Formation of unipolar outflow and "protostellar rocket effect" in magnetized and turbulent molecular cloud cores

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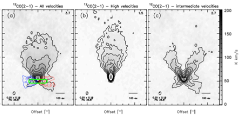
Abstract

We perform the three-dimensional non-ideal magnetohydrodynamics (MHD) simulations to investigate the formation of the asymmetrical protostellar outflows in the early evolution of Young Stellar Objects (YSOs) formed via the collapse of magnetized and turbulent molecular cloud cores. We find that the asymmetrical bipolar outflow is driven in the cloud core where the magnetic energy $E_{\rm mag}$ is comparable to the turbulent energy $E_{\rm turb}$ ($\beta_{\rm turb} \equiv E_{\rm turb}/E_{\rm mag} \sim 1$: the mean Alfvén Mach number $\mathscr{M}_{\rm A} \sim 1$). In contrast, the unipolar outflow is driven in the cloud core where $E_{\rm mag}$ is much smaller than $E_{\rm turb}$ ($\beta_{\rm turb} \sim 4$: $\mathscr{M}_{\rm A} \sim 2$). Furthermore, we find the "protostellar rocket effect" in the unipolar outflow driving system; the linear momentum transport from the unipolar outflow causes the protostar to move from the inner to the outer regions of the cloud cores, and the resulting ram pressure suppresses the additional new outflow driving. The results indicate that the balance of the turbulent and magnetic energies of the parent cloud core plays a key role in the formation of asymmetrical protostellar outflows.

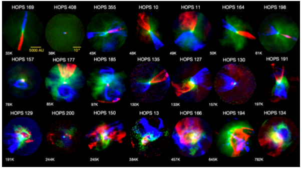
1. Introduction

- Recent observations on star-forming regions have revealed that protostellar outflows driven from the YSOs show a variety of asymmetrical features. (e.g., Louvet et al. 2018; Aso et al. 2019; Habel et al. 2021; Okoda et al. 2021; Hsieh et al. 2023)



Unipolar (monopolar) outflow driven from the HH30 T Tauri star (Louvet et al. 2018)

^{12}CO $J = 2-1$ integrated intensity map (Blue and red) → outflows
C^{18}O $J = 2-1$ integrated intensity map (Green) → envelopes



Protostellar outflows and envelopes around 21 protostars in the Orion A molecular cloud (Hsieh et al. 2023)

Unipolar outflows and **bipolar outflows with asymmetrical features** can be seen in many YSOs.

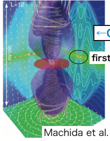
Is it the extinction, geometric effects, and/or observational limits?

Can the unipolar outflows be driven around YSOs?

- Previous studies suggest that the turbulence and magnetic field of parent cloud cores play crucial roles in the formation of outflows and asymmetrical features of YSOs.

Bipolar outflow

Magnetic field + rigid rotation



←Ohmic diffusion→

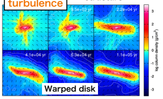
first core

Machida et al. (2008)

No outflow

turbulence

Asymmetrical structure



Warped disk

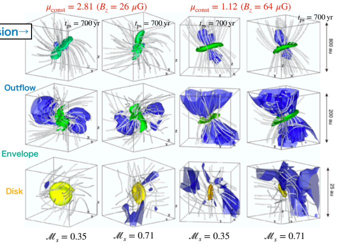
Takaishi et al. (2020)
Sonic Mach number $\mathscr{M}_s = 1.0$

Bipolar outflow $\mu_{\rm const} \leq 4$

Magnetic field + turbulence

$\mu_{\rm const}$: dimensionless mass-to-flux ratio
$\mu_{\rm const} \sim 1-4$ (Crutcher 2012)

$\mu_{\rm const} = 2.81$ ($B_z = 26\ \mu$G) $\mu_{\rm const} = 1.12$ ($B_z = 64\ \mu$G)



$\mathscr{M}_s$: Mach number

Matsumoto et al. (2017)

Ambipolar diffusion of the non-ideal MHD effect is neglected.

- Turbulence of parent cloud cores should generate asymmetric accretions in especially weakly magnetized cloud cores but it is still unclear. $\mu_{\rm mag} \geq 4$

→ We study the formation of unipolar and bipolar outflows with asymmetrical features in magnetized and turbulent cloud cores by using 3D non-ideal MHD simulations.

2. Numerical Method and initial conditions

Basic equations

$$\frac{D\boldsymbol{v}}{Dt} = -\frac{1}{\rho}\left\{\nabla\left(P + \frac{1}{2}|\boldsymbol{B}|^2\right) - \nabla\cdot(\boldsymbol{B}\otimes\boldsymbol{B})\right\} - \nabla\phi,$$

$$\frac{D\boldsymbol{B}}{Dt} = (\boldsymbol{B}\cdot\nabla)\boldsymbol{v} - \boldsymbol{B}(\nabla\cdot\boldsymbol{v}) - \nabla\times\left\{\eta_{\rm O}(\nabla\times\boldsymbol{B}) - \eta_{\rm A}((\nabla\times\boldsymbol{B})\times\hat{\boldsymbol{B}})\times\hat{\boldsymbol{B}}\right\},$$

$$\nabla^2\phi = 4\pi G\rho,$$

$$P = P(\rho) = c_{\rm s,iso}^2\rho\left\{1 + \left(\frac{\rho}{\rho_{\rm crit}}\right)^{2/3}\right\}$$

$$c_{\rm s,iso} = 1.9\times10^4\,{\rm cm\,s^{-1}},\ \ \rho_{\rm crit} = 4\times10^{-14}\,{\rm g\,cm^{-3}}$$

Numerical Method

Godunov Smoothed Particle Magnetohydrodynamics
(GSPMHD; Iwasaki & Inutsuka (2011), (2013))
non-ideal MHD part;
Ohmic diffusion (Tsukamoto et al. (2013))
Ambipolar diffusion (Wurster et al. (2014))
$\eta_{\rm O}$, $\eta_{\rm A}$: single-sized dust model ($a = 0.035\ \mu$m; Tsukamoto et al. (2020))

Initial conditions

Bonner-Ebert sphere (density-enhanced) $J_{\rm c,net} = 4.4\times10^{53}\,{\rm g\,cm^2\,s^{-1}}$

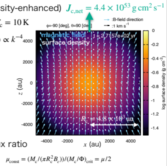
$M_{\rm c} = 1M_\odot$, $R_{\rm c} = 4.8\times10^3$ au, $T_{\rm c} = 10$ K

$\mathscr{M}_{\rm s} = \sigma_{\rm turb,3D}/c_{\rm s,iso} = 0.86$, $P_v(k) \propto k^{-4}$

$\alpha_{\rm thm} = E_{\rm thm}/|E_{\rm grav}| = 0.4$

$\gamma_{\rm turb} = E_{\rm trub}/|E_{\rm grav}| = 0.1$

$f = 2.1$, $\rho_0 = 7.3\times10^{-18}\,{\rm g\,cm^{-3}}$



Parameters: $B_{\rm c}$

$B_c = 31\ \mu$G, $63\ \mu$G, $126\ \mu$G, $252\ \mu$G

Dimensionless mass-to-flux ratio

$$\mu = \frac{(M_{\rm c}/\Phi)}{(M_{\rm c}/\Phi)_{\rm crit}} = 16,\ 8,\ 4,\ 2$$

$$(M_{\rm c}/\Phi)_{\rm crit} = (0.53/3\pi)(5/G)^{1/2}$$

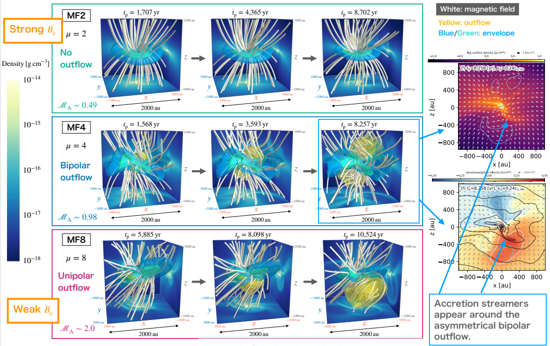
$$\Phi = \pi r^2 B_0/((r/R_{\rm c})^2 + 1)$$

$\mu_{\rm const} = (M_{\rm c}/(\pi R_{\rm c}^2 B_c))/(M_{\rm c}/\Phi)_{\rm crit} = \mu/2$
$\beta_{\rm turb} = E_{\rm turb}/E_{\rm mag} = \gamma_{\rm turb}/\gamma_{\rm mag}$, $\gamma_{\rm mag} = E_{\rm mag}/|E_{\rm grav}|$
$\mathscr{M}_{\rm A} = \sigma_{\rm turb,3D}/v_{\rm A} = \sqrt{\beta_{\rm turb}}$: mean Alfvén Mach number
$v_{\rm A}$: root-mean-square Alfvén velocity
$\sigma_{\rm turb,3D}$: turbulent velocity
$E_{\rm thm}$, $E_{\rm grav}$: thermal and gravitational energies

Model	μ	$B_{\rm c}$ (μG)	$\mu_{\rm const}$	$\gamma_{\rm mag}$	$\beta_{\rm turb}$	$\mathcal{M}_{\rm A}$	Outflow
MF2	2	252	1	0.42	0.24	0.49	no
MF4	4	126	2	0.10	0.96	0.98	bipolar
MF8	8	63	4	0.026	3.8	2.0	unipolar
MF16	16	31	8	0.0065	15	3.9	unipolar

Table: summary on parameters and results

3.1. Results: overview



Strong $B_{\rm c}$

No outflow

Bipolar outflow

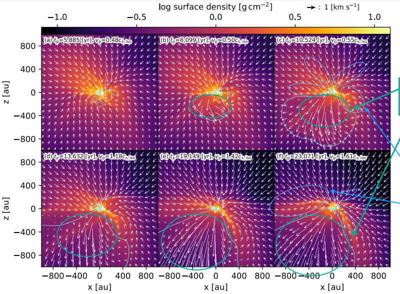
Unipolar outflow

Weak $B_{\rm c}$

Accretion streamers appear around the asymmetrical bipolar outflow.

Magnetic field is twisted in the lower region.

3.2. Protostellar rocket induced by unipolar outflow

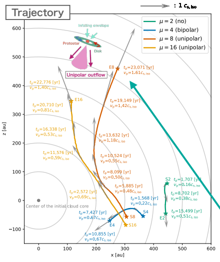


$t_{\rm p}$: elapsed time after the protostar formation

Unipolar outflow is driven. (wide opening angle)

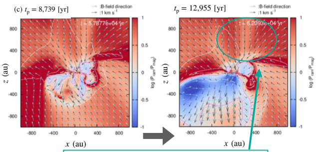
Accretion streamers (Arc-like structures) in infalling envelopes

Trajectory



Ram pressure/magnetic pressure

$\bar{P}_{\rm mom,disk} \sim 0.05M_\odot \times 0.19\,{\rm km\,s^{-1}} \sim 10^{-2}\,{\rm M_\odot\,km\,s^{-1}}$



Ram pressure suppresses the outflow formation in the upper region.

"Protostellar rocket effect"

Linear momentum transport from the unipolar outflow causes the protostar to move from the inner to the outer.

4. Summary

(1) Asymmetrical bipolar outflow is driven in the cloud core with $\beta_{\rm turb} \equiv E_{\rm turb}/E_{\rm mag} \sim 1$.

(2) Unipolar outflow is driven in the cloud core with $\beta_{\rm turb} \sim 4 > 1$.

(3) Unipolar outflow does not evolve into the bipolar outflow because enhanced ram pressures suppress additional new outflow drivings.
→"Protostellar rocket effect"

(4) Accretion streamers can be naturally explained by the turbulent accretions.