Dynamical detection of a magnetocentrifugal wind from a massive protobinary

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Rationale

Radio Source I at the center of the Orion BN/KL nebula (d~414 pc; Fig. 1a,b) provides the nearest example of a high-mass protostar. Based on dynamical arguments, Source I is believed to be a hard 20 solar mass binary (Fig. 1c; Goddi et al. 2011a; Goddi & Moeckel 2012). Multi-epoch observations of different SiO maser transitions at 7mm with the VLA and VLBA enabled us to map in detail the structure and 3D velocity field of molecular gas, tracing a compact edge-on disk and the base of a protostellar wind at radii <100 AU from Source I (Fig. 2a,b,c; Matthews et al. 2010). This study enabled for the first time to resolve the launch/collimation region of an outflow from a compact disk and to follow the dynamical evolution of molecular gas over time. At larger distances of 100-1000 AU, the outflow is narrowly collimated and aligned well with the rotation axis of the edge-on disk and wide angle flow inside 100 AU (Fig. 3; Greenhill et al. in prep.). Preliminary modeling shows that a centrifugally launched MHD wind model may explain the disk-wind from Source I within 100 AU (Fig. 5; Vaidya & Goddi, in prep.). Gas dynamics outside 100 AU also provides dynamical evidence of a magnetocentrifugal disk wind, notably: a measured gradient in l.o.s. velocity perpendicular to the flow axis, in the same direction as the disk rotation and with similar speed, and gradual collimation of the outflow with distance along the flow axis (Fig. 3, 4). Both elements are expected if the material is centrifugally accelerated from a disk along the magnetic field lines, which collimate the flow further downstream via generation of toroidal fields (e.g., Blandford&Payne 1982).

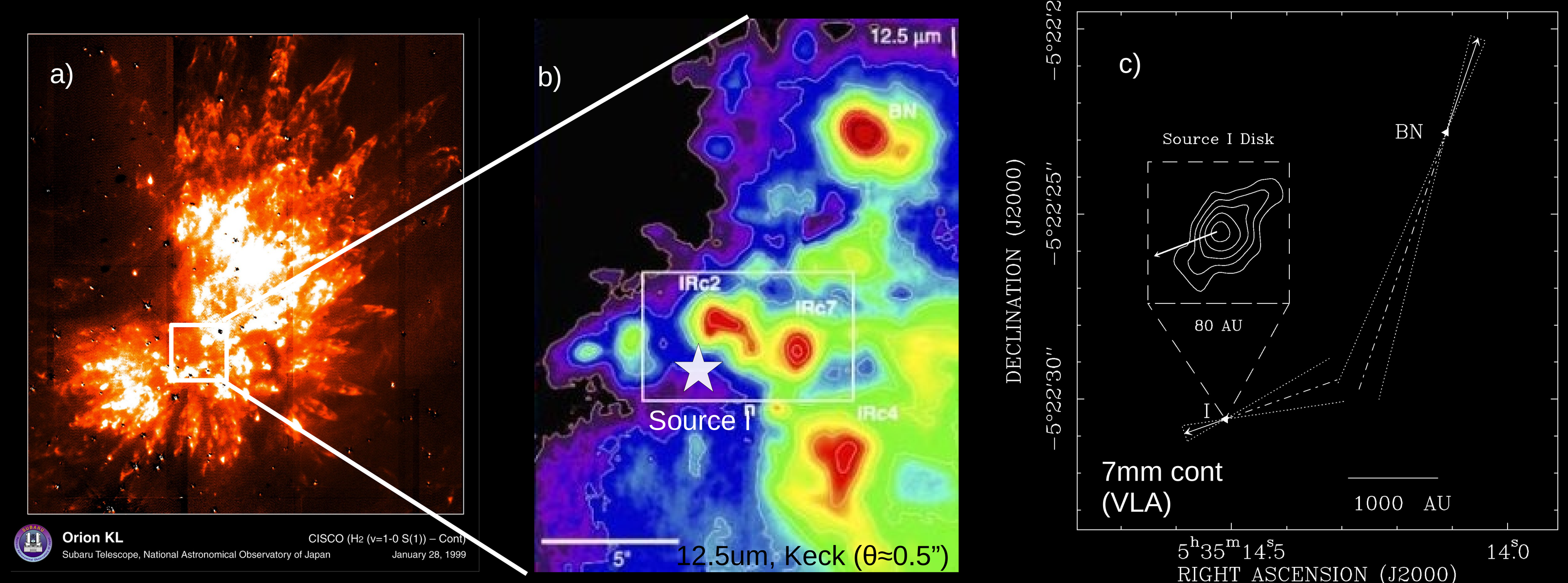
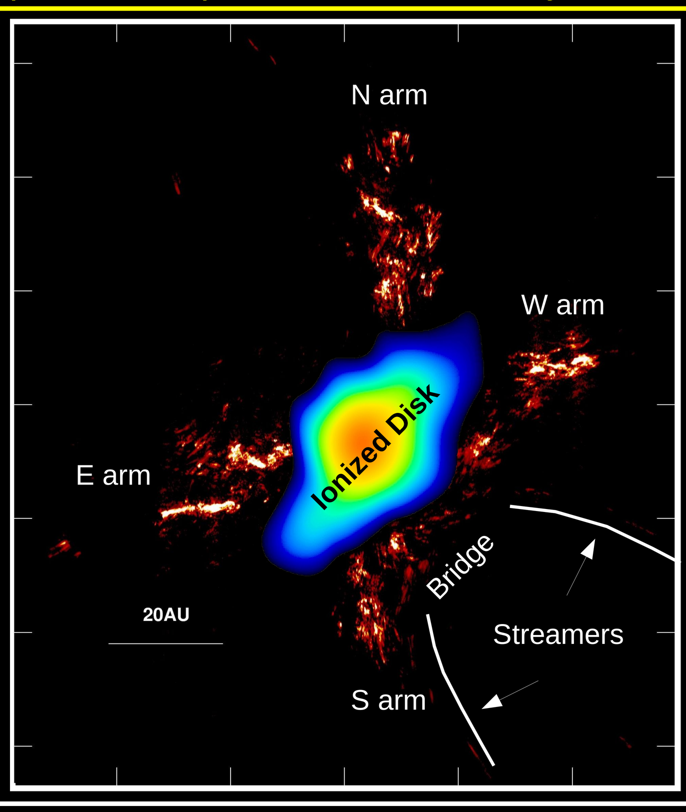


Fig. 1. A NIR view of Orion BN/KL in the H_2 2.14 µm line (Subaru; a) and of its central region at 12.5 µm (Keck; b). c) Measurements of proper motions of 7mm sources in the region show that protostars Source I and BN (4000 AU apart) must have experienced a close passage [O(50 AU)] 500 years ago (Goddi et al. 2011a). N-body numerical simulations show that the dynamical interaction between a binary of 20 solar mass (Source I) and a single star of 10 solar mass (BN) may lead to ejection of both and drive the uncollimated H_2 flow (Goddi & Moeckel 2012).

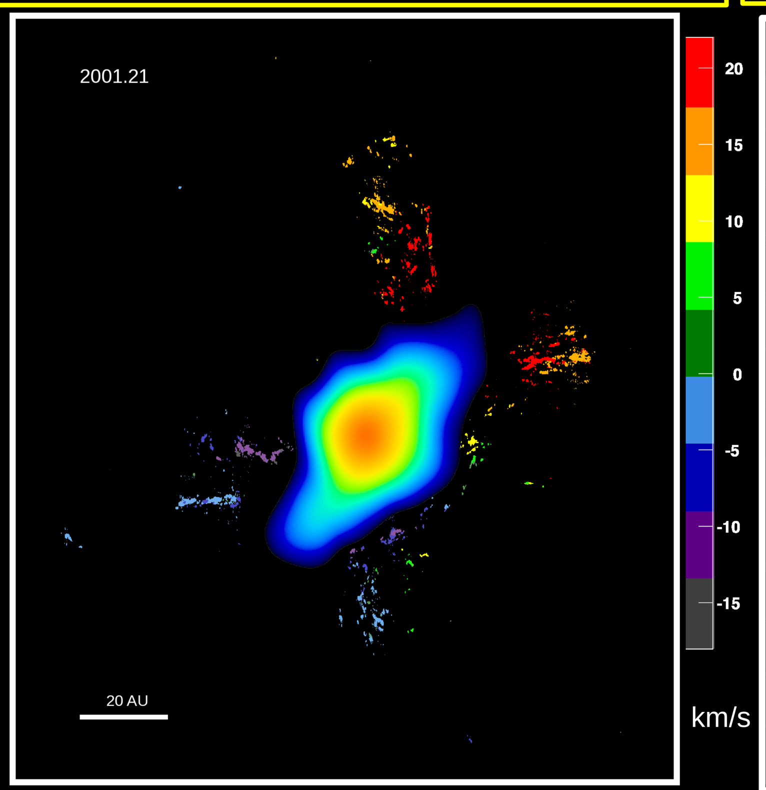
Disk-wind from Source I

Fig.2a: Integrated SiO maser emission (0^{th} moment) summed over two years



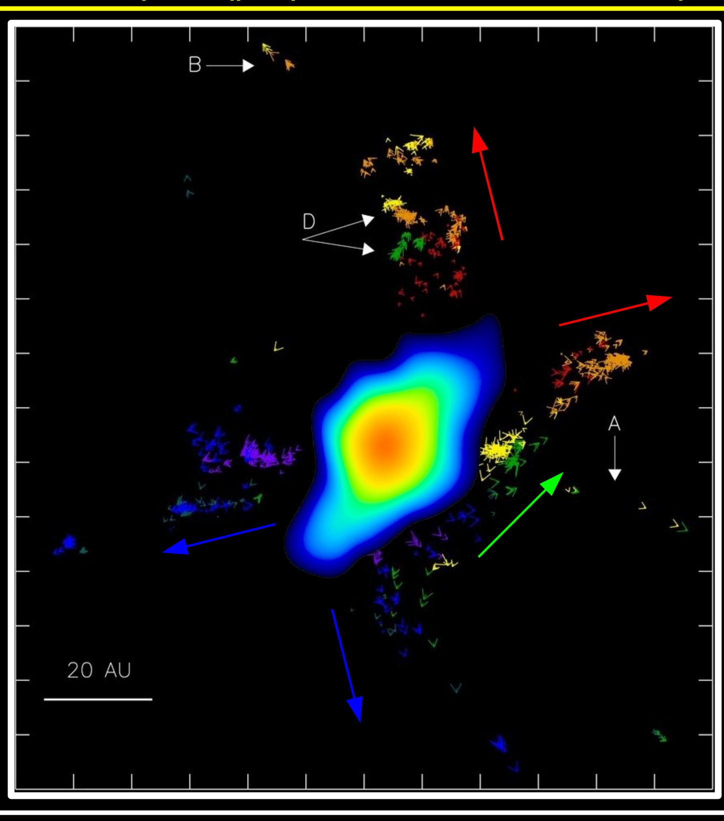
The bulk of the SiO emission is located within four "arms" of an X-shaped pattern. A ~14 AU thick dark band (with no SiO emission) harbors the disk-shaped 7mm continuum source imaged by Reid et al. (2007) and Goddi et al. (2011a). Two "bridges" of emission connecting the arms are parallel to the elongation 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: L.O.S. velocity field of SiO maser emission (1^{h} moment) at a single epoch



The colors indicate l.o.s. velocities in km/s. There is a clear separation between redshifted SiO emission (N and W arms) and blueshifted emission (S and E arms), which represent the receding and approaching sides of the flow. Bridge emission (within a few km/s of the systemic velocity) shows a velocity gradient along the major axis of the radio continuum, indicative of rotation about a NE/SW axis. The velocity gradients along each arm are also consistent with differential rotation.

Fig.2c: 3D velocity field of individual SiO maser spots (proper motions + l.o.s. vel.)



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). No systematic decrease in the magnitudes of proper motions is observed with increasing distance from the star. 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

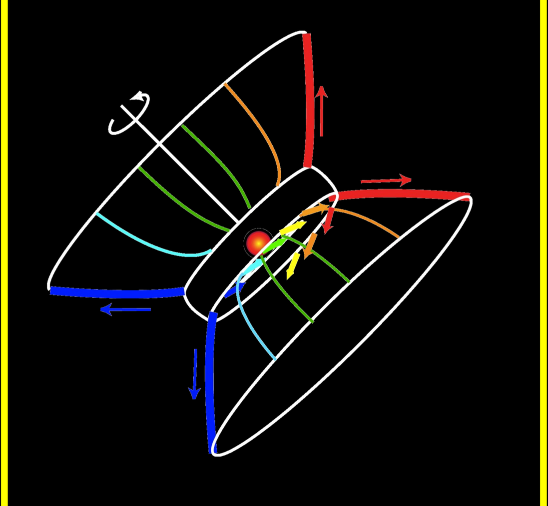
Table 2. Physical parameters of the flow

$M_{dyn\ YSO}$	~ 8 M_{sun}
V_{rot}(20 AU)	= 19 km/s
$<V_{outflow}>$	= 16 km/s
Min($V_{outflow}$)	= 5 km/s
Max($V_{outflow}$)	= 25 km/s
Mass-loss in arms	< 10^{-4} M_{sun}/yr

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
  - traced by SiO masers in the four arms

Toy-Model of the flow inside 100 AU

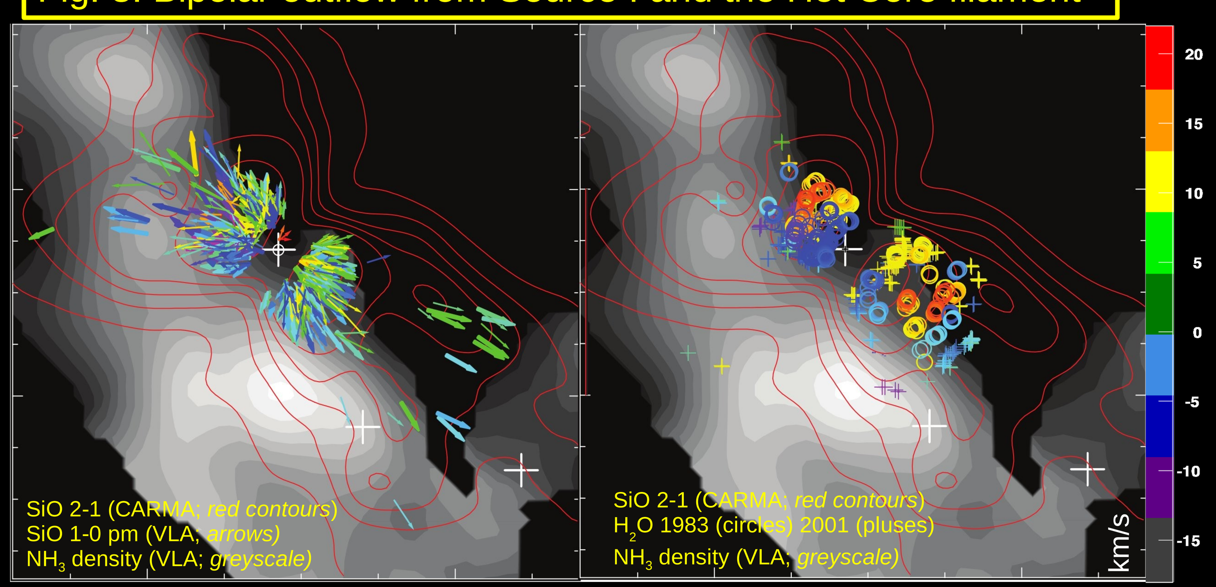


Wide-angle wind emanating from an edge-on disk with a NE-SW rotation axis

Open Question:
What drives the disk-wind from Source I?

Collimated outflow from Source I

Fig. 3. Bipolar outflow from Source I and the Hot Core filament



Left) The proper motions of SiO v=0 masers identify a collimated bipolar outflow, expanding at 18 km/s. Their orientations indicate a gradual collimation of the outflow along its axis further downstream from the driving protostar. *Right)* Positions and l.o.s. velocities of H_2O masers, which probe the same region as the SiO masers. A velocity gradient ~5 km/s is present across the outflow minor axis, indicative of rotation. The extended structure probed by CARMA in the SiO 2-1 line (*red contours*; Plambeck et al. 2009) shows a significant overlap with the hot core filament traced by NH_3 (*greyscale*), which suggests gas external heating (Goddi et al. 2011b).

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)
Physical conditions	10^7 cm^{-3}, 1000 K		10^9 cm^{-3}, >400 K
Scales probed	R~100-1000 AU, Δθ~20-50 AU		

Table 4. Physical parameters of the flow

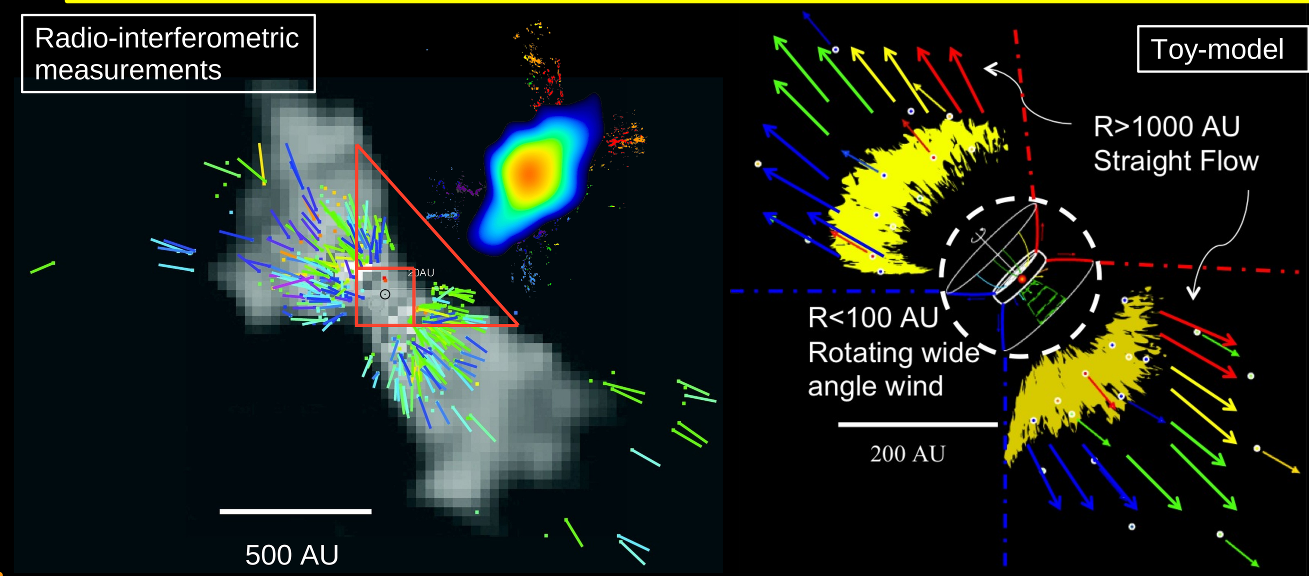
$<V_{outflow}>$	≈18 km/s
R_{inn}	=100 AU
R_{out}	=1000 AU
Mass-loss	~10^{-6} M_{sun}/yr
T_{dyn}	≈500 yrs

Open Questions:

1) ***What confines outflow?***

2) ***What's the origin of flow rotation?***

Fig. 4. A model for the disk/outflow in Source I from 10 AU to 1000 AU



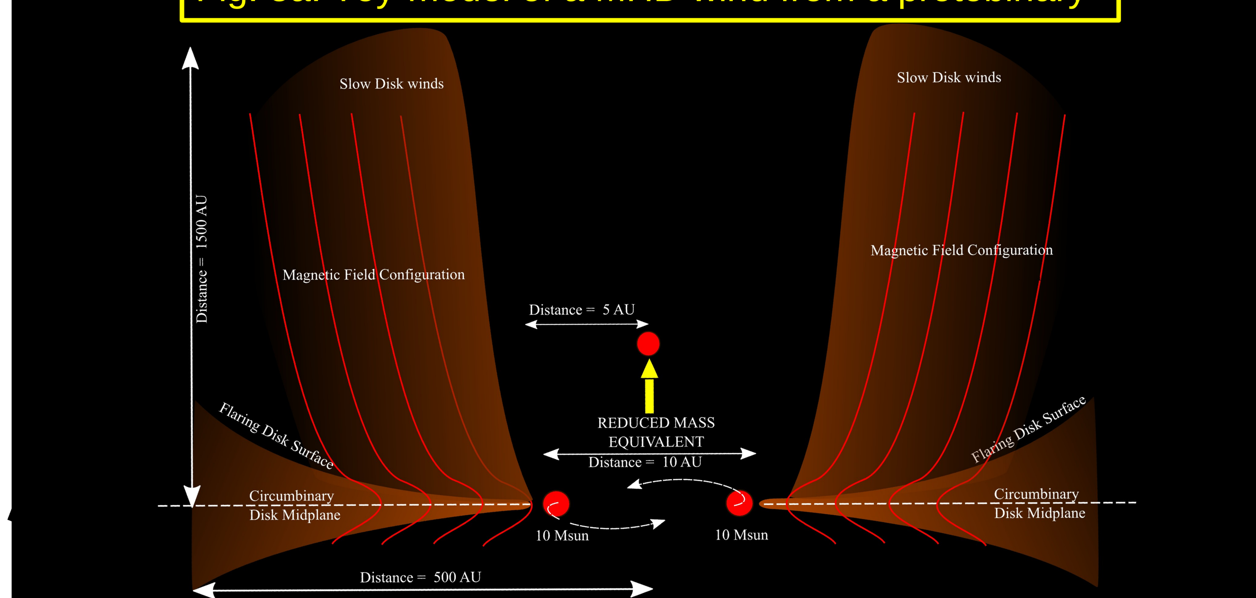
We propose a MHD origin of flow from Source I

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 along the flow axis (>100-1000 AU)
4. l.o.s. velocity gradient perpendicular to the outflow axis

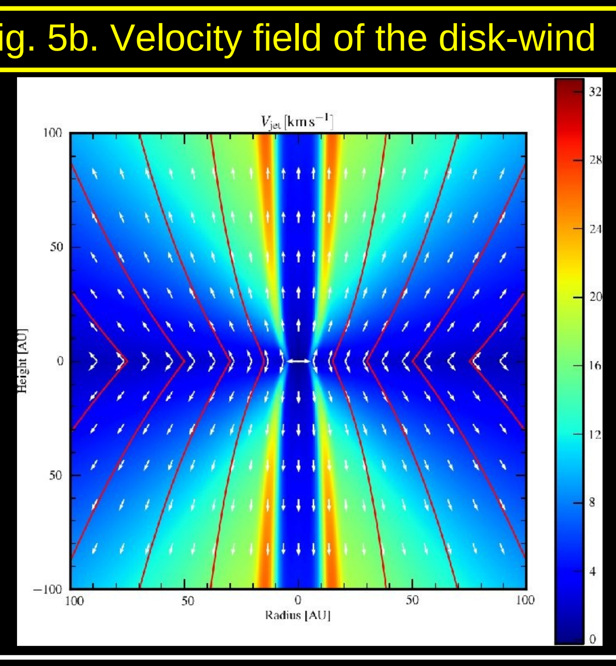
MHD modeling of the disk-wind from the Source I's massive protobinary

Fig. 5a. Toy-model of a MHD wind from a protobinary



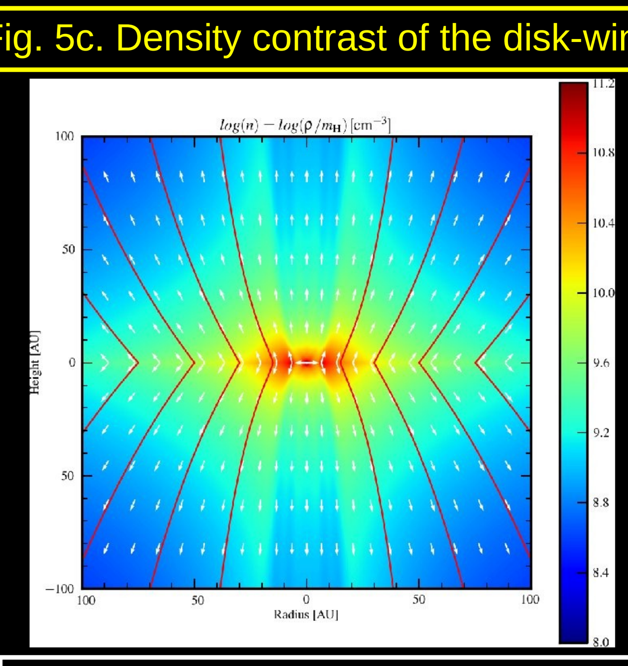
Source I is believed to be a hard binary (a≤5 AU) of 10+10 solar masses (Goddi et al. 2011a). We assume that the outflow is launched from a circumbinary disk with an inner hole with a radius <5 AU (Moeckel & Goddi 2012) and that the reduced mass star is placed at the barycenter of the binary. The relatively low wind velocities predicted by the model (Fig. 5b) are due to the large launching radius (5 AU) and the small reduced mass of the system (5 solar mass). Further, radiation is not expected to affect outflow dynamics (Vaidya et al. 2011).

Fig. 5b. Velocity field of the disk-wind



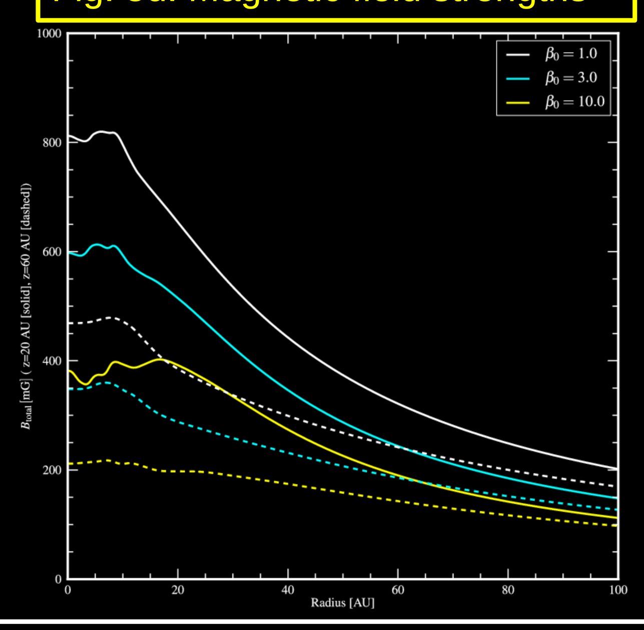
The jet vertical velocity distribution (*color coding*), velocity versors (*white arrows*) and the poloidal magnetic field lines (*red lines*) for a steady-state MHD flow. The color bar represents the velocity scale in km/s. Note that the model reproduces the velocity range probed by maser emission inside 100 AU.

Fig. 5c. Density contrast of the disk-wind



The vertical density distribution of the ionized jet (*color coding*), the velocity versors (*white arrows*), and the poloidal magnetic field lines (*red lines*) for a steady-state MHD flow. The color bar indicates the scale of density contrast.

Fig. 5d. Magnetic field strengths



Radial variation of the total magnetic field strength in steady equilibrium. Colors mark different values of β, the ratio of the thermal gas pressure to the magnetic pressure at launch. The solid line corresponds to z=20 AU and dashes lines to z=60 AU. Larger β implies larger thermal pressure, hence the field strengths decrease as β increases.

Summary

I. Detailed mapping of circumstellar gas with O(AU) resolution within 1000 AU from a massive protostar enbaled to:

✔ demonstrate existence of a compact disk (R~50 AU) and identify a good example of disk-mediated accretion at M ≥ 8 M⊙

✔ resolve outflow at/near launch and collimation (R<100 AU)

✔ prove collimation of the wide-angle wind in a straight bipolar outflow along the disk-axis (100<R<1000 AU)

II. A pure MHD modeling can explain the winds from Source I inside 100 AU, in particular:

✔ It reproduces qualitatively the velocity field and density contrast in the gas probed by molecular masers

✔ we plan to extend the MHD model to the domain 100-1000 AU further downstream from the protobinary

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