Origin of Molecular Outflow Determined from Thermal Dust Polarization

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As the origin of molecular outflows ejected from protostars, there are two major explanations: magnetic drive and entrainment. In the former, gas is magnetically driven and forms an outflow, In the latter, an optical jet which is ejected in the vicinity of a protostar entrains outer molecular gas and forms the outflow.

In order to conclude the problem, it is essential to observe the geometry of the magnetic field. We study the expected polarization for the thermal radiation from the magnetically aligned dust grains in the outflow[1]. Dust grains are aligned with their major axis being perpendicular to the magnetic field. Emission from such dust grains is polarized with the B-vector being perpendicular to the major axis. Figure 1 represents an outflow reproduced in the axisymmetric MHD simulation of the gravitational collapse of the molecular core[2]. This shows that a disk forms in the perpendicular direction to the magnetic field, which extends horizontally, and that an outflow is ejected in perpendicular direction to the disk.

Observing along the line-of-sight (los) specified with the angle from the z-axis θ, the Stokes' parameters q and u, which represent the polarization, are calculated with two angles, γ (the angle between the magnetic field and the celestial plane) and ψ (the position angle of the projected magnetic field) as $q = \int \rho \cos 2\psi \cos^2 \gamma ds$, $u = \int \rho \sin 2\psi \cos^2 \gamma ds$ where we perform the integration along the los.

Figure 2 indicates the expected polarization observation. This indicates (1) the pole-on (θ = 0º: top) view has an axisymmetric pattern. The molecular outflow is observed as a ring with a relatively high polarization degree whose B-vector is toward the azimuth direction. (2) Observing edge-on (θ = 90º: bottom), the pattern is mirror-symmetric and the disk has a higher polarization degree than the outflow. (3) Between these two (θ = 60º: middle), the pattern is 180º rotation-symmetry and both the disk and the outflow have lower polarization degree. These are characteristic for the configuration that the magnetic field has both poloidal and toroidal components.

The fact that the outflow has a toroidal magnetic field is a direct evidence of magnetic drive. When one of the patterns shown above is found, this indicates there exists the toroidal magnetic field and thus the outflow is magnetically driven.

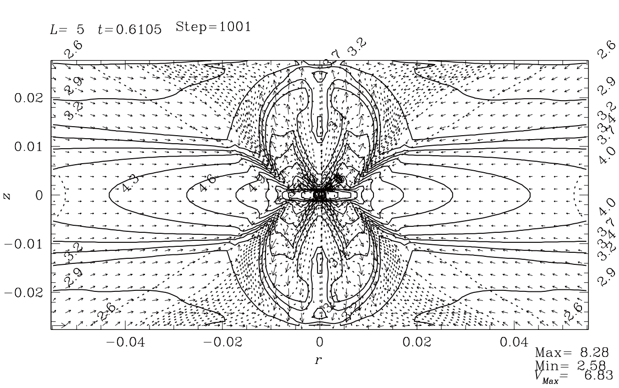

Figure 1: Simulation of molecular outflows. Solid and dashed lines represent, respectively, the isodensity contours and the poloidal magnetic field lines. Spatial extent is as large as 3000 AU × 6000 AU.

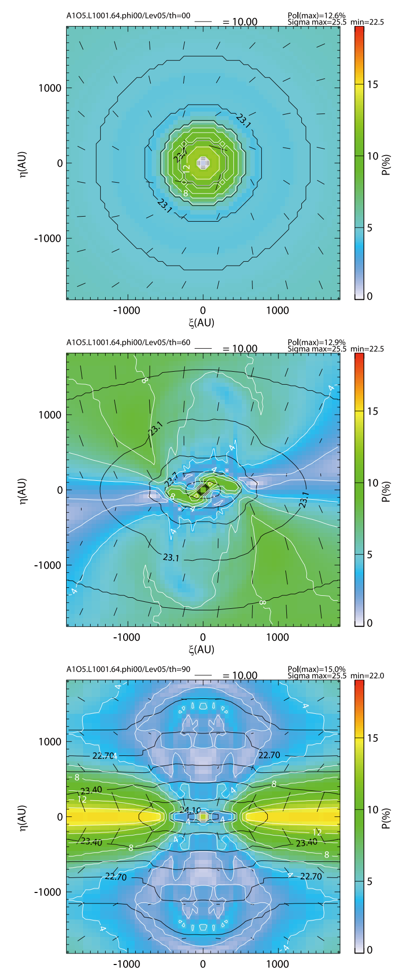

Figure 2: Expected distribution of the total intensity of the dust thermal emissions (black contour), polarization degree (white contour and color), and the directions of observed B-vector (black bar). (top) pole-on, (middle) θ = 60°, and (bottom) edge-on.

References

[1] Tomisaka, K.: 2002, *ApJ*, **575**, 306.
[2] Tomisaka, K.: 2011, *PASJ*, **63**, 147.