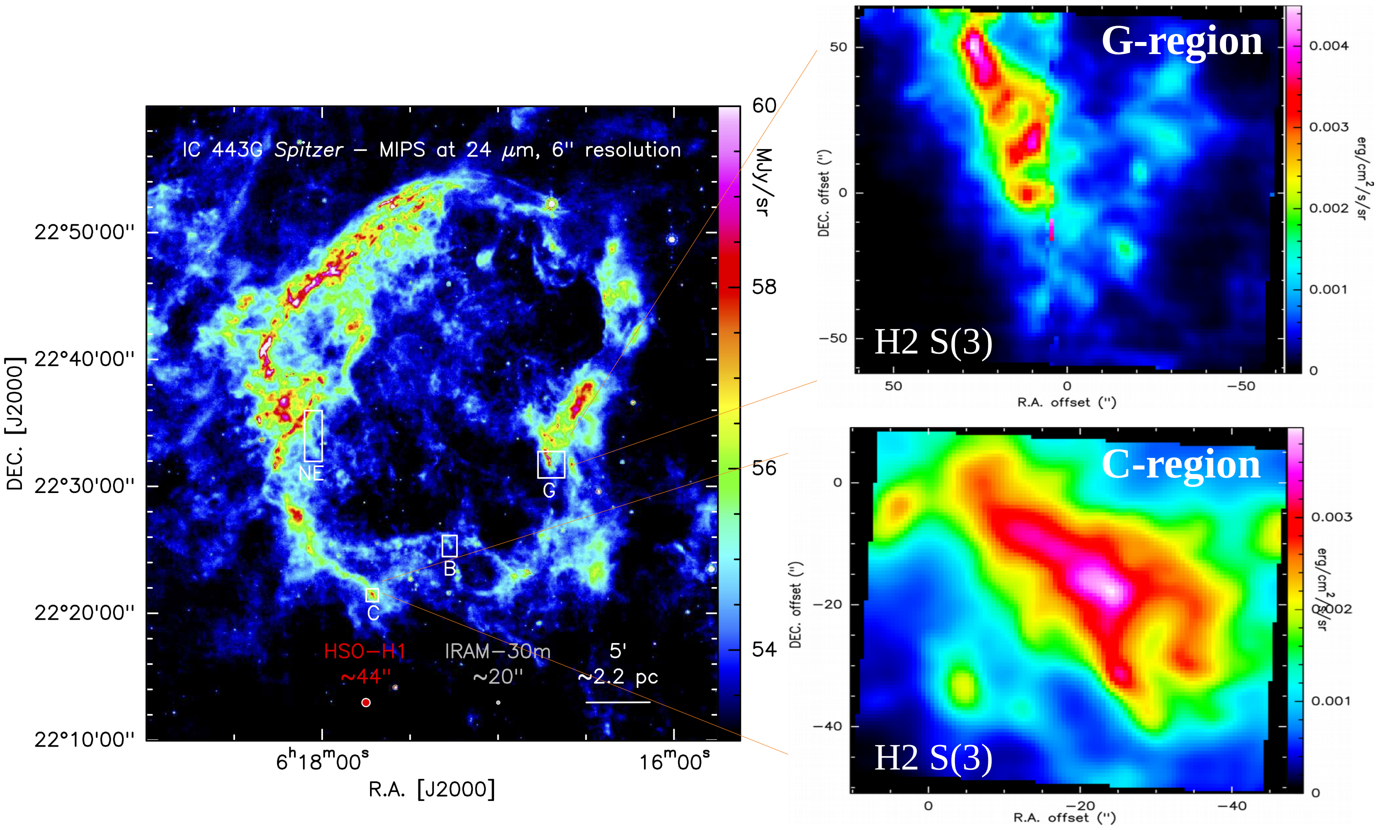
Combination of shocks are needed to explain the emission seen in these atomic and molecular racers

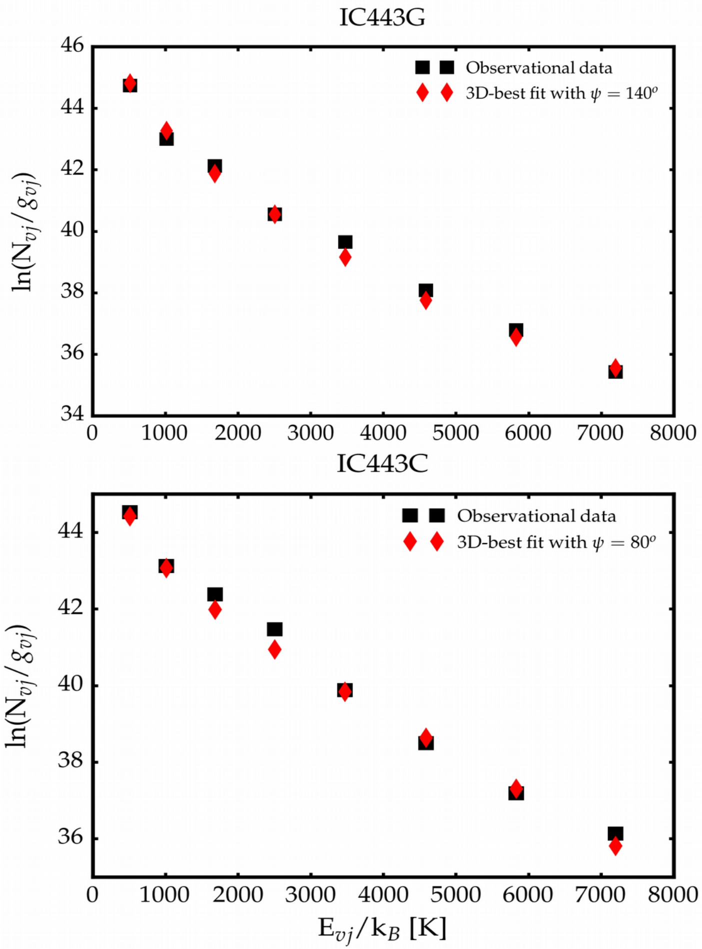
SNR IC443 as seen by Spitzer-IRS



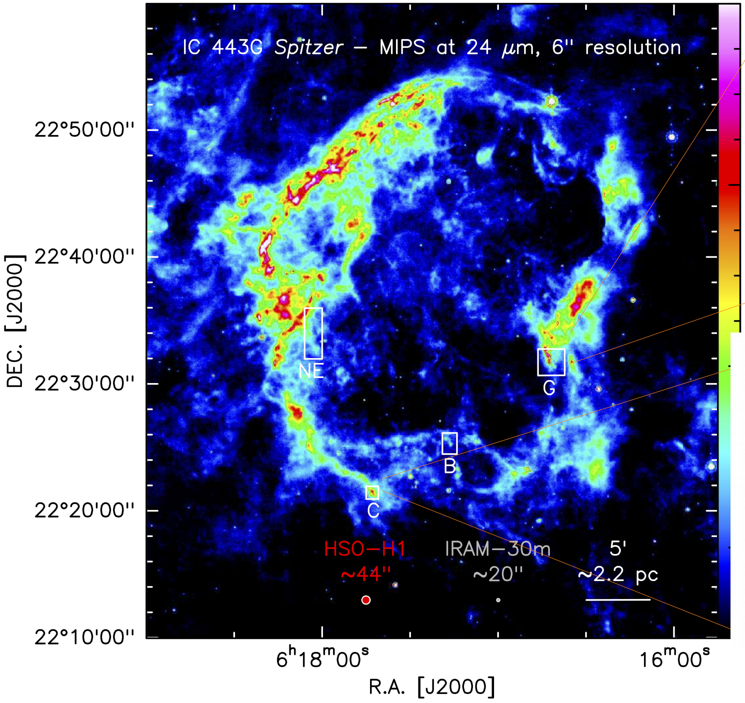
(Neufeld et al. 2007)

SNR IC443 as seen by Spitzer-IRS

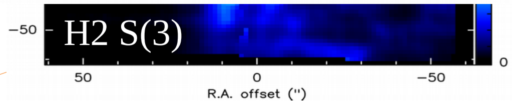




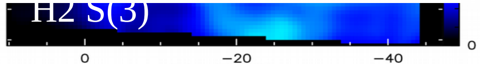
SNR IC443 as seen by Spitzer-IRS

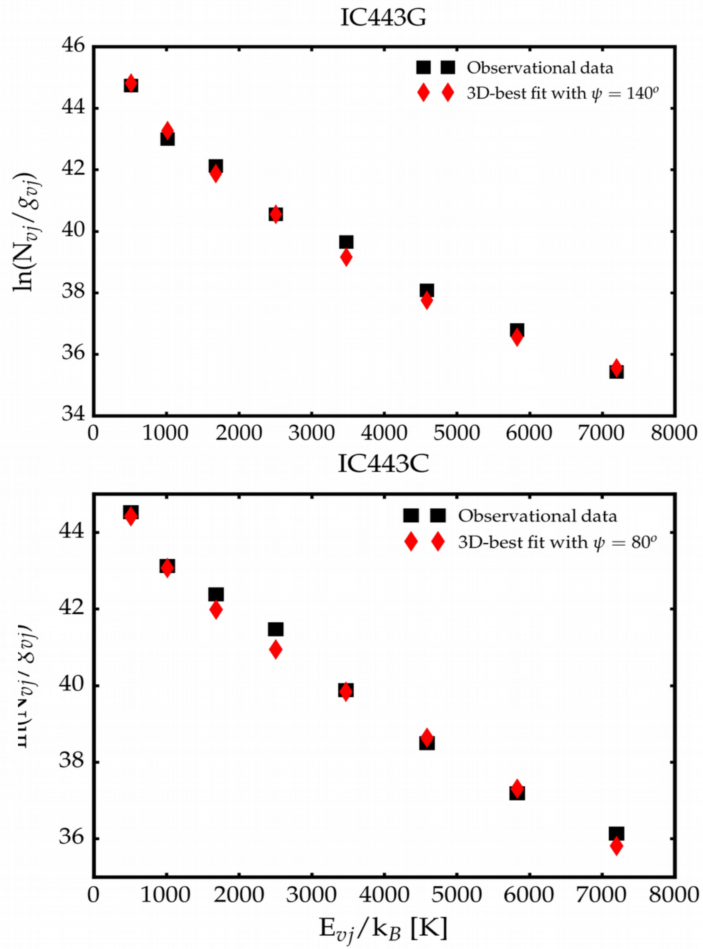


Parameters	**Values**
n_H	10^4 cm^{-3}
b_0	4
v_s	[12-38] km.s^{-1}
age	5.10^3 yr
psi	140°



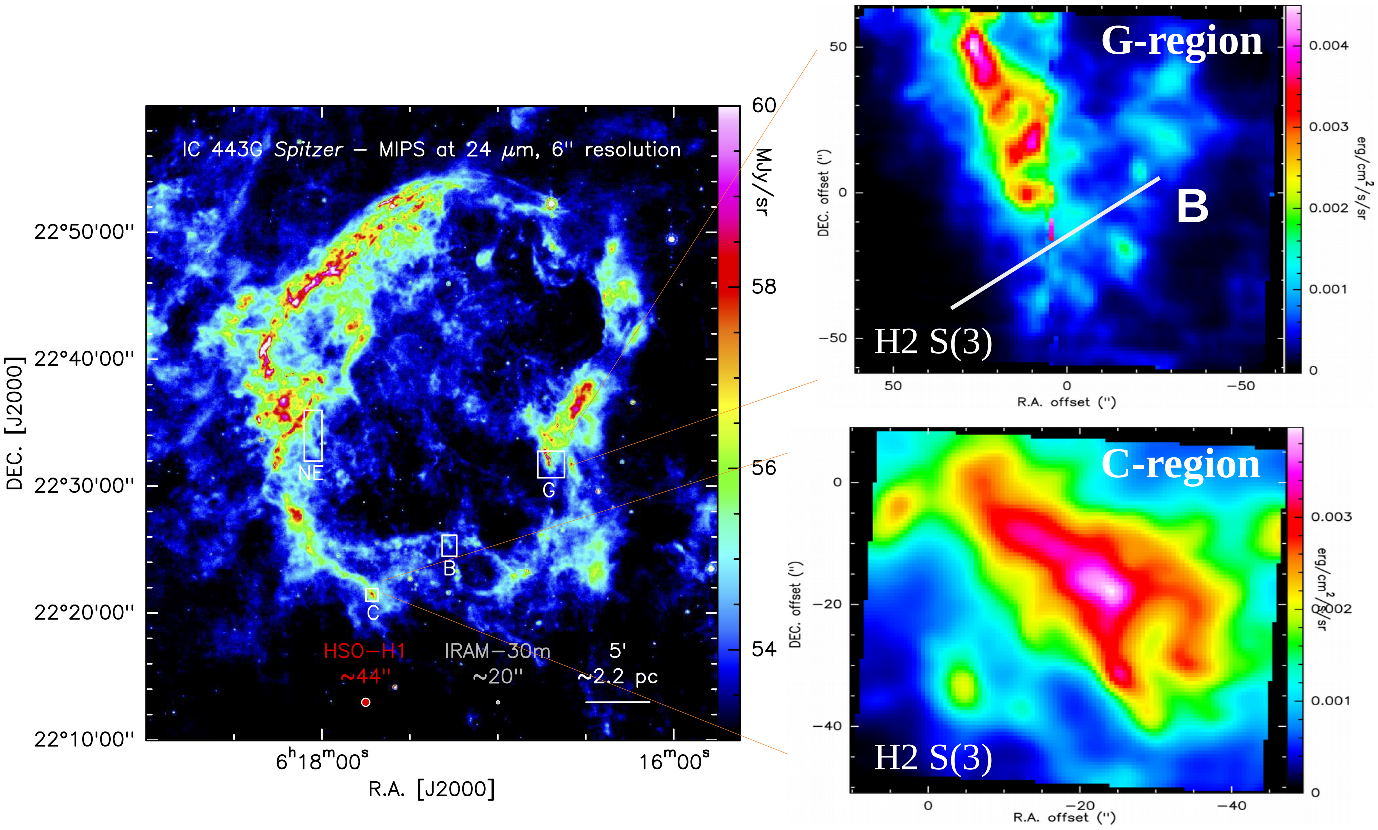
Parameters	**Values**
n_H	10^6 cm^{-3}
b_0	2
v_s	[25-32] km.s^{-1}
age	10^3 yr
psi	80°

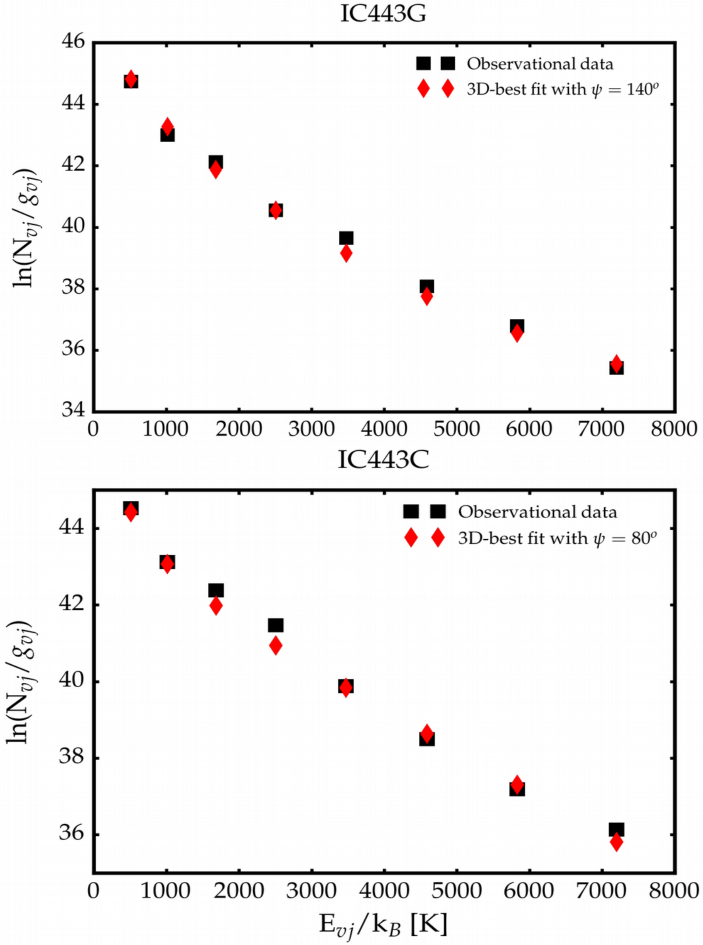




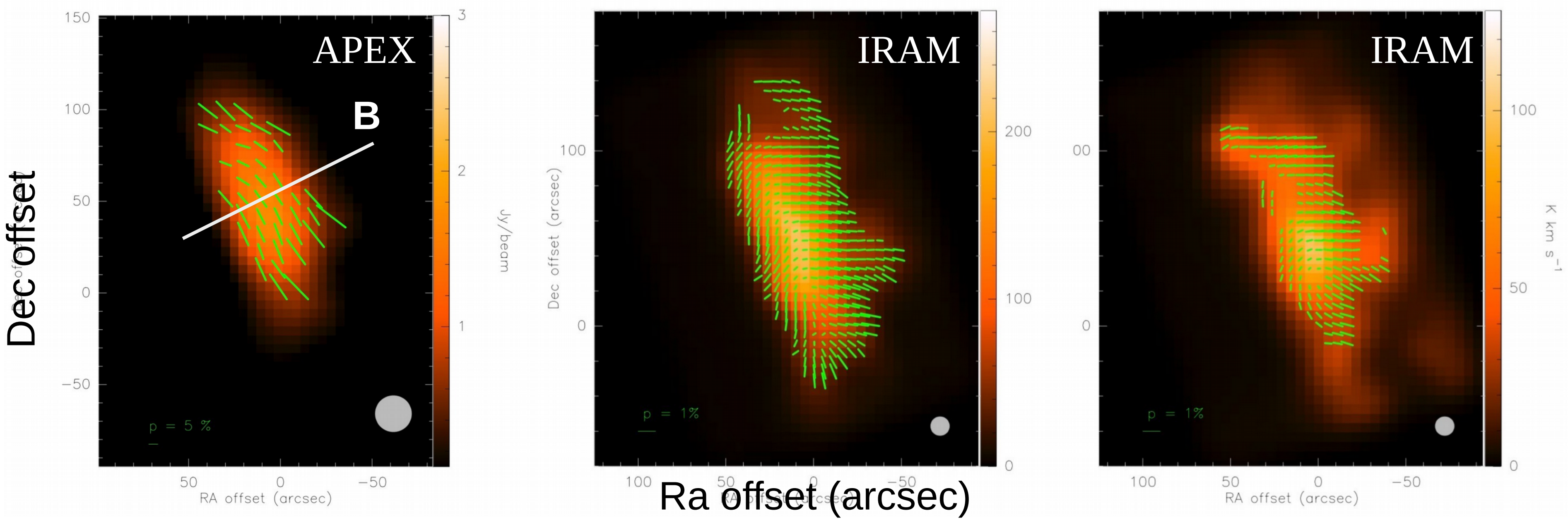
IC443, W28, W44, 3C391 SOFIA/EXE (PI: Reach. B. W)

SNR IC443 as seen by Spitzer-IRS





Magnetic field in SNR IC443G (Hezareh et al. 2013)

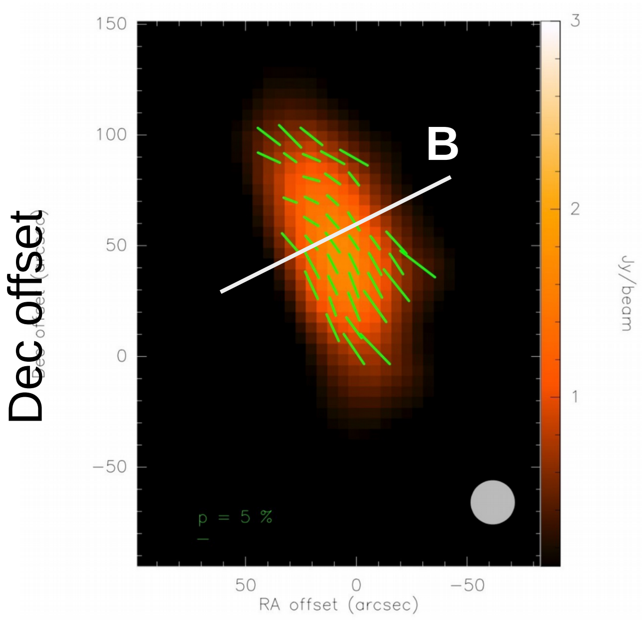


Dust
linear polarization

Blueshifted CO(2-1)
linear polarization

Redshifted CO(2-1)
linear polarization

Magnetic field in SNR IC443G (Hezareh et al. 2013)



Dust
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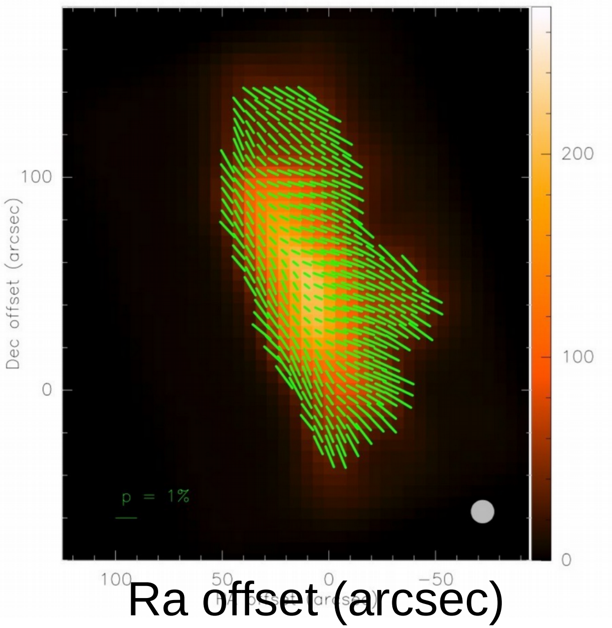
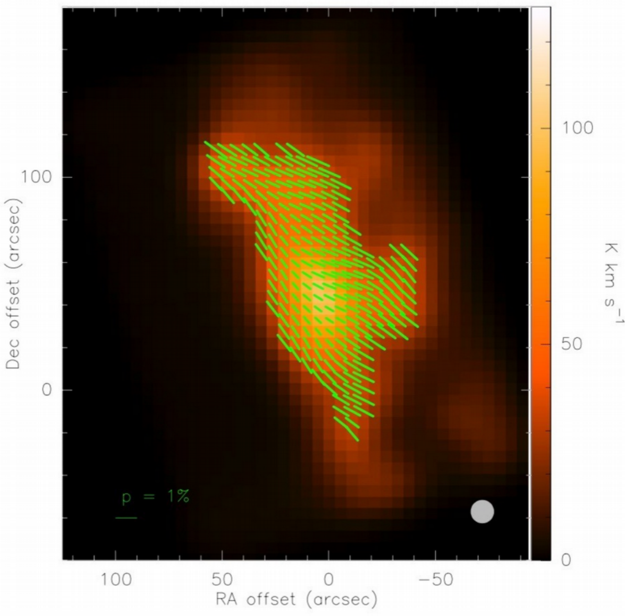


Blueshifted CO(2-1)
corrected linear polarization



Redshifted CO(2-1)
corrected linear polarization

Conclusions

✔ Provide a mathematical formulation which links the bow shape to a distribution with 1D shocks.

✔ Confirm the results of the statistical equilibrium for a power-law distribution of gas temperature.

✔ Illustrations of how 3D bow shock model can improve significantly the match between model and observations in BHR71 and Orion OMC-Peak1.

✔ Show how different lines probe different parts of the shocks depending on the temperature sensitivity of the excitation of their upper level.

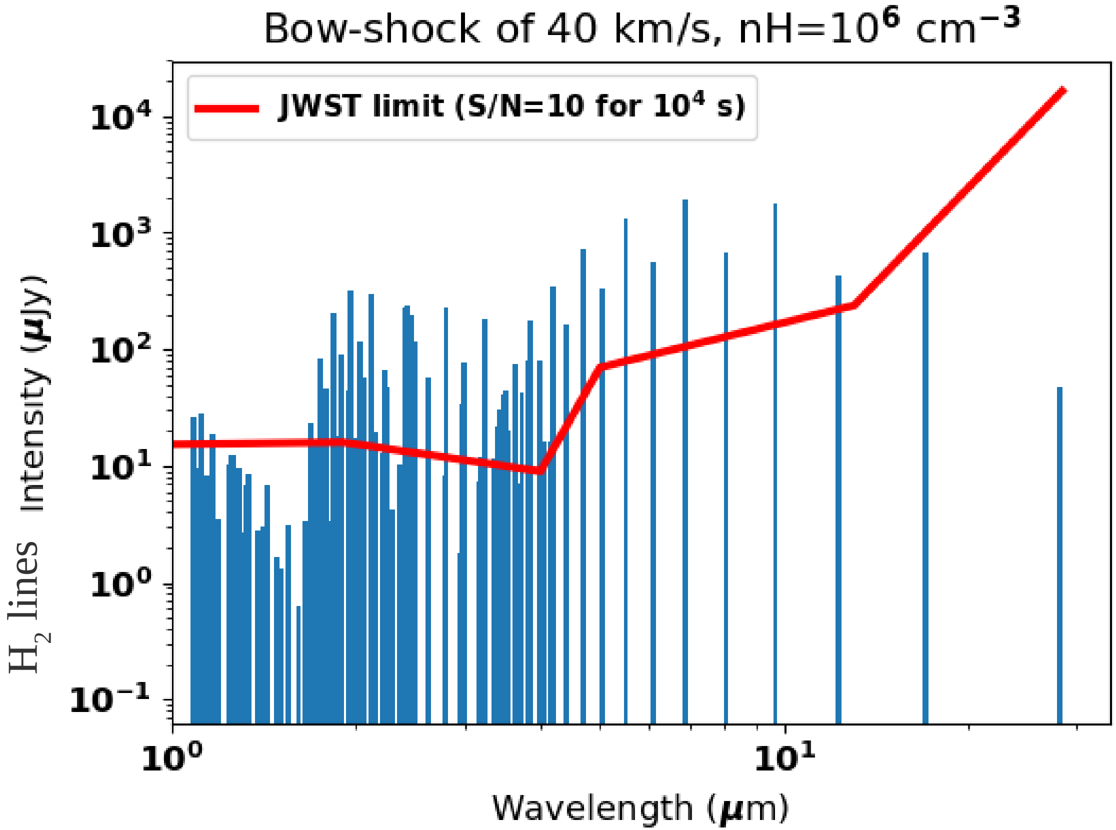
✔ 3D bow shock model can reproduce the broad velocity profile of the H_2 1-0S(1) line in Orion Peak1 with a magnetization compatible with other measurements.

✔ Line shapes provide missing constraints on dynamical information.

I am looking for postdoctoral possibilities ! 🤞

Thanks for your attention!

Orion as seen by JWST



Power-law statistical equilibrium assumption

(Neufeld and Yuan, 2008; Neufeld et al., 2009; Neufeld et al., 2014)

- The gas temperature follows the power-law distribution:

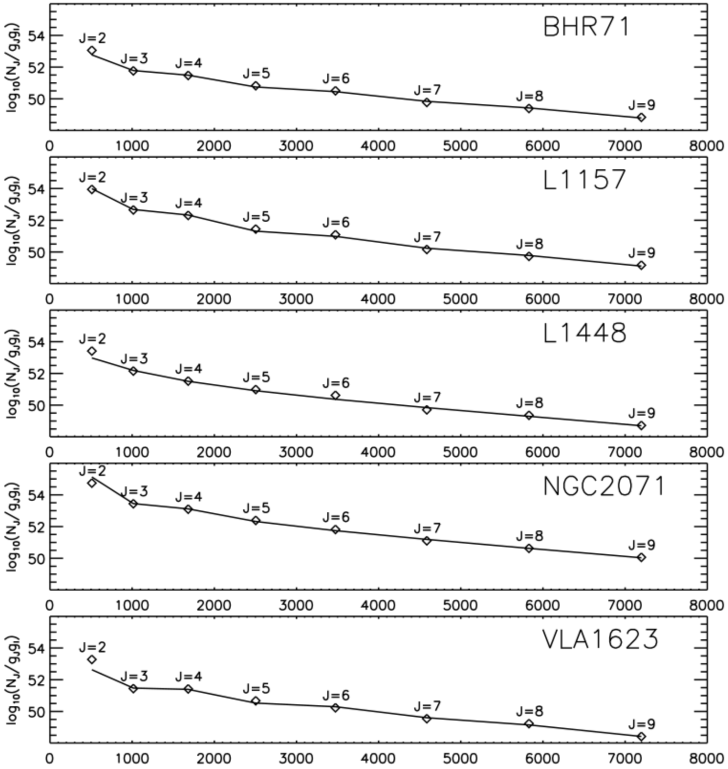
$$f(T) \sim T^{-b}$$

- The column density in T, T + dT

$$dN = a\,T^{-b}\,dT$$

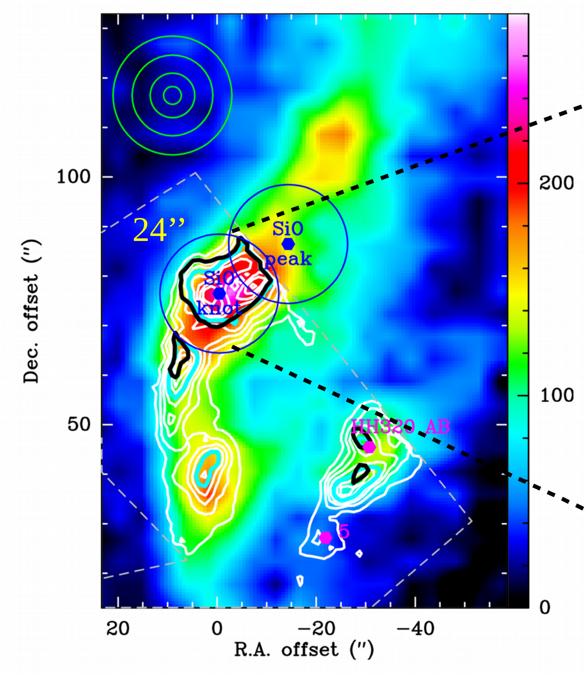
- **For BHR71, b ~ 2.4**

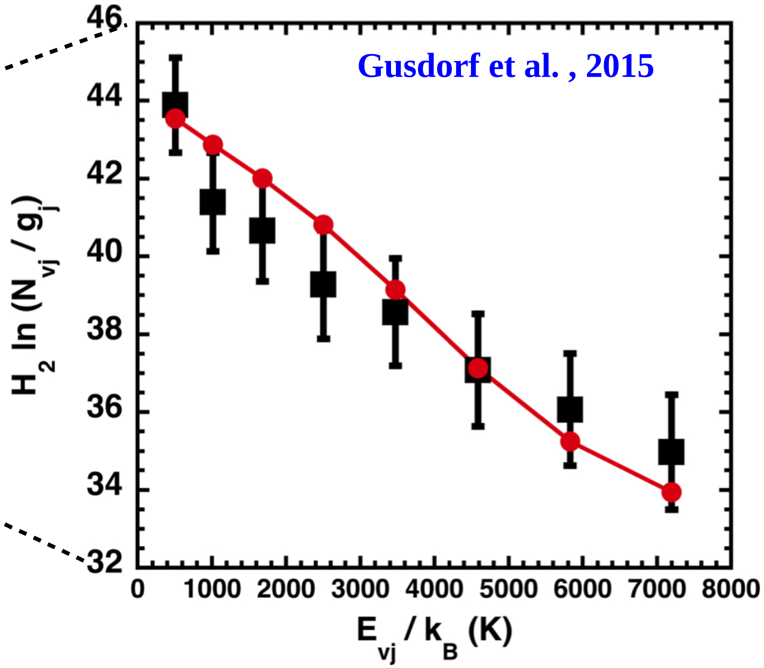
- If the geometry of shock is taken into account, for a parabolic shock shape: **b ~ -3.77**



1D shock model to interpret BHR71

BHR 71 outflow





Best input parameters

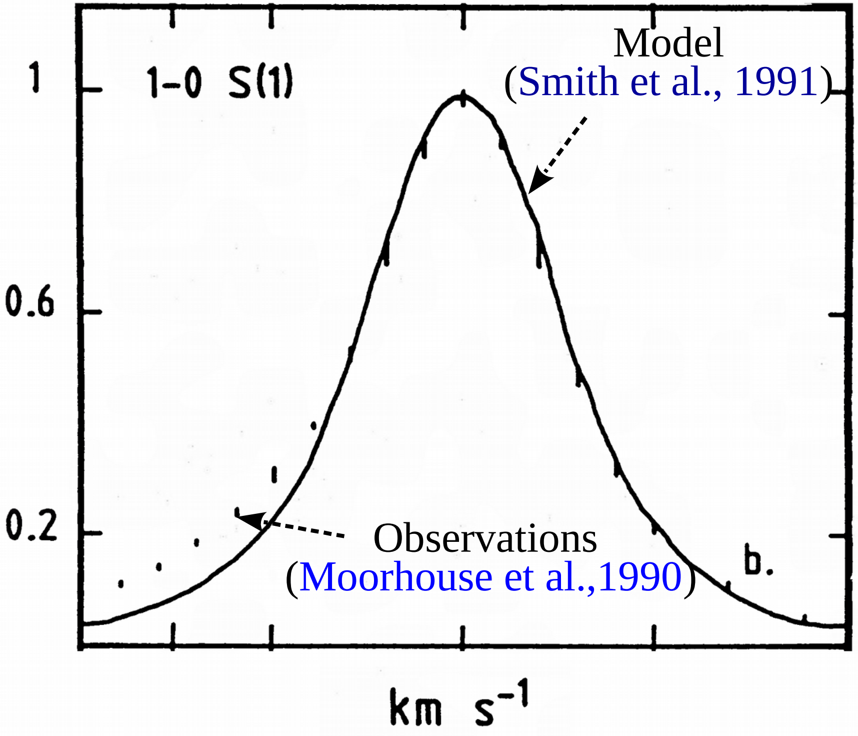
parameters	value
n_H	10^4 cm^{-3}
v_s	22 km s^{-1}
b	1.5
age	3800 yrs

First 3D shock model approximation

- First introduced by Smith et al.,1990a
- Smith et al.,1991b reproduce the H_2 line in OMC-Peak1
  - C-shocks collection,
  - LTE calculated H_2 excitation
  - **B = 50 mG required**

But:

- OH observations: **B ~ 3 mG** (Norris,1984)
- Polarization observation: **B ~ 10 mG** (Chrysostomou et al.,1994)



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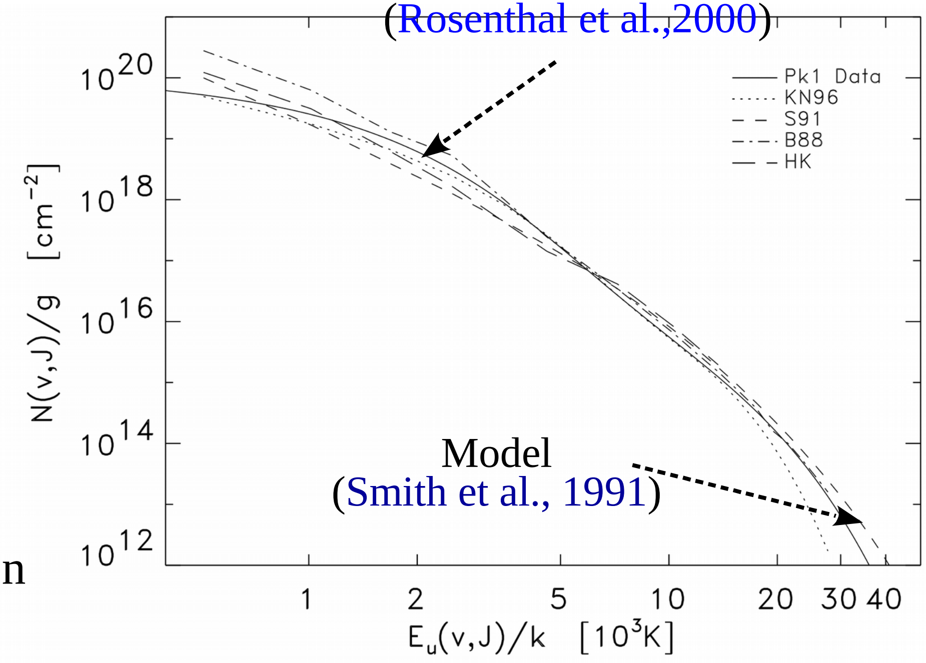
But:

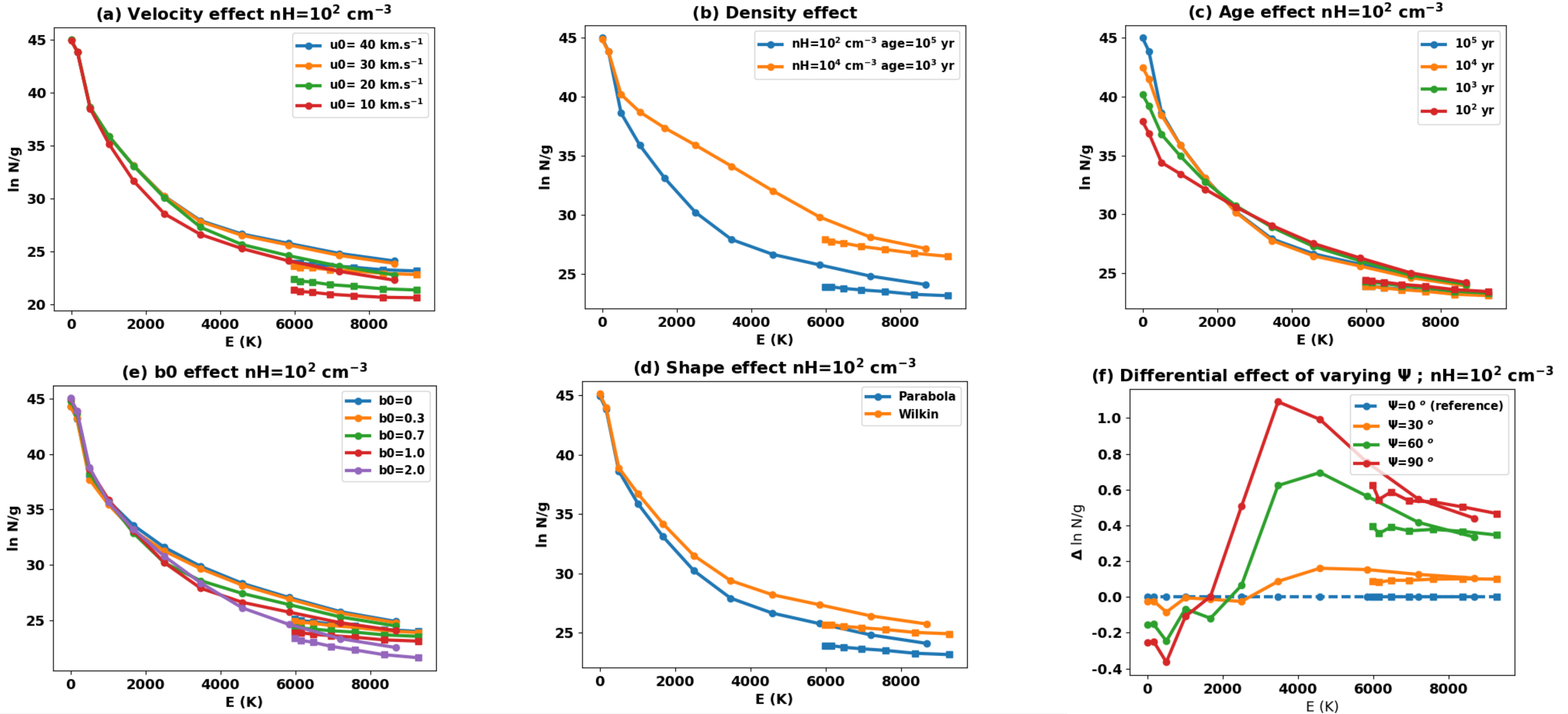
- OH observations: **B ~ 3 mG** (Norris,1984)
- Polarization observation: **B ~ 10 mG** (Chrysostomou et al.,1994)
- Smith et al.,1991b matches well the “**medium**” excitation



Observations
(Rosenthal et al.,2000)

Model
(Smith et al., 1991)

Effect of the bow parameters on H_2 excitation diagram



(a) Velocity effect $nH=10^2\ cm^{-3}$

(b) Density effect

(c) Age effect $nH=10^2\ cm^{-3}$

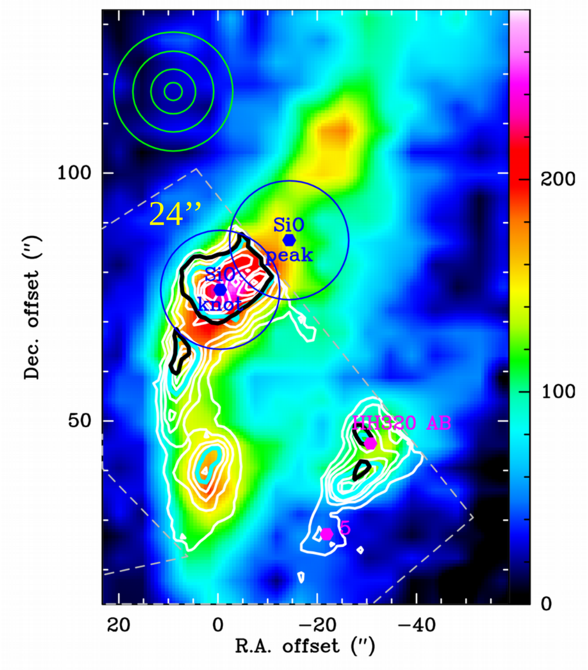
(e) b0 effect $nH=10^2\ cm^{-3}$

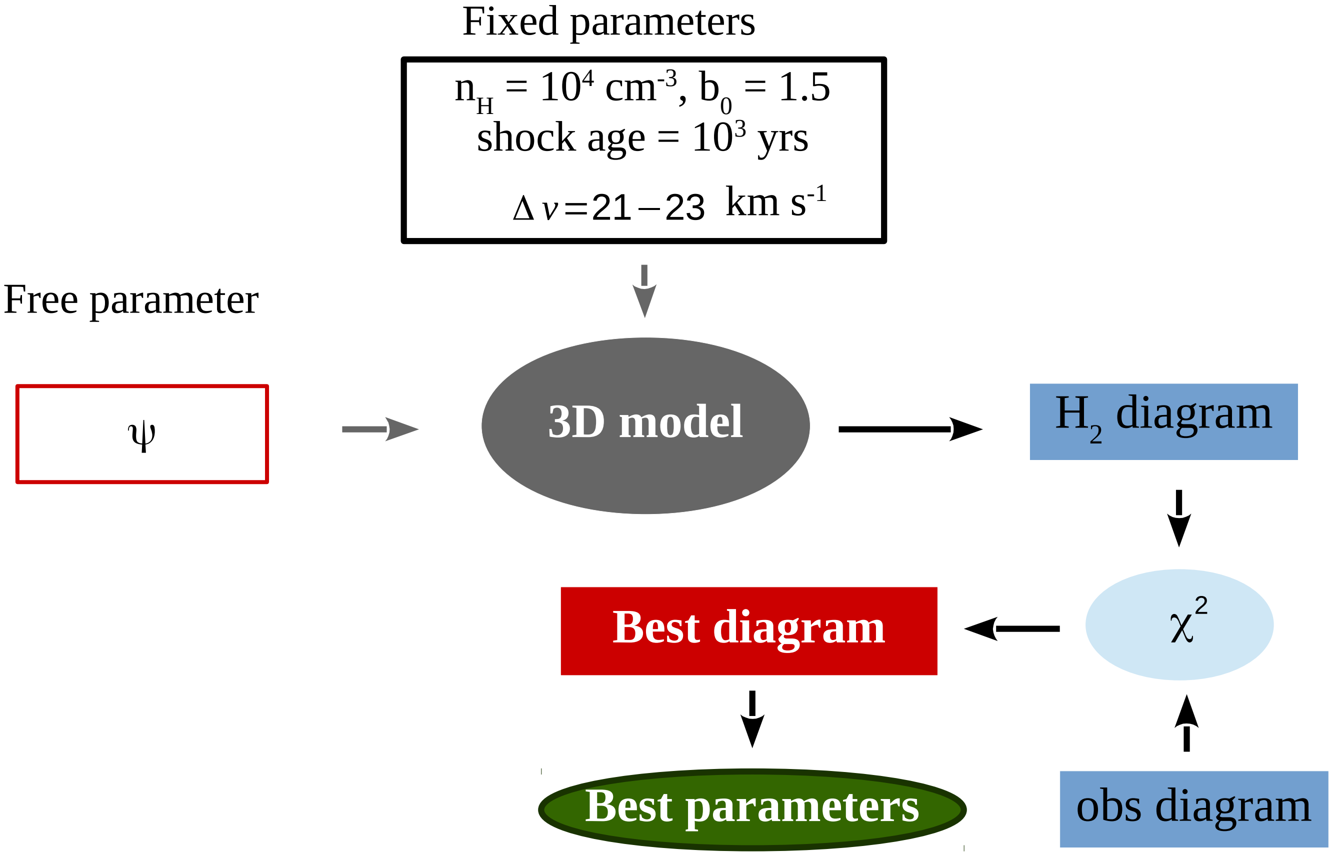
(d) Shape effect $nH=10^2\ cm^{-3}$

(f) Differential effect of varying Ψ ; $nH=10^2\ cm^{-3}$

3D H_2 diagram to interpret observations

BHR 71 outflow





Fixed parameters

$n_H = 10^4$ cm^{-3}, $b_0 = 1.5$
shock age = 10^3 yrs
$\Delta v = 21 - 23$ km s^{-1}

Free parameter

ψ

3D model

H_2 diagram

χ^2

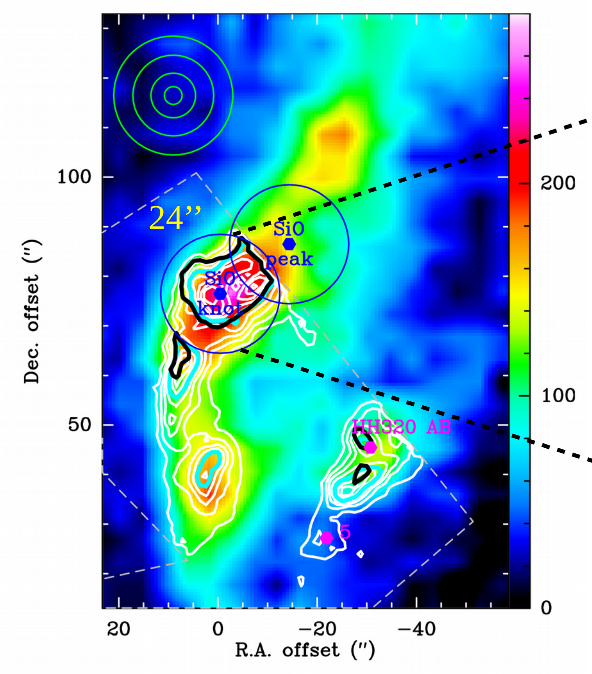
obs diagram

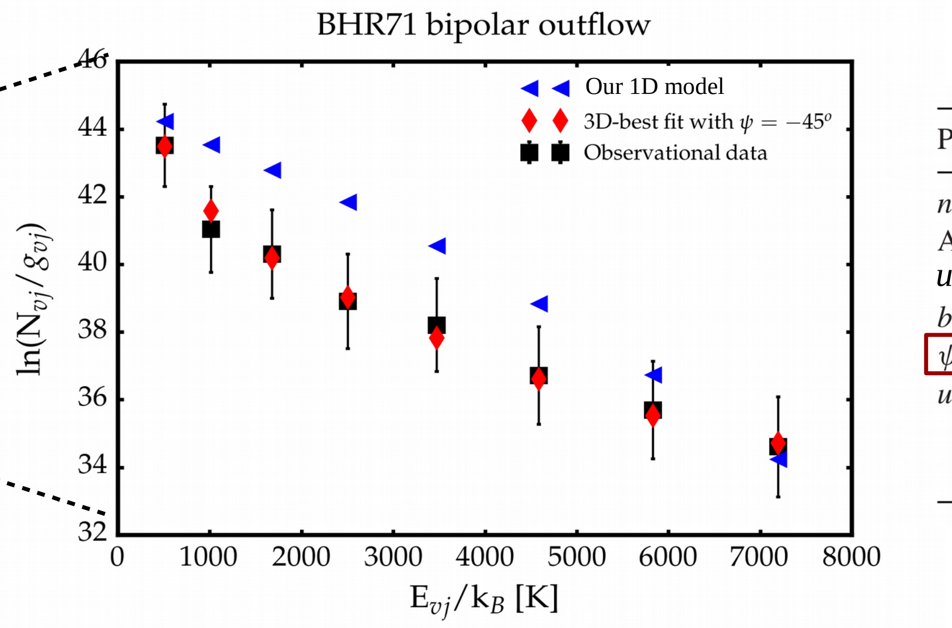
Best diagram

Best parameters

3D H_2 diagram to interpret observations

BHR 71 outflow



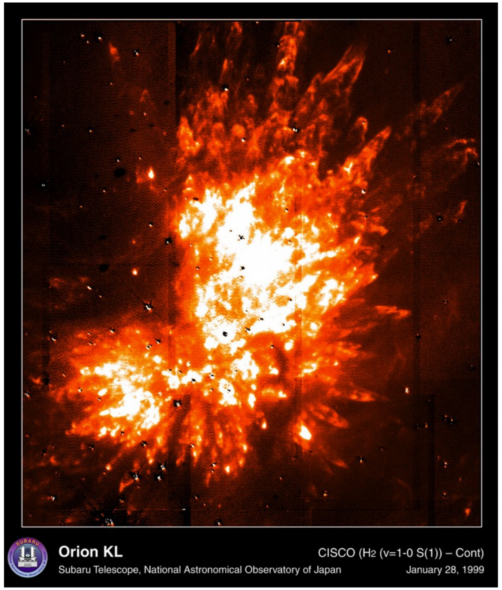


Parameter	Value
n_H	10^4 cm^{-3}
Age	10^3 yr
$u_\perp$	21–23 km s^{-1}
b_0	1.5
ψ	- 45° ± 20°
u_0 and β	NA

3D H_2 diagram to interpret observations

Orion Molecular cloud - Peak 1

- **Fitting results**

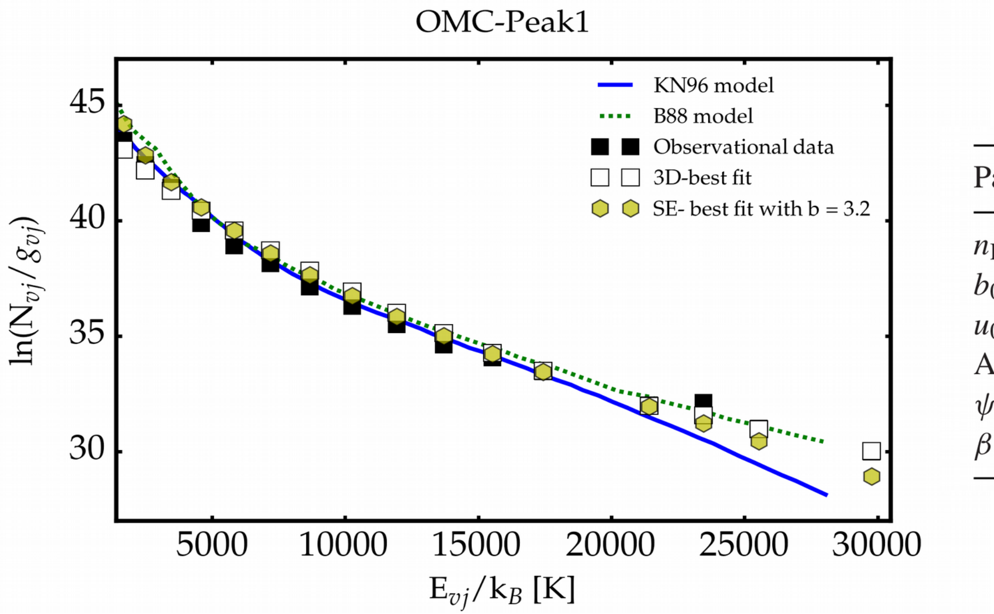


Orion KL

CISCO (H_2 (v=1-0 S(1)) – Cont)

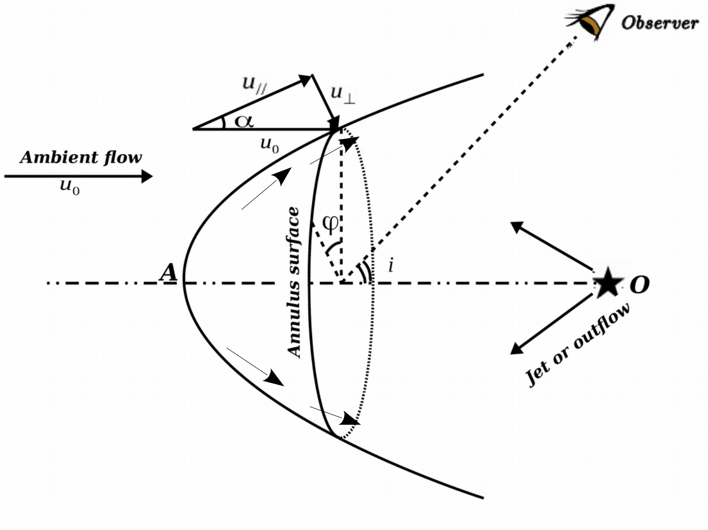
Subaru Telescope, National Astronomical Observatory of Japan

January 28, 1999



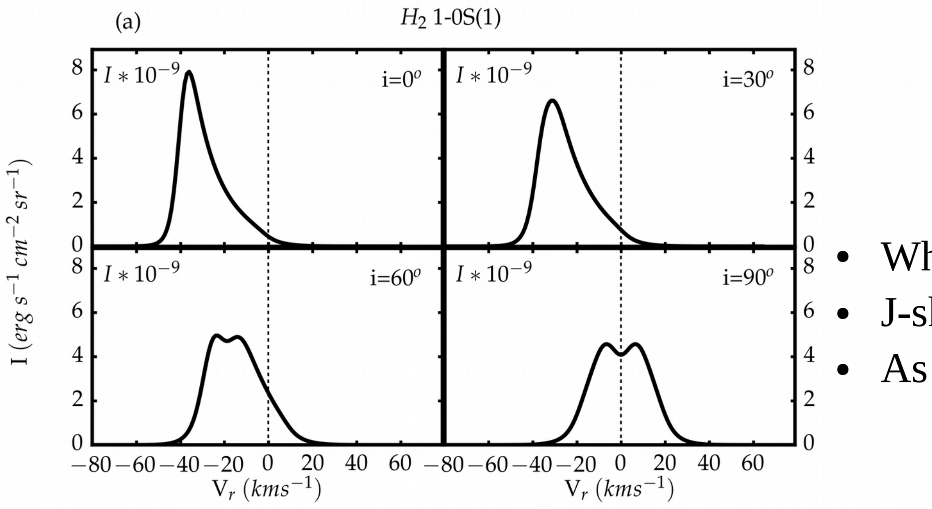
Parameter	Value
n_H	10^6 cm^{-3}
b_0	4.5 ± 0.9
u_0	$\geq 30\,\mathrm{km\,s^{-1}}$
Age	10^3 yr
ψ	$90^o \pm 30^o$
β	2.1 ± 0.2

H_2 line profile



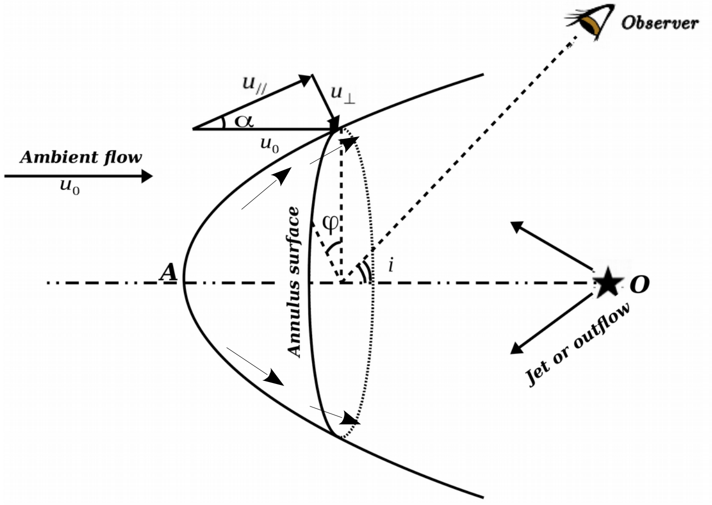
H_2 line profile is affected by

- Viewing angle



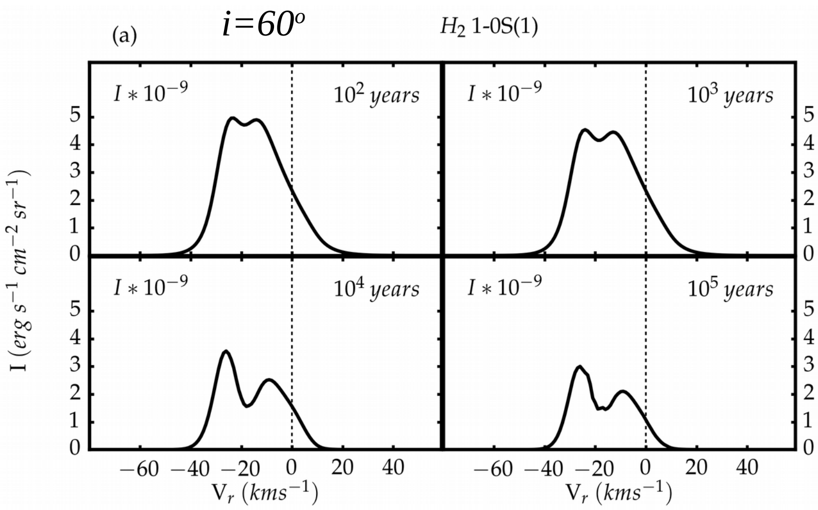
- When i = 0°, all the emission is blue-shifted.
- J-shock part of the bow shock structure causes the stronger emission
- As *i* increases, the line profile then becomes doubly peaked.

H_2 line profile



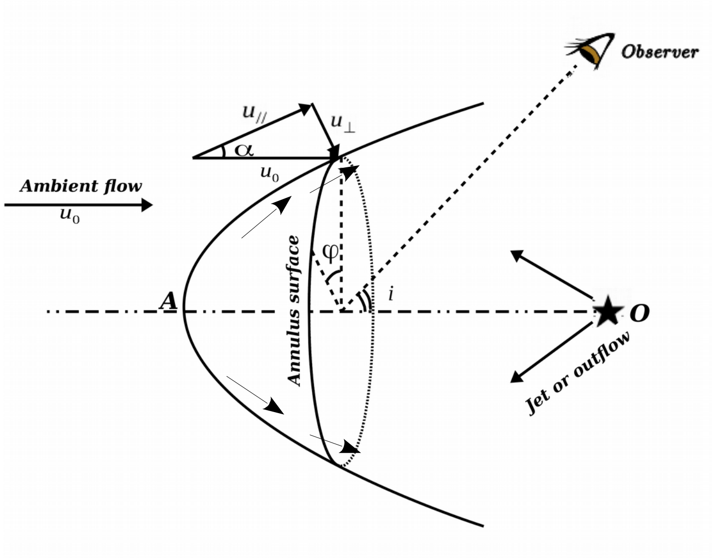
H_2 line profile is affected by

- Viewing angle
- Shock age



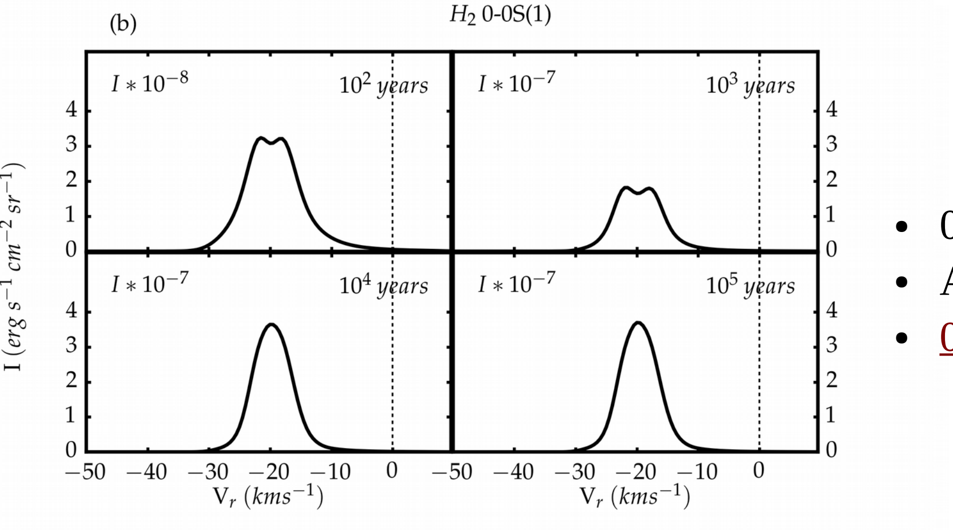
- When age proceeds, the J-type tail decreases,
- The temperature inside the J-shock decreases accordingly,
- The line profile becomes narrower,
- The width of 1-0S(1) can be used as the age indicator.

H_2 line profile



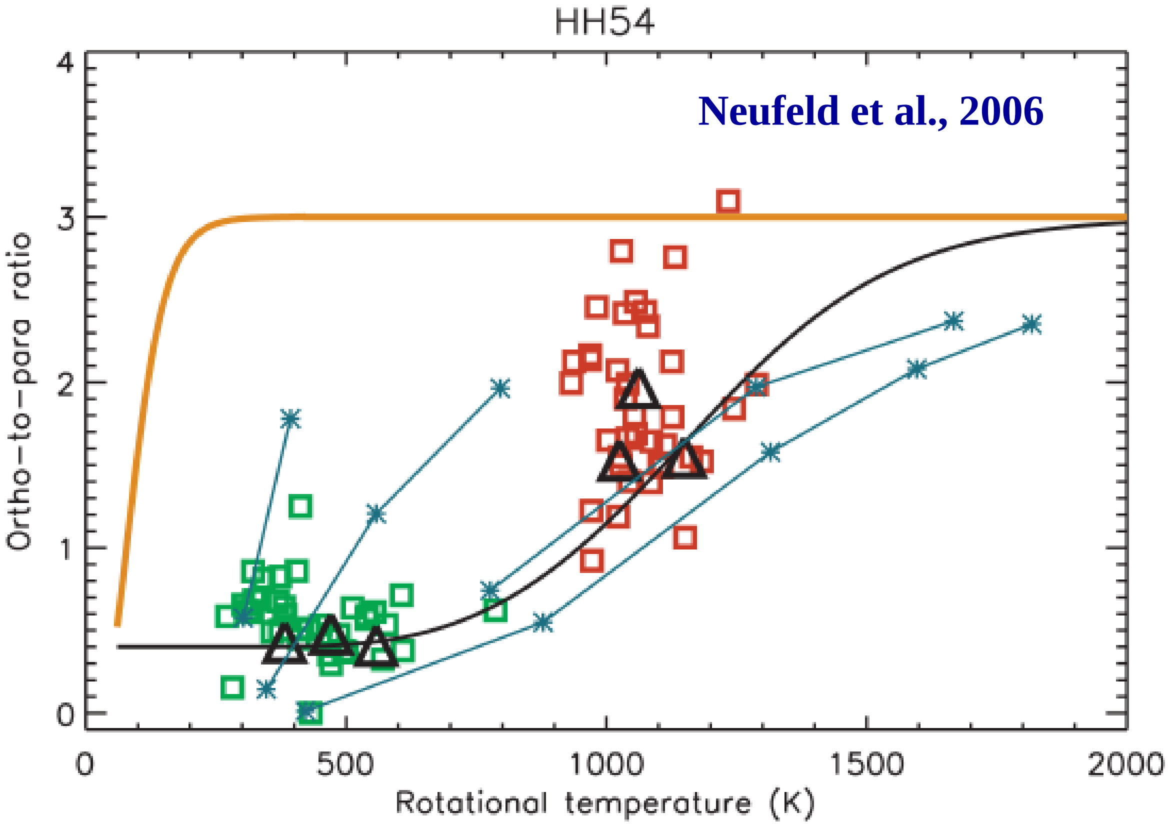
H_2 line profile is affected by

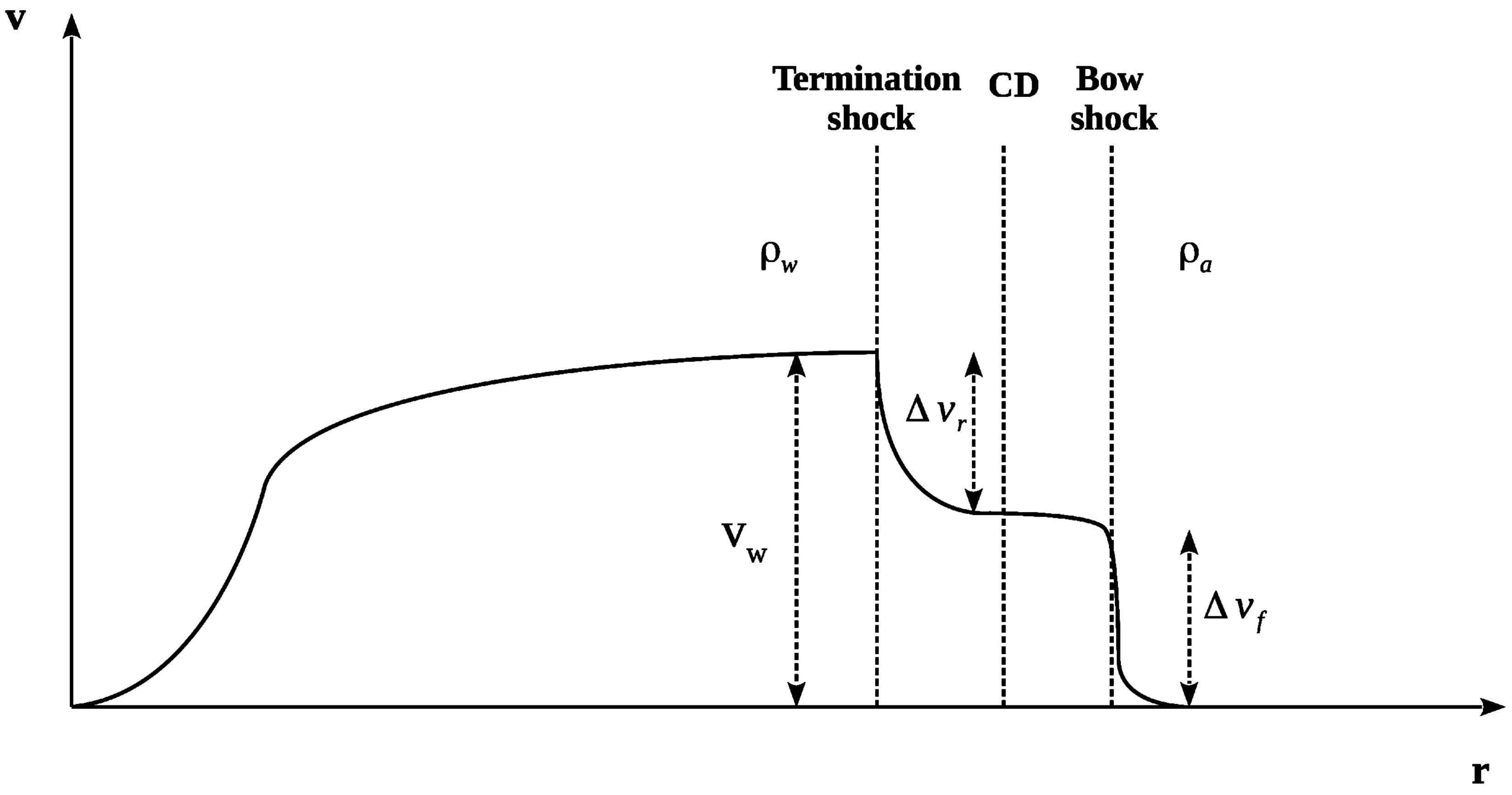
- Viewing angle
- Shock age



- 0-0S(1) probes the cold gas medium, the line profiles are narrower
- At early stages, there are still two peaks (signature for the J-shock)
- 0-0S(1) can be used as the J-shock indicator.

H_2 Ortho/Para ratio




v
Termination shock
CD
Bow shock
ρ_w
ρ_a
Δv_r
V_w
Δv_f
r