Orion BN/KL: A Laboratory for High-Mass Star Formation

C. GODDI[1]; L. GREENHILL[2]; L. MATTHEWS[3]; E. HUMPHREYS[4]; F. NIEDERHOFER[4] B. VAIDYA[5]; N. MOECKEL[6]; C. CHANDLER[7]

[1]Joint Institute for VLBI in Europe;[2]Harvard-Smithsonian Center for Astrophysics; [3]MIT-Haystack;[4]European Southern Observatory; [6]University of Leeds; [5]University Observatory Munich; [7]National Radio Astronomy Observatory

Rationale

The details of how massive stars form are poorly known. Orion BN/KL, at ~414 pc, is the closest known region with ongoing massive star formation (Fig. 1), and hence offers unique chances for a detailed study and an excellent laboratory to test competing theories. Several complex phenomena are simultaneously present in BN/KL: a dense protostellar cluster including high-mass YSOs Source I and BN; dense gas and rich chemistry in the Hot-Core (e.g., Goddi et al. 2011b; Zapata et al. 2011); the uncollimated “bullet” H_2 outflow, reminiscent of an explosion (e.g. Bally et al. 2011); recent history of a dramatic stellar interaction (e.g., Goddi et al. 2011a).

In this poster, I report some highlights from a long-term study of the region based on a wealth of interferometric data from (E)VLA, VLBA, and ALMA. In particular, I will describe:

I. A dynamical model to explain the large velocities of massive YSOs Source I and BN as well as the famous ”explosive” BN/KL flow (*Goddi et al. 2011a*).

II. A beautiful example of disk-mediated accretion and outflow recollimation regulated by magnetic fields in a high-mass protostar (*Matthews et al. 2010; Greenhill et al. 2013*).

III. A new hypothesis for the excitation of the eponymous Orion Hot Core through the shocks generated by the impact of the outflow driven by Source I (*Goddi et al. 2011b*).

IV. The effects of the complex (clustered) environment on the structure of the outflow from Source I (*Niederhofer et al. 2012)*.

This detailed study suggests that although similar physics, in terms of mass-accretion and mass-loss, may be at work in the formation of low-mass and high-mass stars (at least up to 20 Msun), the environment in dense proto-clusters (e.g. stellar dynamical interactions) may play a crucial role in shaping massive star formation.

I. Dynamical History of BN/KL

Fig. 1a: Explosive BN/KL flow in the H_2 2.14 µm line (Subaru)

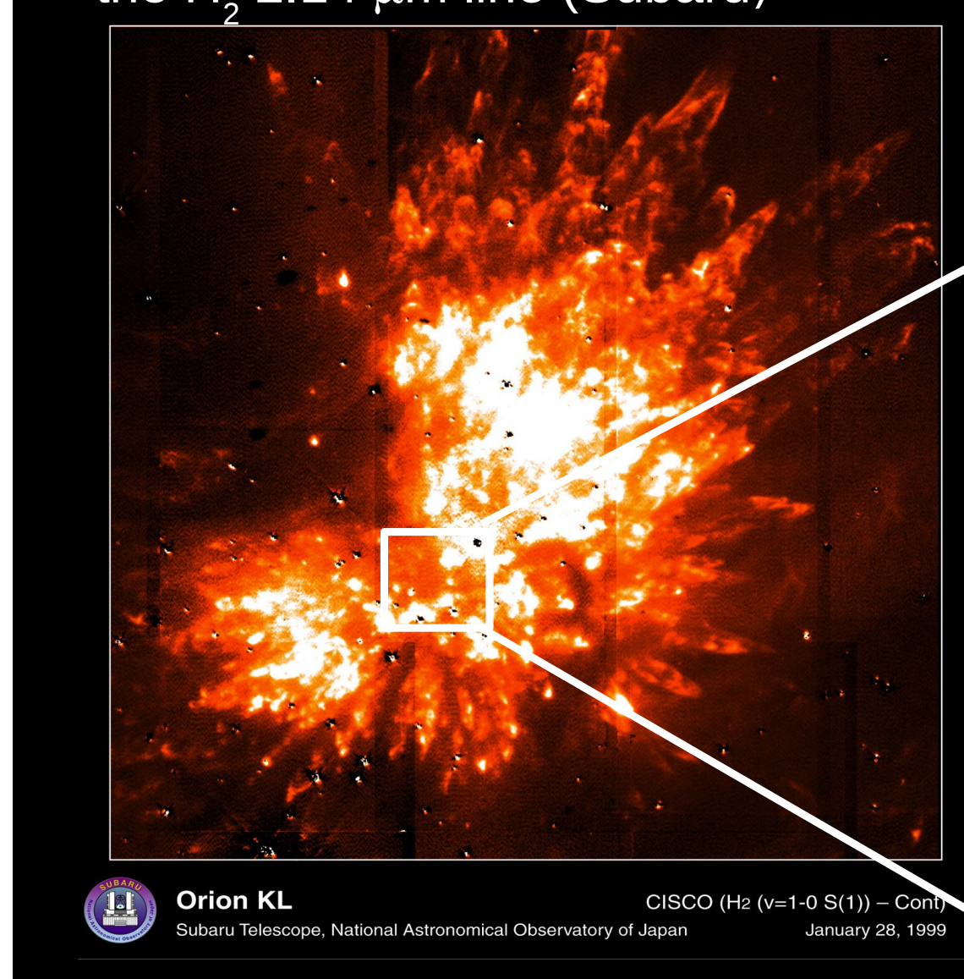


Fig. 1b. Dense protocluster at the centre of BN/KL at 12.5 µm (Keck)

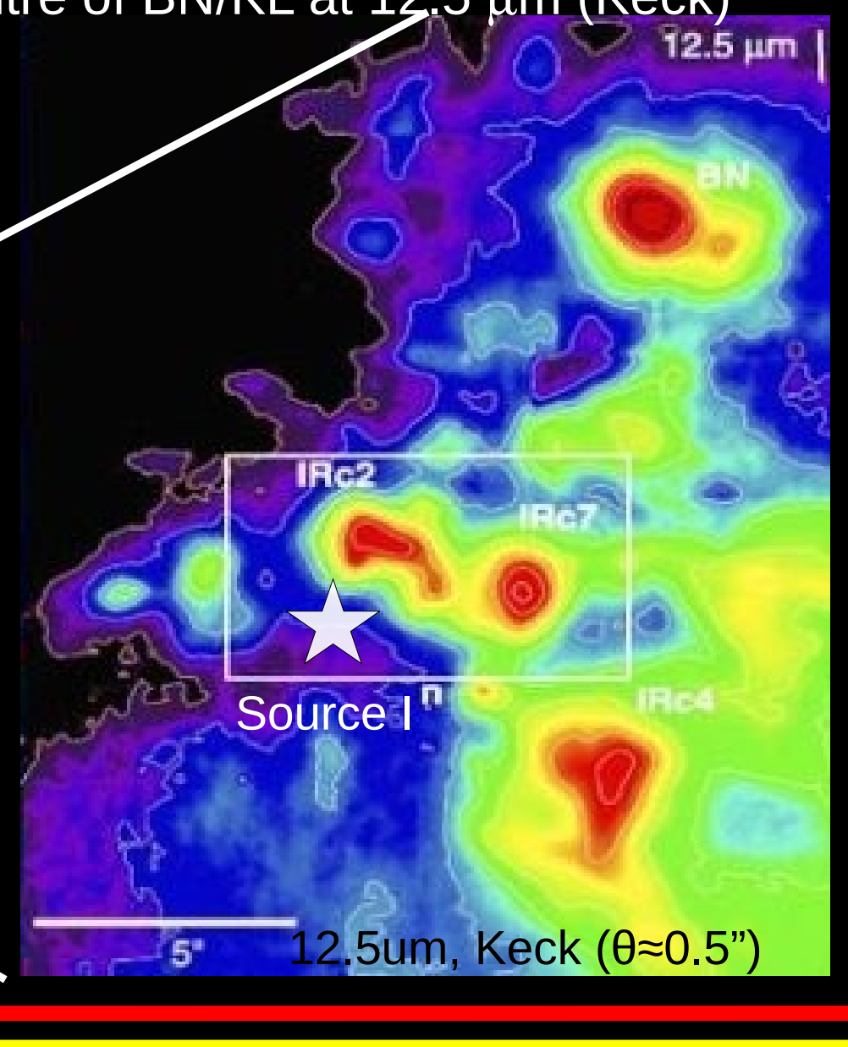
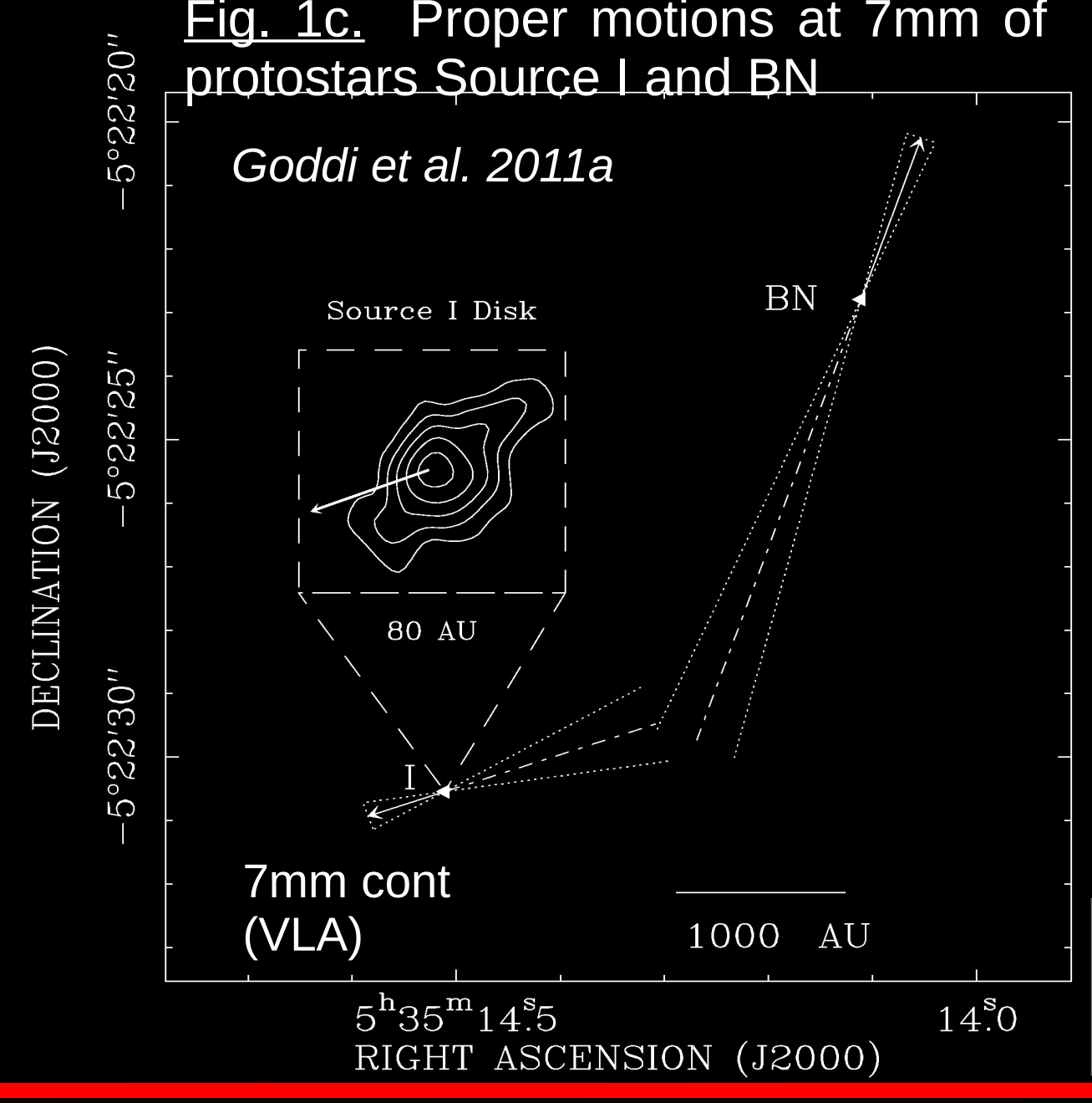


Fig. 1c. Proper motions at 7mm of protostars Source I and BN

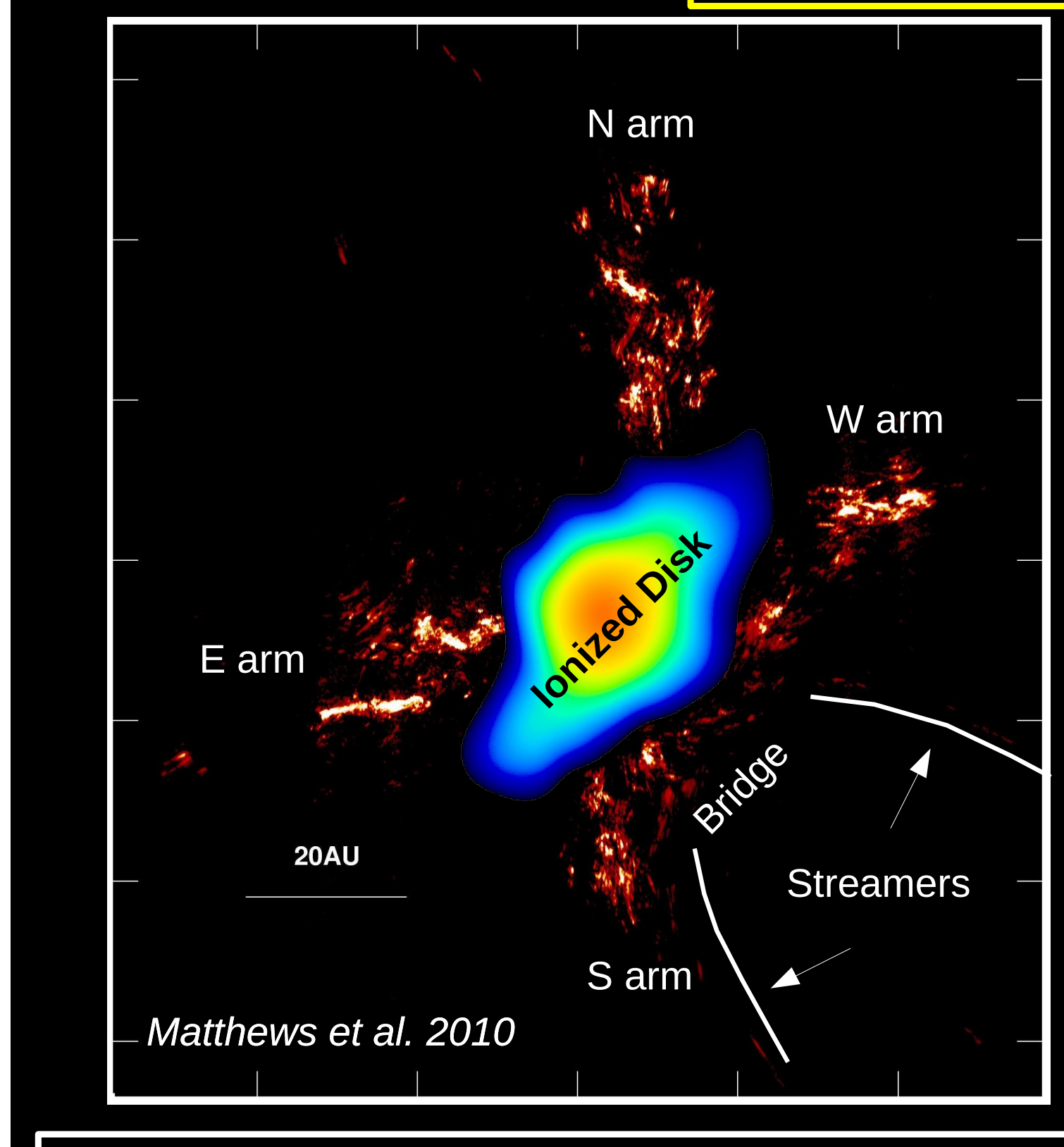


- Measurements of proper motions of 7mm sources in the region show that protostars Source I (v~12 km/s) and BN (v~26 km/s), now 4000 AU apart, must have experienced a close passage [O(50 AU)] 500 years ago (Goddi et al. 2011a).
- N-body numerical simulations show that the dynamical interaction between a hard binary of 20 Msun (Source I) and a single star of 10 Msun (BN) may lead to ejection of both and drive the uncollimated H_2 flow (Goddi & Moeckel 2012; Bally et al. 2011).
- The material observed today in the uncollimated flow was previously bound (in the form of disks and envelopes) to the protostars undergoing scattering and got ejected with different velocities (Zapata et al. 20009; Bally et al. 2011)

The explosive outflow is not a typical outflow powered by protostellar accretion, but rather the product of an explosive, episodic event of (proto)stellar scattering

II. MHD Disk-wind and collimated flow from Source I

Disk-wind at R=10-100 AU



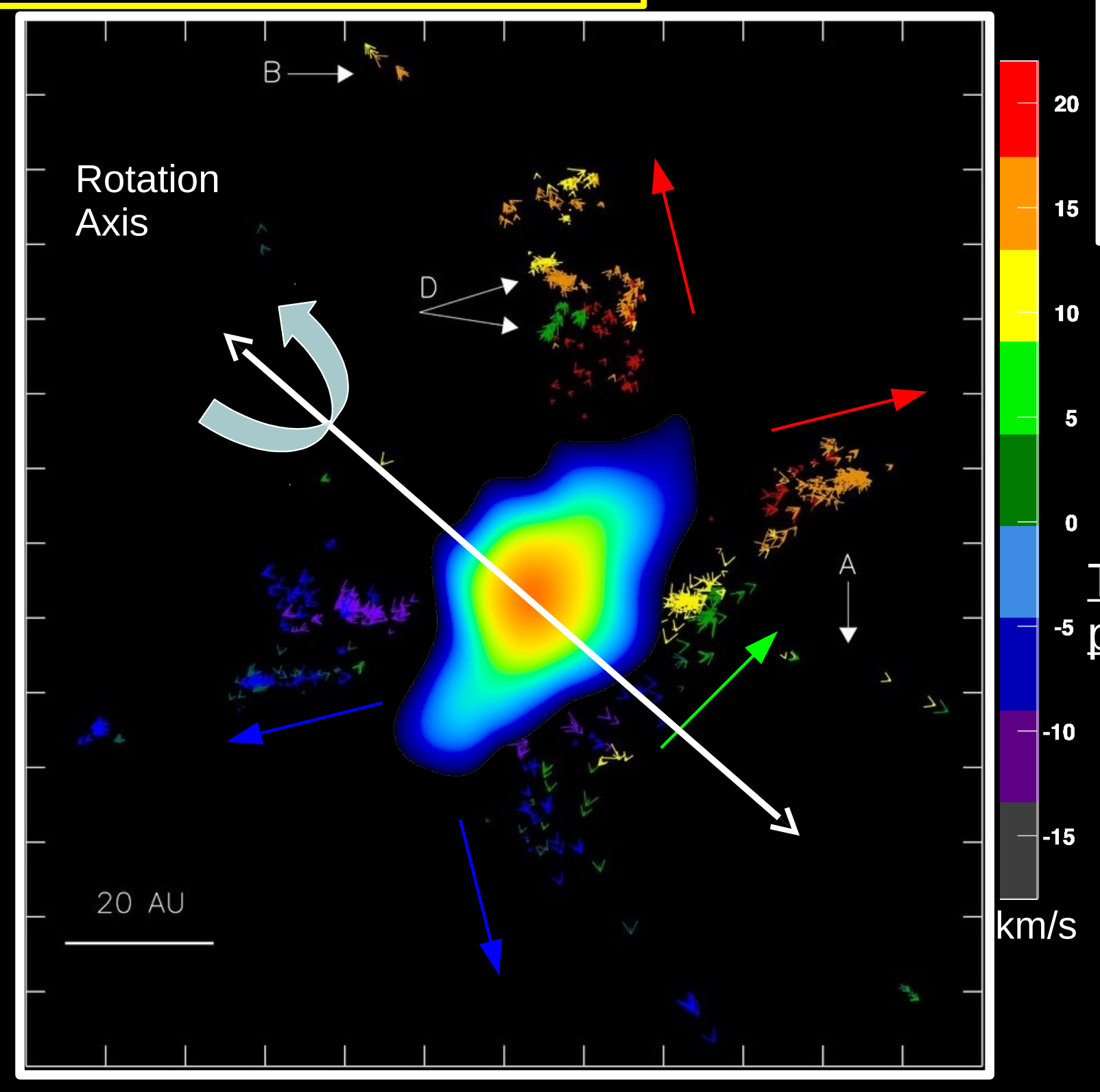


Fig.2a: Integrated SiO maser emission
The bulk of the SiO emission is located within four "arms" of an X-shaped pattern. A ~14 AU thick dark band (with no SiO emission) harbors the disk-shaped 7mm continuum source imaged by Reid et al. (2007) and Goddi et al. (2011a). Two "bridges" of emission connecting the arms are parallel to the elongation axis of the radio continuum. The detection of masers along extended, curved filaments suggests that magnetic fields may play a role in shaping gas dynamics.

Fig.2b: 3D velocity field of SiO masers (proper motions + $V_{l.o.s.}$)
The colors indicate l.o.s. velocities in km/s. There is a clear separation between redshifted (N & W arms) and blueshifted SiO emission (S & E arms). Bridge emission shows a V_{grad} along the major axis of the radio continuum, indicative of rotation about a NE/SW axis. V_{gra} along each arm is consistent with differential rotation.
We measured proper motions of over 1000 individual maser spots, which show a combination of radially outward migrations along the four main arms (tracing the wind) and motions tangent to the bridges (tracing the disk). Curved and helical trajectories of certain SiO maser features (labeled D, A), hint at a possible role of magnetic fields.

Table 1. Long-term VLBA study

Transitions	SiO v=1,2 J=1-0
Physical conditions	$10^{10\pm1}$ cm^{-3}, 1000-3000 K
Time span	T=21 months, ΔT~1 month
Linear scales probed	R<100 AU, Δθ=0.2 AU

$M_{dyn\ YSO}$	~ 8 M_{sun}
V_{rot} (20 AU)	= 19 km/s
$<V_{outflow}>$	= 16 km/s
Max($V_{outflow}$)	= 25 km/s
Mass-loss in arms	< 10^{-4} M_{sun}/yr

Table 2. Physical parameters of the flow

Bipolar collimated outflow at R=10-100 AU

$<V_{outflow}>$	≈18 km/s
R_{inn}	=100 AU
R_{out}	=1000 AU
Mass-loss	~10^{-6} M_{sun}/yr
T_{dyn}	≈500 yrs

Table 4. Physical parameters of the flow

Table 3. VLA+CARMA study

Transitions	SiO v=0 J=1-0	v=0 J=2-0	H_2O
Instrument	VLA	CARMA	VLA
Time span	9 yrs (4 epo)	1 epo	18 yrs (2 epo)
Phys. Condit.	10^7 cm^{-3}, 1000 K		10^9 cm^{-3}, >400 K
Scales probed	R~100-1000 AU, Δθ~20-50 AU		

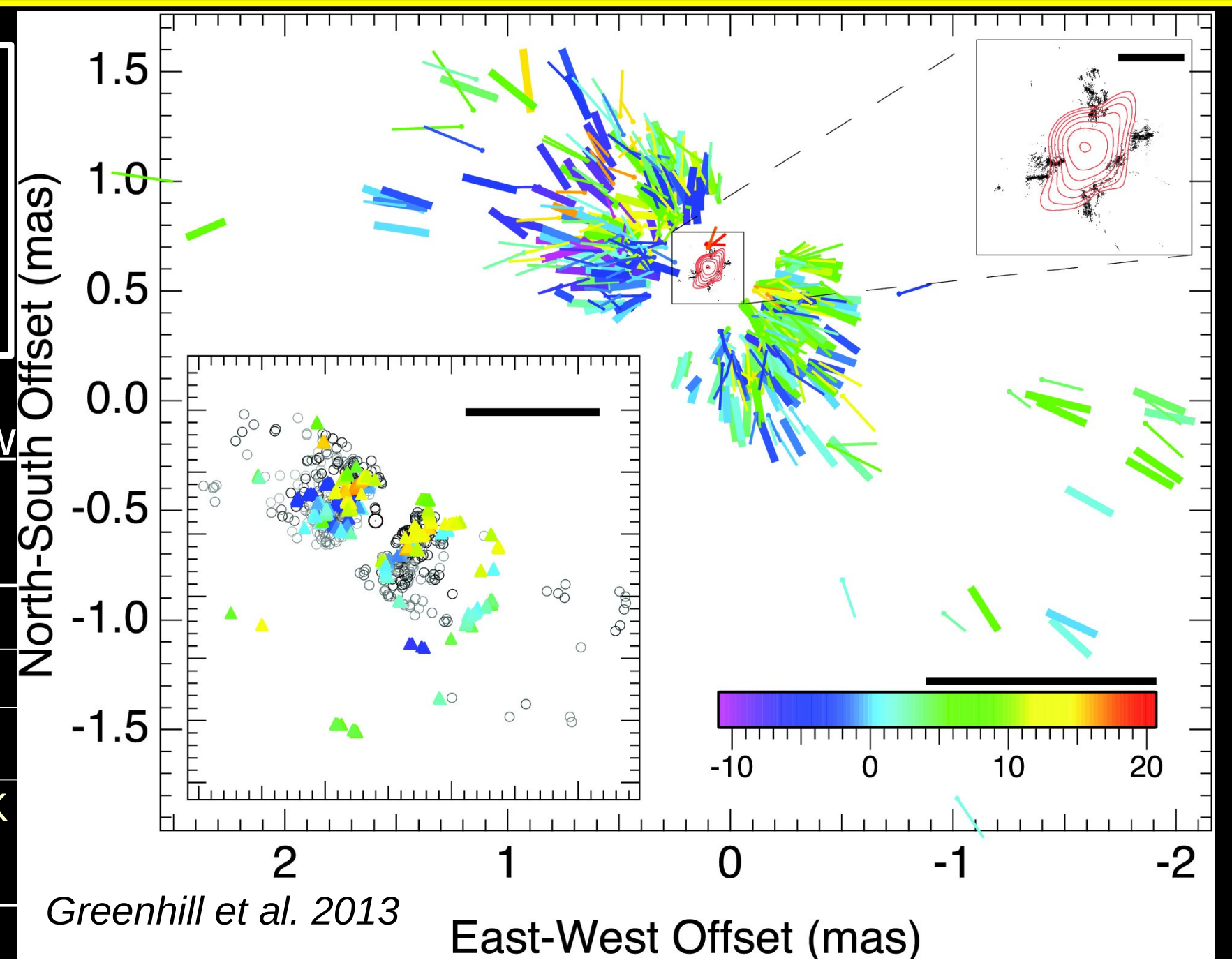


Fig.3: *v=0 SiO and H_2O maser emission*
The proper motions of SiO v=0 masers over 9 years (VLA) identify a collimated bipolar outflow, expanding at 18 km/s. *Inset bottom left*) Positions and l.o.s. velocities of H_2O masers. A velocity gradient ~5 km/s is present across the outflow minor axis, indicative of rotation.

These measurements identified:

- A rotating and expanding disk with R~50 AU (traced by SiO masers in the bridge + 7mm cont)
- A wide-angle, rotating wind from the disk within 100 AU (traced by SiO v=1,2 masers in the four arms)
- A collimated, bipolar rotating outflow beyond 100 AU (traced by SiO v=0 and H_2O masers)

SiO masers could be excited in the interaction of an MHD with the ambient molecular medium (via shocks)

Open Questions:

- ***What drives the disk-wind from Source I?***
- ***What confines outflow?***
- ***What’s the origin of flow rotation?***

We propose a MHD origin of flow from Source I

The magnetic hypothesis is based on four lines of evidence:

1. wide-angle flow at launch (<100 AU)
2. curved tracks close to the disk (<100 AU)
3. gradual collimation of the outflow with distance (>100-1000 AU)
4. l.o.s. velocity gradient perpendicular to the outflow axis

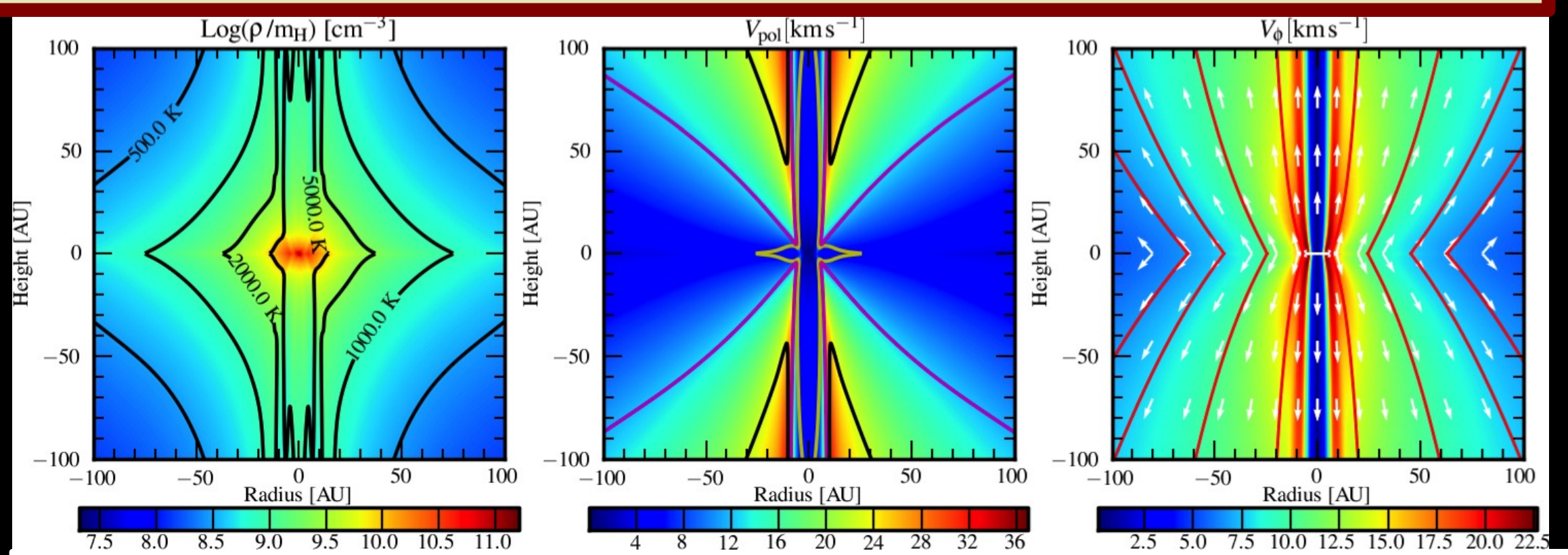


Fig. 4. Jet-profiles of the MHD model Vaidya & Goddi 2013
The vertical density and temperature distribution of the ionized jet (left), the poloidal velocity (middle), and the azimuthal velocity (right). Also shown the velocity versors (*white arrows*), and the poloidal magnetic field lines (*red lines*) for a steady-state MHD flow.
Note the model reproduces the velocity range probed by maser emission inside 100 AU.

III. What is exciting the Orion Hot Core?

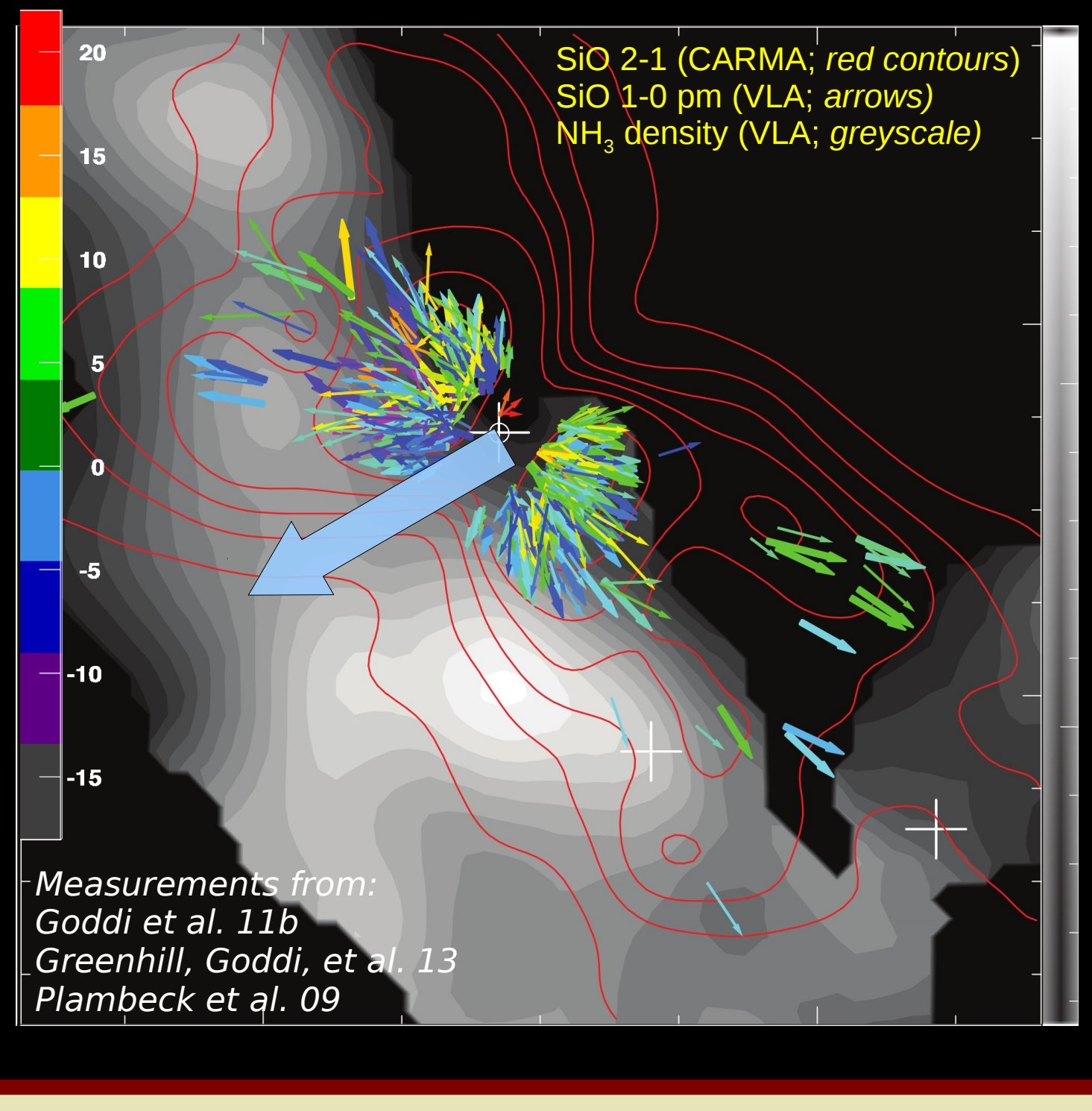
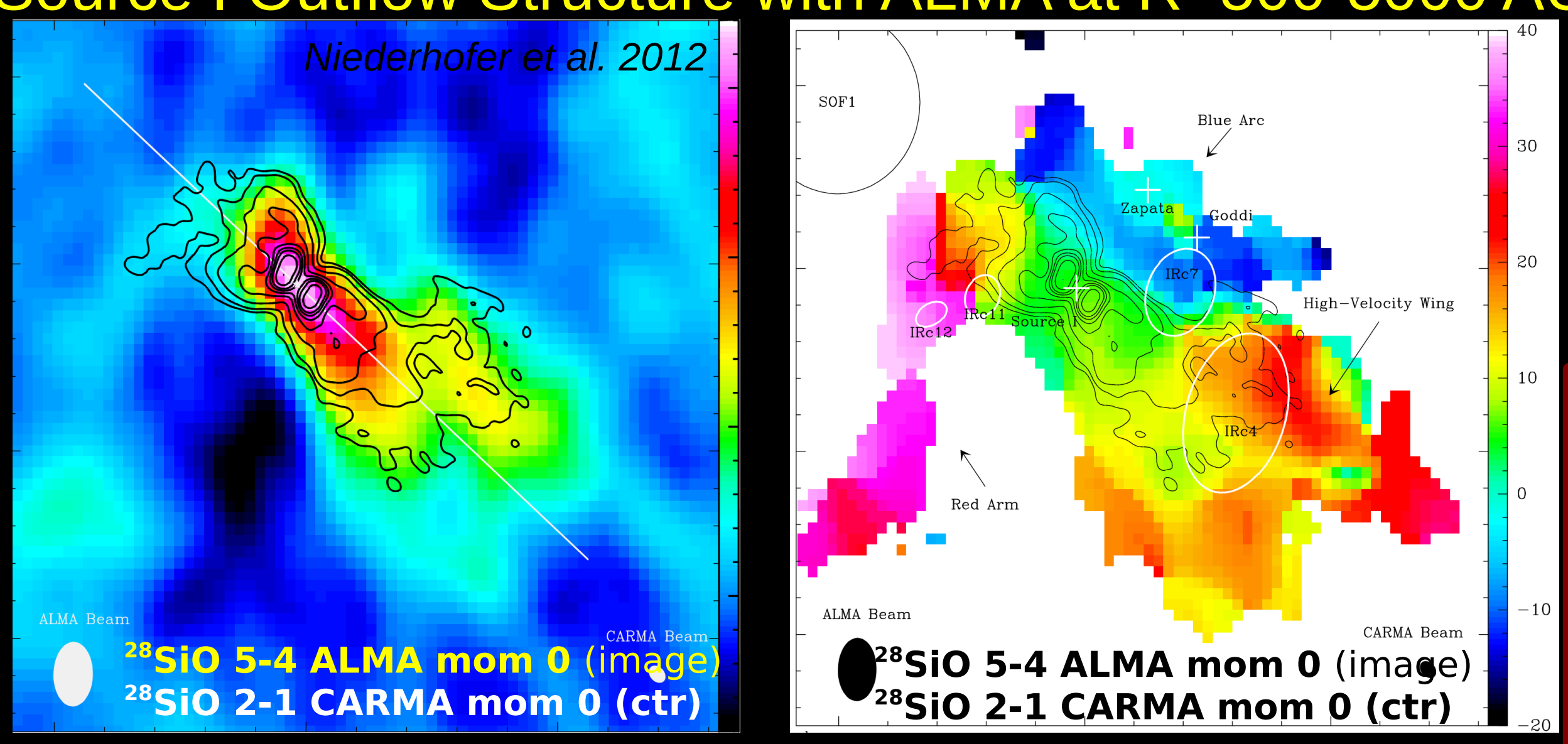


Fig. 5. Source I outflow and Hot-Core
The extended structure probed by CARMA in the SiO 2-1 line emission from CARMA (*red contours*; Plambeck et al. 2009) and NH_3 column density from EVLA (*greyscale*; Goddi et al. 2011b).
The outflow shows a significant overlap with the hot core filament traced by NH_3, and is moving towards it, which suggests gas external heating.

The Hot Core is not internally heated by a star forming at the center, but externally heated by dissipation of mechanical energy of the outflow from Source I impinging on a pre-existing dense filament.

IV. Effect of the environment on outflow structure

Source I Outflow Structure with ALMA at R=500-5000 AU



^{28}SiO 5-4 ALMA mom 0 (image)
^{28}SiO 2-1 CARMA mom 0 (ctr)

Fig. 6. Large-scales of the Source I outflow from ALMA
Moment 0 (left) and Moment 1 (right) of the 5-4 SiO line imaged with ALMA in Cycle 0 CSV (Niederhofer et al. 2012) overlayed with the 2-1 line imaged with CARMA (Plambeck et al. 2009) and MIR sources in the region. Note the complex morphology/velocity structure with respect to scales <1000 AU: we see now an *asymmetric, wider-angle, bipolar* flow.

Outflow rotation is remarkable at R<100 AU, and still evident up to R=500 AU, but NO coherent velocity structure is visible on scales of thousands of AU

The complex morphology/velocity structure of the outflow at the largest scales result from the interaction of the outflow with the complex environment in BN/KL

Summary

I. A dramatic stellar interaction between BN (as a single) and Source I (as a pre-existing binary), occurred in BN/KL just about 500 yrs ago, and may be the origin of the explosive BN/KL outflow.

II. Detailed mapping of circumstellar gas with O(AU) resolution within 1000 AU from a Source I enabled to identify a good example of disk-mediated accretion at 8 M⊙, resolve outflow at/near launch and collimation (R<100 AU), prove flow recollimation at larger distances (100<R<1000 AU), and provided evidence of the dynamic importance of magnetic fields in massive star formation.

III.The famous Orion Hot Core is not actually a “hot core”, but the result of shocked chemistry externally excited by the impact of a massive outflow on a dense clump.

IV.The complex morphology and velocity structure of the Source I outflow on large scales can be attributed to its propagation and interaction with members of a dense protocluster.

References

Bally et al. 2011, ApJ,727, 113
Blandford & Payne, 1982, MNRAS, 199, 883
Goddi C. et al. 2011a, ApJ, 728, 15
Goddi C. et al. 2011b, ApJL, 739, 13
Matthews L. D., Greenhill L.J., Goddi C., et al. 2010, ApJ, 708, 80
Greenhill L. J., Goddi C., et al., 2013, ApJL, .771, 18
Moeckel N. and Goddi C. 2012, MNRAS, 419, 1390
Niederhofer et al. 2012, A&A, 548, 69
Plambeck et al. 2009, ApJL,704, 25
Vaidya & Goddi, 2013, MNRAS, 429, 50