Outflows from Young Stellar Objects

MHD, Radiation & Chemistry

Bhargav Vaidya[1]

[1] School of Physics and Astronomy, University of Leeds, Leeds.

Astro Seminar, TIFR

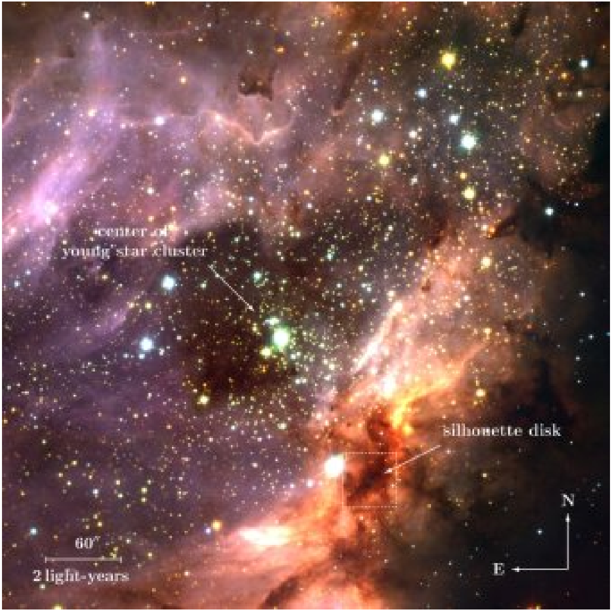
January 13, 2014

Collaborators:

Paola Caselli (Uni. Leeds), Thomas Douglas (Uni. Leeds), Oliver Porth (Uni. Leeds), Christian Fendt (MPIA), Henrik Beuther (MPIA), Somayeah Sheiknezami (MPIA), Ciraco Goddi (JIVE), Andrea Mignone (Uni. Torino).

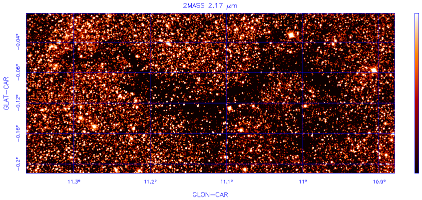
Outline

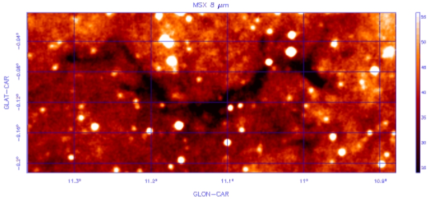
Typical HII region

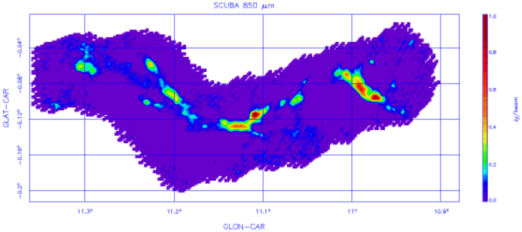


Star formation : Dark clouds

Filamentary, dense Infra-red dark clouds are birth place of stars (e.g.,Rathborne 2008)



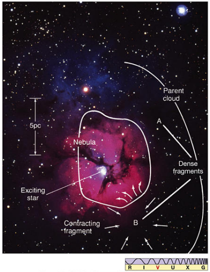




Star formation : Feedback

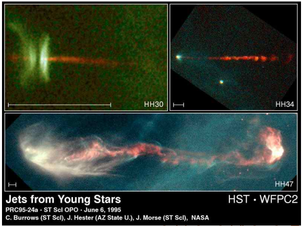
Outflows

- An ubiquitous feature in star forming regions. First signpost of formation.
- Driven magnetically from the underlying accretion disk.
- Entrain molecules along the flow : Molecular Outflow.
- Stellar winds : Trigger star formation, Pollute ISM with new metals.
- 3 stages : Launching < 100 AU, Propogation few 100s AU to 0.1 pc, Interaction > 0.1 pc.

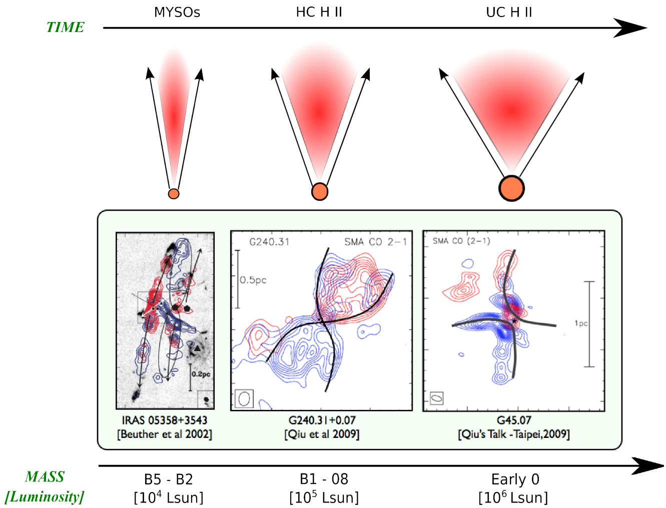


M20 (Trifid Nebula)

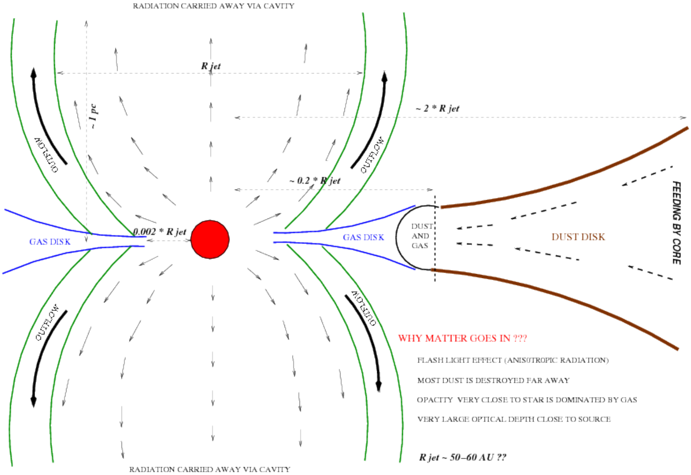
Jets from YSOs



Outflow Evolutionary Picture (Beuther & Sheperd 2005, Vaidya 2011)



Global Outflow Picture



(Vaidya 2009)

Chemistry in outflows

Young Class 0 Outflows

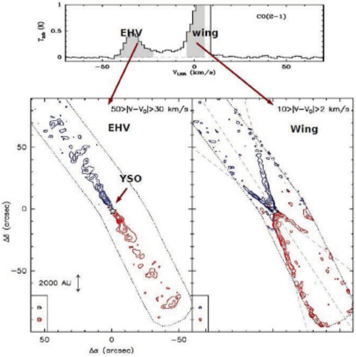
- Largely studied in form of molecular outflows using sub-mm telescopes.
- Bulk gas motion is traced by CO while SiO and H_2 (Infrared) traces the shocked regions.

Class I jets

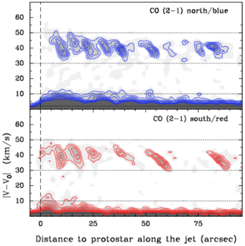
- They are traced mainly using optical telescopes.
- Signatures of forbidden emission lines from various atomic species.
- Lack or neglible molecular emission.

Molecular bullets and EHV emission

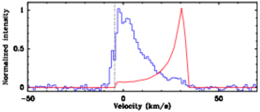
EHV Emission (Tafalla 2011)



PV Diagram (Santiago-Garcia 2009)



1D Models fail (Tafalla 2013)



Goals

Outflow Evolution

- What is the physical motivation of widening of outflow with age and central mass.?
- Does the central massive star and hot inner disk play a role?
- How do magnetic fields fit into the picture of outflows dynamics?

EHV Emission

- What causes the EHV emission in young outflows?
- Is 2D the answer to the failure of 1D models to predict spectra?
- What happens if we extend the model to 3D?

Goals

Outflow Evolution

- What is the physical motivation of widening of outflow with age and central mass.?
- Does the central massive star and hot inner disk play a role?
- How do magnetic fields fit into the picture of outflows dynamics?

EHV Emission

- What causes the EHV emission in young outflows?
- Is 2D the answer to the failure of 1D models to predict spectra?
- What happens if we extend the model to 3D?

Goals

Outflow Evolution

- What is the physical motivation of widening of outflow with age and central mass.?
- Does the central massive star and hot inner disk play a role?
- How do magnetic fields fit into the picture of outflows dynamics?

EHV Emission

- What causes the EHV emission in young outflows?
- Is 2D the answer to the failure of 1D models to predict spectra?
- What happens if we extend the model to 3D?

Goals

Outflow Evolution

- What is the physical motivation of widening of outflow with age and central mass.?
- Does the central massive star and hot inner disk play a role?
- How do magnetic fields fit into the picture of outflows dynamics?

EHV Emission

- What causes the EHV emission in young outflows?
- Is 2D the answer to the failure of 1D models to predict spectra?
- What happens if we extend the model to 3D?

Goals

Outflow Evolution

- What is the physical motivation of widening of outflow with age and central mass.?
- Does the central massive star and hot inner disk play a role?
- How do magnetic fields fit into the picture of outflows dynamics?

EHV Emission

- What causes the EHV emission in young outflows?
- Is 2D the answer to the failure of 1D models to predict spectra?
- What happens if we extend the model to 3D?

Goals

Outflow Evolution

- What is the physical motivation of widening of outflow with age and central mass.?
- Does the central massive star and hot inner disk play a role?
- How do magnetic fields fit into the picture of outflows dynamics?

EHV Emission

- What causes the EHV emission in young outflows?
- Is 2D the answer to the failure of 1D models to predict spectra?
- What happens if we extend the model to 3D?

Numerical code

PLUTO

- A modular code for computational astrophysics.
- Solve systems of conservation laws using the finite volume or finite difference approach based on Godunov-type schemes.
- The static grid version of PLUTO is entirely written in the C programming language
- AMR module uses the Chombo library.

PLUTO v. 4.0 (November 2012)

User's Guide

(http://plutocode.ph.unito.it)

Developer: A. Mignone[1,2] (mignone@ph.unito.it)

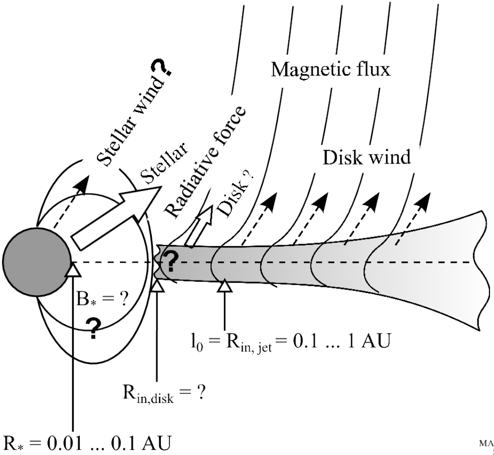
Contributors: C. Zanni[2] (AMR) (zanni@oato.inaf.it)
P. Tzeferacos[1] (Viscosity, MHD, STS, Finite-Difference)
(petros.tzeferacos@ph.unito.it)

G. Muscianisi[3] (Parallelization, I/O)
T. Matsakos[4] (Resistivity, Thermal Conduction, STS)
O. Tesileanu[5] (Cooling)
B. Vaidya[6] (pyPLUTO visualization tool)

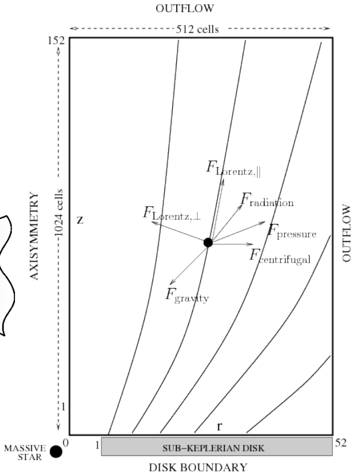
1 Dipartimento di Fisica Generale, Turin University, Via P. Giuria 1 - 10125 Torino (TO), Italy
2 INAF Osservatorio Astronomico di Torino, Via Osservatorio, 20 10025 Pino Torinese (TO), Italy
3 Consorzio Interuniversitario CINECA, via Magnanelli, 6/3, 40033 Casalecchio di Reno (Bologna), Italy
4 CEA, IRAMIS, Service Photons, Atomes et Molècules, 91191 Gif-sur-Yvette, France
5 Department of Physics, University of Bucharest, Str. Atomistilor nr. 405, RO-077125 Magurele, Ilfov, Romania
6 School of Physics and Astronomy, University of Leeds, Leeds LS29JT

Launching Model

Cartoon Model



Simulation Box



Radiation force

Castor Abbott & Klein Model

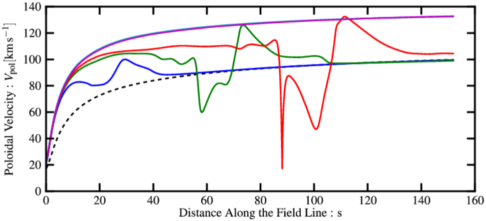
- *Line Driving force:* Main driving mechanism from evolved massive stars.
- *Physics:* Momentum transfer from photon to the gas. Optical depth depends on local flow variables - Sobolev Approximation.
- *Formulae:* $f_{\rm line} = f_{\rm cont}\mathcal{M}(t)$ where t is a function of Q_0 and α.

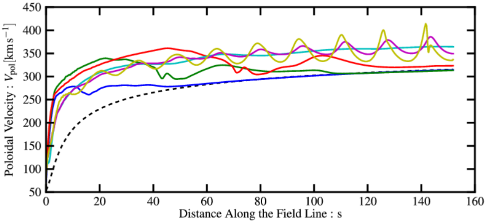
Quantity	Value
Stellar Mass	30 $M_\odot$
Plasma β	5.0
$R_{\rm in}$	1.0 AU
Eddington γ	0.236
Q_0	1400.0
α	0.55
ρ_0 (g cm^{-3})	5.0×10^{-14}

MHD Acceleration

Impact of Stellar radiation force.

- Initial MHD flow achieves a steady state.
- Jet perturbed after MHD steady state : Addition of radiation force from star or disk.
- The flow ultimately achieves a steady state **BUT** with increase in jet velocity.
- Intensity of the force scales with the jet launching radius.

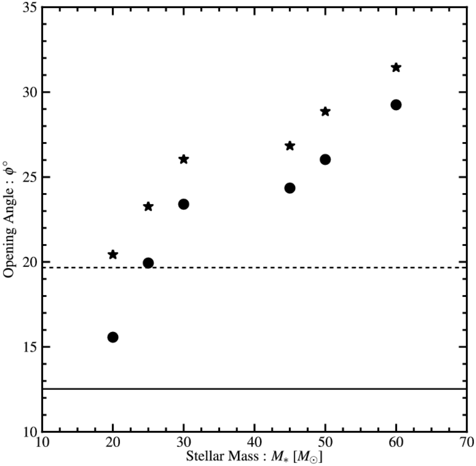




Collimation and Radiation (Vaidya et. al. 2011)

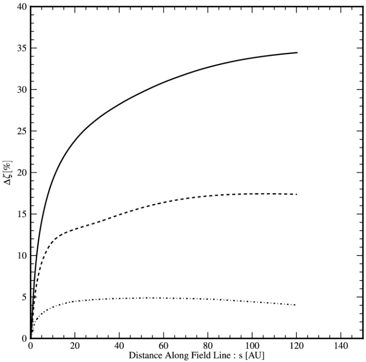
Impact of Stellar radiation force.

- Star's mass and luminosity - (Hosokawa 2008)
- Collimation : Opening angles at critical points in the steady flow.
- Without radiation – Alfven point : Dotted line, Magnetosonic-fast : Solid line.
- With radiation – Alfven point : Stars, Magnetosonic-fast : dots.
- Radiation force from Central Star – **WIDENS THE FLOW**

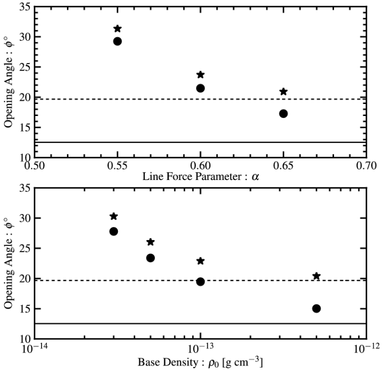


Force Parameters and its impact

Magnetic field

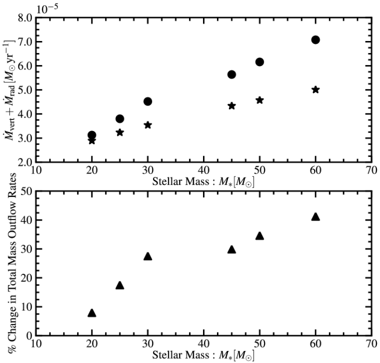


Density and α

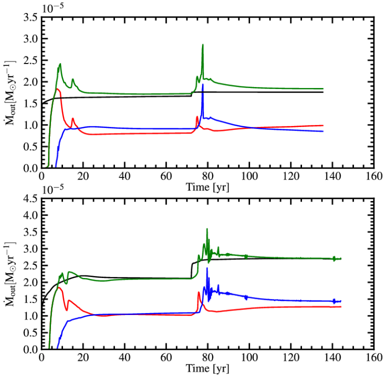


Fixing mass flux?

Floating mass flux

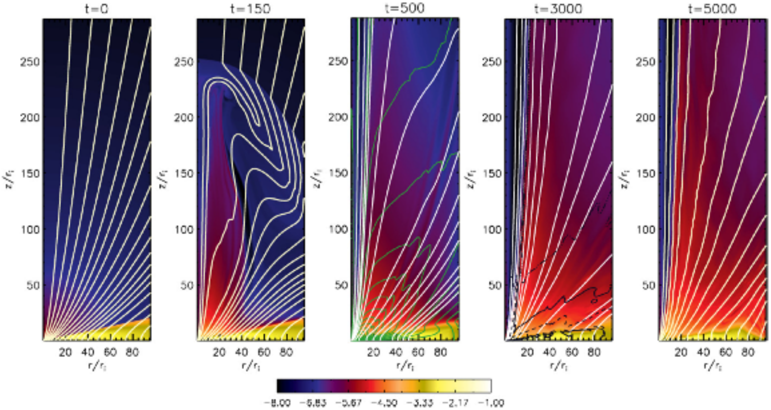


Direct Influence



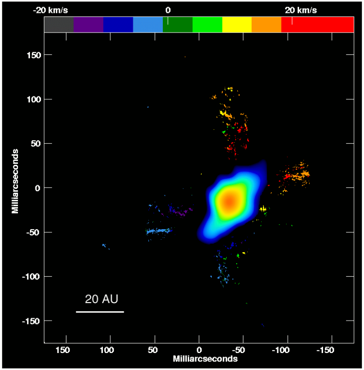
Resistive effects

Diffusive Disk Jet Launching (Sheikhnezami et. al 2012)

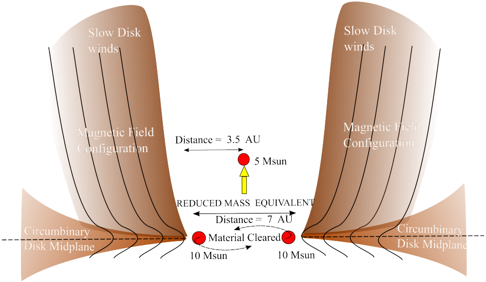


A case of Orion Source I

Orion Source I - Masers



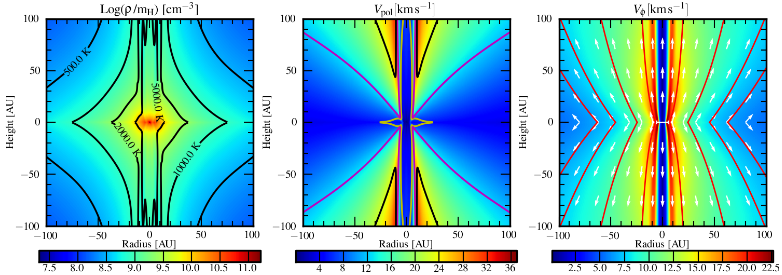
Simulation Model



A case of Orion Source I

Simulation Results (Vaidya 2013)

- SiO Masers : n (H_2) $\sim 10^9 \mathrm{cm}^{-3}$ and T $\sim$ 2000 K (Goddi et. al. 2009)
- *Dark band* - R $<$ 14 AU. T and ρ optimum to produce SiO masers within 15-60 AU : Consistent with Observations
- 3D Velocities lie within observed range and show signatures of rotation (Matthews 2010)



Chemistry in Jets

Initial Setup

- Young jets – largely atomic (Dionatos 2009), Ionization fraction around 1% (Bacciotti 1995), Molecules survive in jet (Glassgold 1991)
- Axisymmetric dense jet (η > 1) enters into a fully molecular ambient medium with density varying in height - $\rho_{\rm amp} \sim z^{-2}$
- Simplified Hydrogen chemistry : Tracks fraction of H_2, HI and HII.

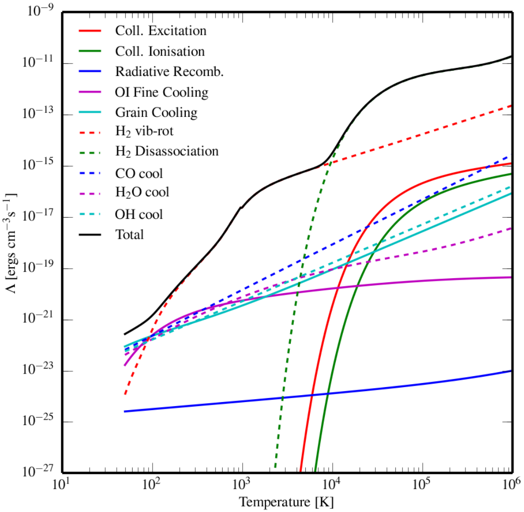
No.	Reaction	Rate Coefficient ($\rm cm^3 s^{-1}$)	Reference [a]
1.	$H + e^- \rightarrow H^+ + 2e^-$	$k_1 = 5.85 \times 10^{-11}\ T^{0.5}$ exp(-157,809.1/T)/(1.0 + $T_5^{0.5}$)	1
2.	$H^+ + e^- \rightarrow H + h\nu$	$k_2 = 3.5 \times 10^{-12} (T/300.0)^{-0.8}$	2
3.	$H_2 + e^- \rightarrow 2H + e^-$	$k_3 = 4.4 \times 10^{-10} T^{0.35} \exp(-102,000.0/T)$	3
4.	$H_2 + H \rightarrow 3H$	$k_4 = 1.067 \times 10^{-10} T_{\rm eV}^{2.012} (\exp(4.463/T_{\rm eV})^{-1} ((1. + 0.2472 T_{\rm eV})^{3.512})^{-1}$	4
5.	$H_2 + H_2 \rightarrow H_2 + 2H$	$k_5 = 1.0 \times 10^{-8} \exp(-84,100/T)$	2
6.	$H + H \xrightarrow{\rm dust} H_2$	$k_6 = 3.0 \times 10^{-17} \sqrt{T_2}(1.0 + 0.4\sqrt{T_2 + 0.15} + 0.2T_2 + 0.8T_2^2)$	5

[a] REFERENCES – (1) (Cen 1992 (Eq. 26a)); (2) (Woodall 2007 (UMIST Database)) (3) (Galli 1998 (Eq. H17)); (4) (Abel 1997 (Tab. 3 Eq. 13)); (5) (Hollenbach 1979 (Eq. 3.8))

Cooling in Jets

Cooling is important

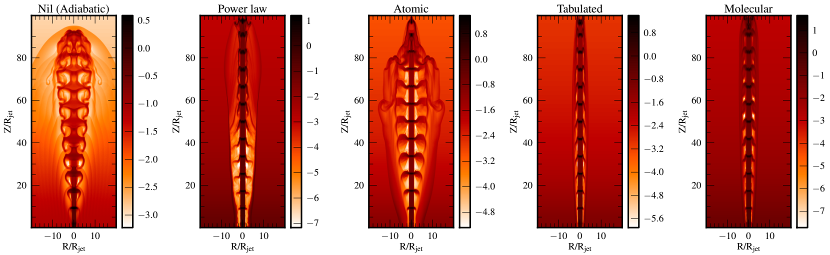
- $t_{\rm cool} \sim n_0/\Lambda(T) < t_{\rm dyn}$ (e.g, Blondin, 1990)
- Cooling rate for a molecular medium with $n_0 = 10^5$ cm^{-3}



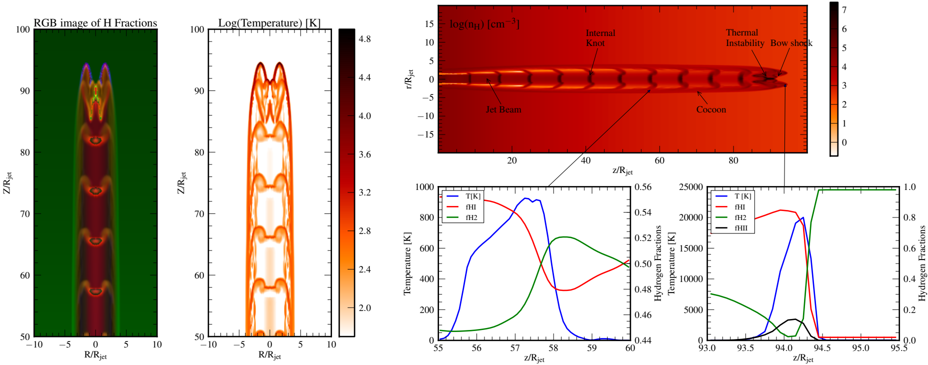
Cooling in Jets

Dynamical Effects

- Thinner jets with less pronounced coccoon
- Enhanced density in the internal knots with instable features.
- Thermal Instability in bow-shock of the jet.



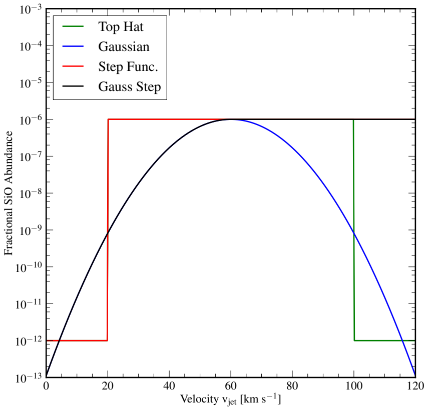
Molecular Interplay



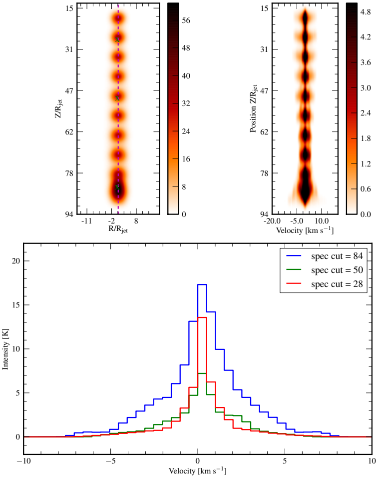
SiO Abundance and Jet Velocity

SiO in outflows

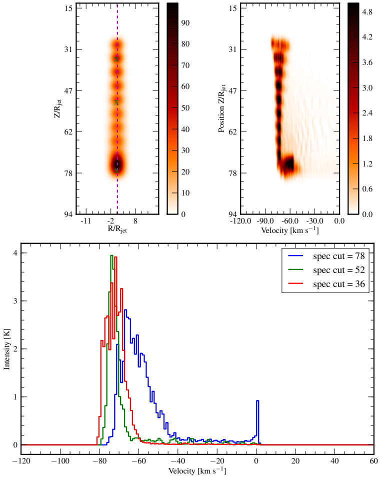
- SiO production by grain-grain collision (Caselli 1997), mantle evaporation (Schilke 1997), gas-grain interaction (sputtering) (Gusdorf 2008)
- Empirical dependence of $n(SiO)/n(H_2)$ on flow velocity.
- SiO Abundance - 10^{-12} in quiescent dark clouds (Ziurys 1989)
- SiO Abundance - 10^{-7} to 10^{-6} in outflows with flow speeds > 60 km s^{-1} e.g. L1448 (Martin-Pintado 1992, Dutrey 1997)



Spectra and PV diagrams : SiO (2-1)



$\phi = \pi/2$ (Plane of Sky)

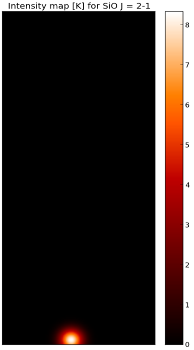


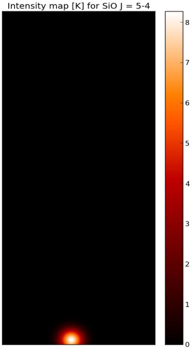
$\phi = \pi/4$

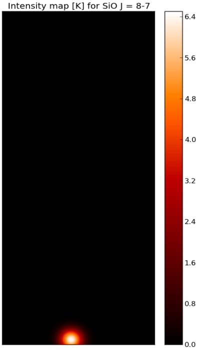
Multi-Line survey : Emission I

- Molecular Jet with η = 3.0
- Line Intensities with Top Hat Profile.
- Jet is in plane of sky and convolved with a Gaussian beam of 2.5″

J = 2->1 **J = 5-> 4** **J = 8-> 7**



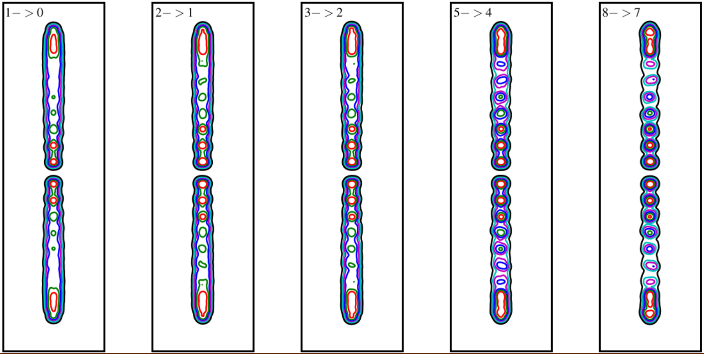




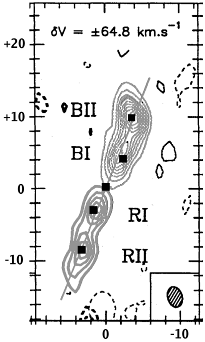
Multi-Line survey : Emission II

Multi-line transitions : HH 211

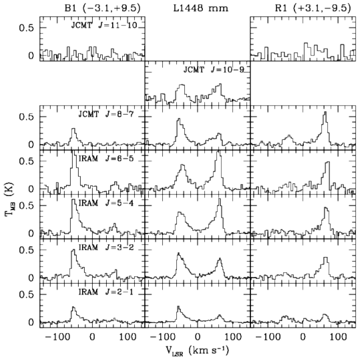
- Lower energy transitions - SiO J=1-0,2-1 show more turbulent features.(Chandler 2001)
- Higher energy transitions - SiO J=5-4,8-7 are more compact and trace the inner most jet (Hirano 2006, Palau 2006, Nisini 2007)



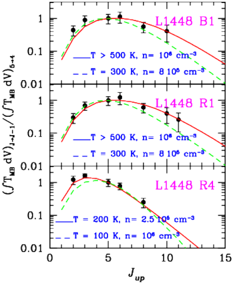
Case of L1448 (Nisini 2007)



Contours SiO 2-1



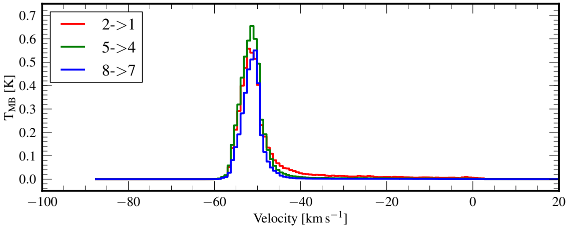
Spectral Features

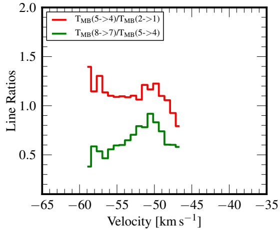


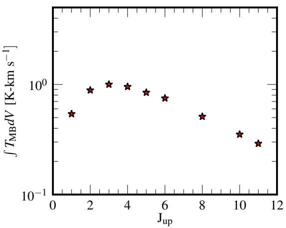
Kinematic Study (LVG)

Multi-line survey : Line Ratios

- EHV emission of 0.5 K.
- Line ratios close to Unity.
- Multi-line emission show a distinct fall at high J_{up}.



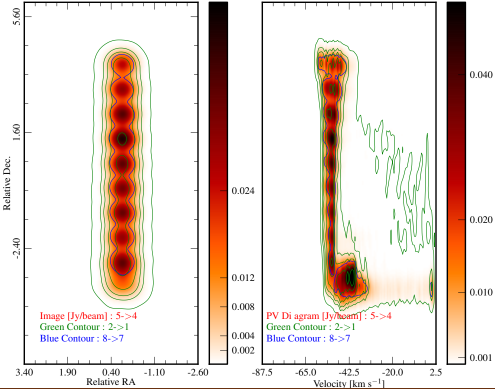




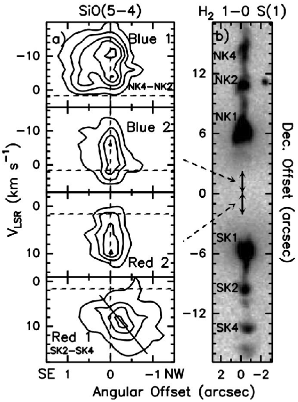
Predictions for ALMA

ALMA Cycle 2

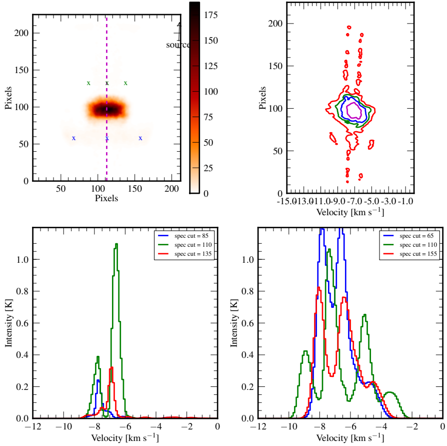
Bands 3, 6, 7: Assuming a source placed at 400 pc.(Orion - HH 212 (Zinnecker,1998))



Focussing on a single knot



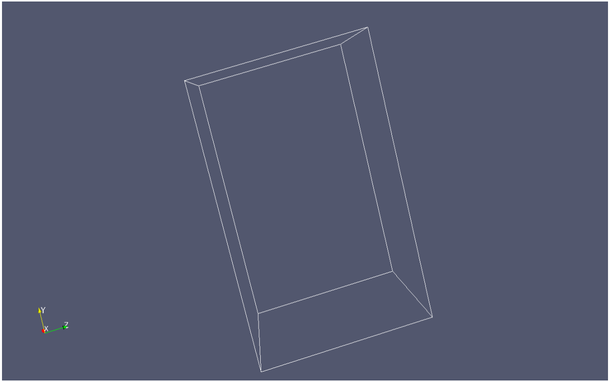
HH 212 (Codella 2007)



Rotation or Wiggles?

Work in Progress

- Extention to 3D opens up slew of instabilities.
- Self generated internal shocks create stationary knots.
- Wiggles are evident at later stages of evolution.



Conclusions

Outflow Evolution

- Radiative Line force from star plays a crucial role in widening the flow for stars with mass $> 30\ M_\odot$.
- The Collimation degree increases with increase in mass (luminosity) and decrease in magnetic fields, density and line force parameters.
- *Radiation MHD Interplay* : Magnetic fields initially drive the outflow and then radiative force takes over to compliment the dynamics.

EHV Emission

- Axisymmetric jet driven molecular outflows can very well reproduce features of EHV emission.
- PV diagrams show a distinct zig-zag pattern specific of EHV emission from young outflows.
- Higher energy transition lines traces compact knots in the flow while jet interaction regions are traced by low excitation lines.
- *Chemistry and Dyanmics* : Synthetic observations by combining chemistry with dynamical models provides a link between future observations and theory.
- 3D Modelling with enhanced chemical network is the way forward.