Magnetically Driven Outflows During Massive Star Formation

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Abstract. We present 3-D magnetohydrodynamical (MHD) collapse simulations of magnetized, rotating prestellar cores. We examine the influence of the magnetic field strength and the rotational energy on protostellar accretion rates and on the formation of outflows and protostellar disks. We find a strong dependency of the outflow morphology and the disk properties on the magnetic field strength. Interestingly, the accretion rates depend only weakly on the initial conditions.

1. Introduction

The formation of massive stars and the evolution of associated protostellar outflows is still a highly debated question. A growing number of discs and outflows observed around massive protostars (Beuther & Shepherd 2005; Cesaroni et al. 2007) points to a formation scenario via disc accretion for massive stars under the influence of magnetic fields. In our work we analyze the influence of the initial conditions on protostellar accretion rates and the formation of discs and outflows around massive protostars. For this purpose we perform 12 simulations of collapsing 100 M☉ cloud cores with variable initial rotational and magnetic energies. We solve the MHD equations with the astrophysical code FLASH (Fryxell et al. 2000) making use of sink particles. The cloud cores have a diameter of 0.25 pc and a density profile ρ(r) ~ r⁻¹.5. The initial rotational (β_rot) and magnetic (γ) energies, normalized to the gravitational energy, range from 10⁻⁴ to 0.1 bracketing the line where β_rot = γ (see Seifried et al. 2011a, for details).

2. Results

We run the simulations over a some 1000 yr after the first sink particle has formed. The time averaged accretion rates are of the order of a few 10⁻⁴ M☉ yr⁻¹ varying within a factor of ~ 3 between the individual runs. This variation is remarkably small considering the large range of initial conditions. We attribute this fact to two competing effects of the magnetic field. On the one hand, magnetic braking enhances accretion by removing angular momentum from the disc thus lowering the centrifugal support against gravity. On the other hand, the combined effect of magnetic pressure and magnetic
tension counteracts gravity by exerting an outward directed force on the gas in the disc thus reducing the accretion onto the protostars.

In contrast to the accretion rates, the properties of the protostellar discs strongly depend on the initial conditions, in particular on the magnetic field strength. For strong fields with mass-to-flux ratios < 10 only sub-Keplerian discs form. This is due to the very efficient magnetic braking removing angular momentum from the midplane resulting in discs with infall velocities close to free-fall. Only for runs with weak magnetic fields (µ ≥ 10) Keplerian discs with radii exceeding 100 AU build up.

The outflow morphologies are also strongly affected by the initial magnetic field strength. Well collimated fast jets are only found for runs with weak fields and high rotational energies whereas for the remaining runs poorly collimated, low-velocity outflows occur. This shows that the formation of well collimated jets is coupled to the build-up of well defined Keplerian discs. By analyzing the outflows with a new criterion derived from MHD wind theory, which can also deal with sub-Keplerian disc rotation (Seifried et al. 2011b), we show that all outflows are launched by centrifugal acceleration (Blandford & Payne 1982) whereas the toroidal magnetic field contributes to gas acceleration further away from the disc. The morphological differences are caused by varying hoop stresses responsible for outflow collimation. The outflow/accretion ratios of the runs scatter around 0.3 in accordance with theoretical predictions.

3. Conclusion

The observed suppression of Keplerian discs formation for moderately magnetized cores raises the question of how Keplerian discs and well collimated jets can form around massive protostars. Possible solutions are non-ideal MHD effects but also the observed outflows themselves, evacuating the regions above/below the midplane, hence reducing the magnetic braking efficiency. On the base of our results we suggest that poorly collimated outflows are typical for the earliest stage of massive star formation. Over time the outflow collimation will increase due to the development of a well collimated, fast jet overtaking the slowly expanding outflow. We also show that contradictory results in literature concerning the driving mechanism of outflows can be due to the use of insufficient properties like the magnetic field line inclination or the ratio of the toroidal to poloidal magnetic field when analyzing the outflow. We therefore recommend to use a fully self-consistent criterion as presented in Seifried et al. (2011b).

References