**OUTFLOWS AND JETS FROM COLLAPSING MAGNETIZED CLOUD CORES.** Robi Banerjee, Ralph E. Pudritz, *Department of Physics and Astronomy, McMaster University, Hamilton, Ontario L8S 4M1, Canada*.


**Abstract**

Star formation is usually accompanied by outflow phenomena. There is strong evidence that these outflows and jets are launched from the protostellar disk by magneto-rotational processes. Here, we report on our three dimensional, adaptive mesh (AMR), magneto-hydrodynamic (MHD) simulations of collapsing, rotating, magnetized Bonnor-Ebert-Spheres. Our inital setup resembles the properties of the well studied Bok globule, Barnard 68, which follows a close to perfect Bonnor-Ebert-Sphere (Alves et al., 2001).

In contrast to the pure hydro case (Banerjee et al., 2004) where no outflows are seen, our present simulations show an outflow from the protodisk surface at $\sim 130$ AU and a jet at $\sim 0.07$ AU after a strong toroidal magnetic field build up. The large scale outflow, which extends up to $\sim 600$ AU at the end of our simulation, is driven by toroidal magnetic pressure (spring), whereas the jet is powered by magneto-centrifugal force (fling). Furthermore, we find that the jet-wind and the disk-anchored magnetic field extracts a considerable amount of angular momentum from the protostellar disk. This influences the fragmentation of the disk – we find a close binary system (separation $\sim 3\,R_\odot$) – resulting from the fragmentation of an earlier formed ring structure. The magnetic field strength in these protostars reaches $\sim$ 3kGauss and becomes about 3 Gauss at 1 AU from the center.

For massive star formation, outflows lead to anisotropies in the protostellar envelope which reduce the radiation pressure and help to accrete material more efficiently onto the protostar (Krumholz et al., 2005).


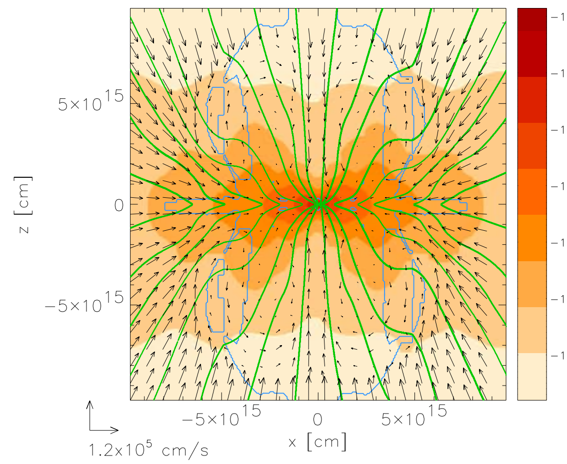


Figure 1: Shows the large scale outflow. The magnetic pressure drives a “bubble” which is surrounded by shock fronts and reverses the gas flow. Shown are the density (color scale), magnetic field lines (green), Alfvén surface (blue), and the velocity field.

**Large scale outflow**

A strong toroidal magnetic field component builds up as the magnetic field lines are wound up during the core’s contraction phase. By the time when the central density reaches $\sim 10^{10}\,\mathrm{cm}^{-3}$, the magnetic pressure from the toroidal field component has become strong enough to prevent the shock fronts below and above the disk plane from moving towards the center. Now, material inside the magnetized bubble is pushed outward leading to a large scale outflow (Fig. 1 and Fig. 2).

This collimated bipolar outflow can be understood in terms of a magnetic tower flow (Lynden-Bell, 2003; Kato et al., 2004) that consists of an annulus of highly wound magnetic field lines that pushes into the ambient pressure environment. The toroidal magnetic field component that is continuously produced by the rotating disk acts like a compressed spring which lifts some material off the disk surface and sweeps up material in the external medium. At this stage where the large scale outflow begins to sweep up material the magnetic pressure becomes stronger than the thermal pressure ($\beta \sim 0.1 - 1$) and the interior of the “magnetic bubble“ cools further by adiabatic expansion. Such an outflow may be the origin of the molecular flow that is seen from all young stellar objects (YSOs) (e.g., Uchida & Shibata, 1985). Measurements of CO emission lines of outflows from young stellar objects indicate higher veloc-

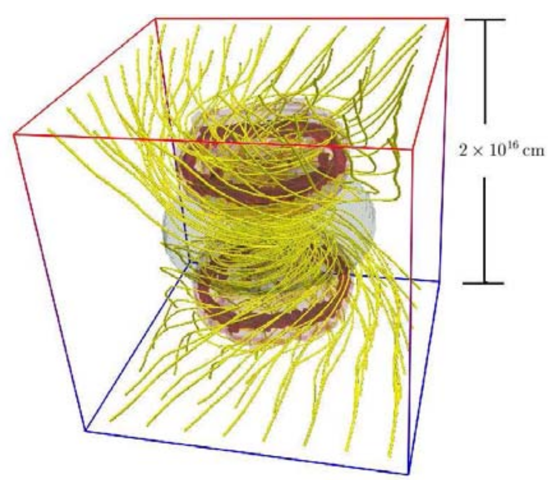


Figure 2: Shows the magnetic field line structure of the large scale outflow region. A strong poloidal gradient of the magnetic field is clearly visible which drives this large scale outflow. The red isosurfaces show the outflow velocities and the the gray isosurface is the density.

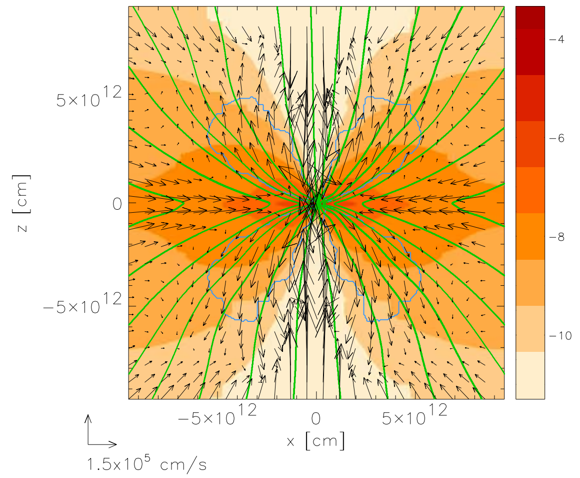


Figure 3: Shows the jet launched from the protostellar disk. Here, magneto-centrifugal force drives the outflow.

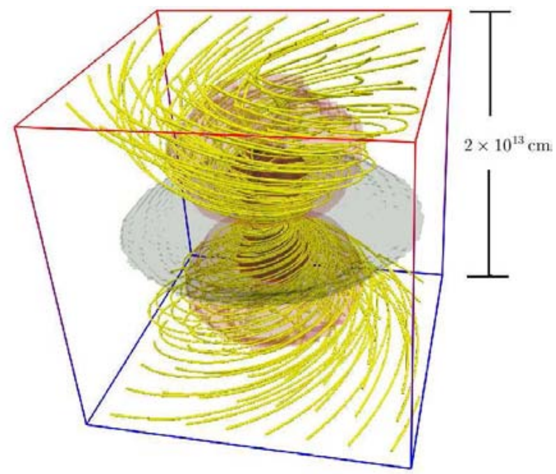


Figure 4: Shows the magnetic field line structure of the jet region (see Fig. 3). Strongly backwards bend field lines fling material off the protodisk surface (outflow velocities marked as red isosurfaces).

ities, but our simulations show the star formation phase in a very early stage wherein the central mass of the protostar is still tiny. Since the outflow velocity is related to the escape speed (Pudritz & Banerjee, 2005), this is the expected result. The outflow speed will increase with time as central stellar mass grows. In Fig. 1 one can see that the outflow velocity exceeds the poloidal Alfvén velocity where the outflow is the fastest. The outflow forces the region enclosed by the outer shock fronts to expand and the shock fronts are moving outward. By the end of our simulation the shock fronts are pushed to a disk height of $\sim 600$ AU and would presumably continue to rise.

We point out that the collimation of the large scale outflow is not due to the initially uniform field which extends to infinity but rather to the dynamically built up field structure which provides hoop stresses to confine the outflow. The fact that toroidal field component dominates the poloidal component in the outflow region shows that the large scale outflow is driven by (toroidal) magnetic pressure and confined by by the same toroidal field structure as shown in Lynden-Bell (2003).

**The disk jet**

An even more dramatic outflow phenomenon erupts from the interior regions of the disk, in the deepest part of the gravitational potential well generated by the assembling protostar. In Fig. 3 and Fig. 4, we snapshots of the disk and surrounding infalling region focused AU scale. In comparison with the outer regions of the disk, the magnetic field lines towards the disk interior have been significantly distorted as they are dragged inwards by the disk's accretion flow. They take the appearance of a highly pinched-in, hour-glass. This configuration is known to be highly conducive to the launch of disk winds (Blandford & Payne, 1982; Pudritz & Norman, 1983): magnetic field lines threading the disk with an angle with the vertical that is greater than $30^\circ$ are able to launch a centrifugally driven outflow of gas from the disk surface. Our simulations clearly confirm this picture as the angles of the magnetic field lines with the vertical axis that are much greater than $30^\circ$. Moreover, this disk wind achieves super-Alfvénic velocities above which it begins to collimate towards the outflow axis.

**Binary system and angular momentum**

Although, magnetic fields prevent early fragmention of the protostellar disk we find that a ring structure forms that has diameter of only $\sim 9\,R_\odot$. This subsequently fragments into a binary system with $\sim 3\,R_\odot$ separation at a core density of $\sim 10^{20}$ cm$^{-3}$.

Furthermore, we find that the disk-threading magnetic field and the disk wind extract a large amount of angular momentum from the protodisk which results in the spin-down of the protostar(s) and in a very efficient mass accretion. The latter point might have important implications for massive star formation.

**References**


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