Outflows and mass accretion in collapsing dense cores with misaligned rotation axis and magnetic field

Andrea Ciardi[★] and Patrick Hennebelle

LERMA, Obervatoire de Paris, École Normale Supérieure, Université Pierre et Marie Curie, UMR 8112 CNRS, 24 Rue Lhomond, 75231 Paris, France

ABSTRACT

Outflows and jets are intimately related to the formation of stars, and play an important role in redistributing mass, energy and angular momentum within the dense core and parent cloud. The interplay between magnetic field and rotation is responsible for launching these outflows, whose formation has been generally carried out for idealized systems where the angle α between the rotation axis and large-scale magnetic field is zero. Here we explore, through three-dimensional ideal magnetohydrodynamic simulations, the effects of a non-zero α on the formation of outflows during the collapse of dense pre-stellar cores. We find that mass ejection is less efficient for increasing angle α and that outflows are essentially suppressed for $\alpha \sim 90°$. An important consequence is a corresponding increase of the mass accreted on to the adiabatic (first) core. In addition, mean flow velocities tend to increase with α, and misaligned configurations produce clumpy, heterogeneous outflows that undergo precession, and are more prone to instabilities.

Key words: instabilities – MHD – stars: formation – stars: winds, outflows – ISM: clouds – ISM: kinematics and dynamics.

1 INTRODUCTION

The ejection of plasma in the form of more or less collimated bipolar flows (jets) is arguably one of the most spectacular displays staged by a forming star. Over a million years, these outflows trace the creation of stars from their embryonic emergence as protostars, still enveloped in their dense parental cloud, to their birth as T Tauri stars surrounded by protoplanetary discs. The existence of a close relation between the ejection and accretion of matter throughout the (low-mass $M_\star \lesssim 2\,M_\odot$) star's formation history (Cabrit & Bertout 1992; Hartigan et al. 1995; Wu et al. 2004) suggests the presence of a single launching mechanism, which is now widely thought to rest on the presence of a large-scale magnetic field mediating the extraction of gravitational energy from the accreting plasma, and redirecting mass and energy, in the form of kinetic and Poynting flux, into bipolar jets. The fundamental magnetohydrodynamic (MHD) mechanism for launching and collimating an axisymmetric, self-similar outflow was detailed in analytical work by Blandford & Payne (1982) and applied to young stellar systems by Pudritz & Norman (1983); it was later extended to include non-self-similar solutions by Pelletier & Pudritz (1992) and global disc–jet solutions by Ferreira (1997). The basic ideas underlying MHD jet launching were confirmed in time-dependent two-dimensional, axisymmetric numerical simulations (Uchida & Shibata 1985) which either included a disc (Kudoh et al. 1998; Zanni et al. 2007)

or prescribed it as boundary conditions (Ouyed & Pudritz 1997; Ustyugova et al. 1999; Anderson et al. 2005; Fendt 2006; Pudritz et al. 2006). Furthermore, the early ejection of bipolar outflows was also demonstrated in two-dimensional (Mellon & Li 2008) and three-dimensional MHD simulations of the collapse of pre-stellar dense cores (Hennebelle & Fromang 2008), which notably included the second collapse and the formation of jets from the protostar (Banerjee & Pudritz 2006; Machida et al. 2006b, 2008). In fact, far from being a passive tracer of star formation, these outflows play an active role which is still to be fully understood. Examples include the removal of angular momentum from the accreting flow (Bacciotti et al. 2002), determining the efficiency of star formation by dispersing the accreting envelope (Matzner & McKee 2000), and sustaining turbulence in their local environment (Nakamura & Li 2007).

In general, the modelling of collapsing cores and jet launching has been carried out under the simplifying assumption that the angle α between the rotation axis and the large-scale magnetic field is zero. Exceptions are the simulations of Machida et al. (2006a), Price & Bate (2007) and Hennebelle & Ciardi (2009) which however focused mostly on the core and disc dynamics. Here we present simulations of the collapse of pre-stellar dense cores with misaligned initial configurations ($\alpha = 0°$–$90°$), and show that angle α is fundamental in determining not only the properties of the outflow, but also the mass accretion on to the core. In particular we observe the gradual decrease in the mass ejection with increasing angle α, until its total suppression for nearly perpendicular configurations.

★E-mail: andrea.ciardi@obspm.fr

2 RESULTS

2.1 The numerical model

We follow numerically the gravitational collapse of dense pre-stellar cores, up to, and including the formation of the first (or adiabatic) core. The numerical simulations were performed with RAMSES (Teyssier 2002; Fromang et al. 2006), an adaptive mesh refinement code which uses a Godunov-type scheme and constrained transport to solve the ideal MHD equations. Throughout the simulations the Jeans length is resolved with at least 10 cells, and a HLLD solver is employed. The initial conditions consist of a one solar mass core whose density profile resembles the observed cores, and is given by $n(r) = n_c/[1 + (r/r_0)^2]$ where $r_0 \sim 1000$ au is the inner cloud radius. This isothermal cloud ($T \sim 10$ K) is placed inside a warm and diffuse medium in pressure equilibrium with the cloud edge, with a contrast of 10 between central, $n_c = 8 \times 10^6$ cm^{-3}, and edge densities. The cloud is initially in solid body rotation and threaded by a uniform magnetic field along the z-axis, whose intensity is proportional to the column density of the cloud. The rotation axis is in the xz plane and makes an angle α with respect to the magnetic field. For ease of presentation we define, in addition to the Cartesian coordinates (x, y, z), cylindrical coordinates (ϖ, ϕ, Z) with Z parallel to the initial rotation axis. All simulations are characterized by four parameters: the ratio of rotational over gravitational energy ($\simeq 0.03$), the ratio of thermal over gravitational energy ($\simeq 0.25$), the degree of magnetization μ and angle α. Only the effects of different μ, the mass-to-flux over critical mass-to-flux ratio and α are investigated in this work.

2.2 Outflow dynamics, precession and instabilities

The general outflow formation and dynamics are presented in Fig. 1. As the initially spherical, magnetized pre-stellar core undergoes gravitational collapse it flattens preferentially along the magnetic field lines, producing a dynamically collapsing, magnetized disc-like structure or *pseudo-disc*. Following the isothermal collapse phase, an adiabatic core with densities $\gtrsim 10^{10}$ cm^{-3} and a radius $\sim$10–20 au forms at the centre of the infalling envelope. The ensuing build-up of a centrifugally supported disc (or simply *disc*), with characteristic diameters $\sim$50–200 au, depends on the efficiency of magnetic torques to remove angular momentum from the pseudo-disc. In Hennebelle & Ciardi (2009) it was argued that the magnetic braking efficiency is proportional to $h^{-1/2}$, where the characteristic scaleheight h of the disc is in turn determined by the angle α between the initial magnetic field and rotation axis. Increasing their misalignment produces thicker pseudo-discs which are less efficiently braked by the magnetic field, and thus lead more easily to the formation of centrifugally supported discs. In general we find that outflows are launched for all angles $\alpha \lesssim 80°$ independently of the existence of a centrifugally supported disc. However, when $\alpha \sim 90°$ the ejection of matter is essentially suppressed, even when a disc is present. The remaining outward motions observed in the perpendicular configuration are particularly interesting because mass ejection does not produce either a magnetic cavity or a jet. In fact, mass is not launched from the core, but the *outflow* traces dense regions of the disc which are at large radii from the core ($\sim$200 au) and are being radially expelled by the highly twisted magnetic field. The outflowing gas propagates perpendicularly to the rotation axis (see Fig. 2) and in the plane of the disc, with radial ejection and azimuthal speeds, $v_\varpi \approx v_\phi$.

For $\alpha \lesssim 80°$ the formation of bipolar outflow begins as the magnetic field lines, connecting the outer regions of the cloud to its rapidly rotating inner regions, undergo strong shear which results in a significant azimuthal component (B_ϕ) of the magnetic field being generated close to the adiabatic core and disc (if present). The growing magnetic pressure gradient accelerates the plasma,
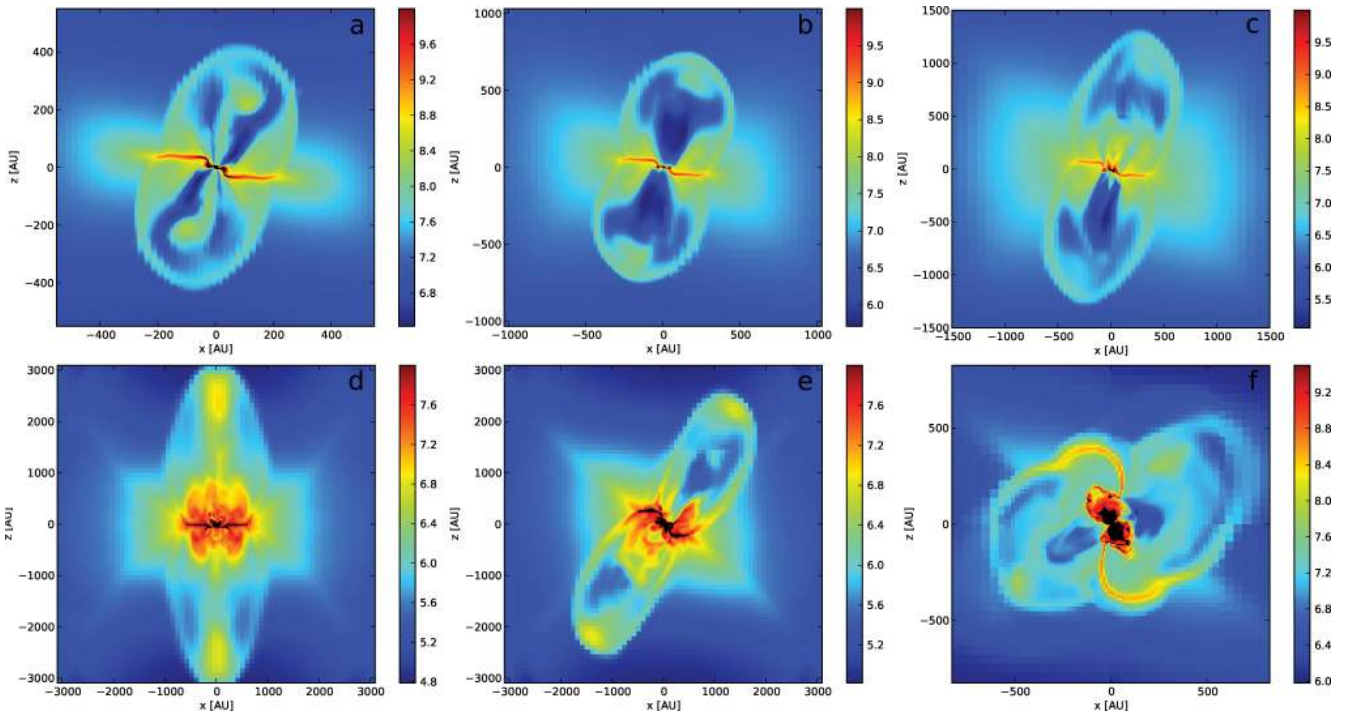

Figure 1. Slices in xz plane of the particle number density (cm^{-3} on a logarithmic scale) for the case $\mu = 5$. The first row shows for $\alpha = 20°$ the times (a) 20 300 yr, (b) 21 300 yr and (c) 22 200 yr. The second row shows at $\sim$27 000 yr the angles (d) $\alpha = 0°$, (e) $\alpha = 45°$ and (e) $\alpha = 70°$. Note the use of the different scales between images.

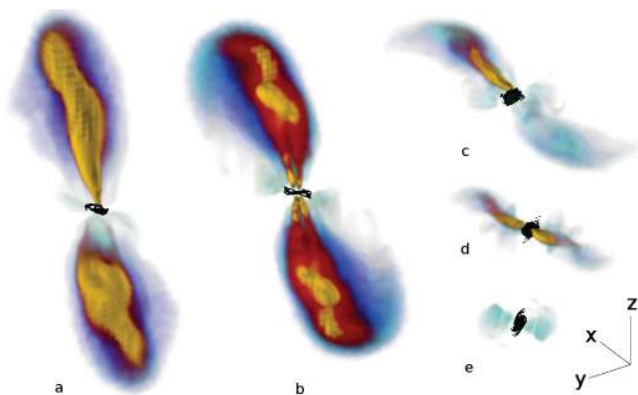**Figure 2.** Volume rendering of the outflows at ~23 000 yr, for $\mu = 5$ and α equal to (a) 20°, (b) 45°, (c) 70°, (d) 80° and (e) 90°. The colours show increasing speeds (from blue to yellow) in an onion-like structure. The black disc-like regions represent densities $>10^{10}$ cm^{-3}.

inflating bipolar magnetic cavities within the infalling envelope. At this stage the ratio of MHD Poynting to kinetic flux magnitudes, $\Gamma = v_\perp B^2/2\pi\rho v^3$, where $v_\perp$ is the component of the velocity perpendicular to the magnetic field, and the plasma-β, defined as the ratio of the thermal to magnetic pressure, are typically $\Gamma \sim 2$–10, and $\beta \sim 10^{-3}$ to 0.1 in the magnetic cavity. Such 'magnetic tower' structure is similar to that described by Lynden-Bell (2003) and re-produced in scaled laboratory experiments by Lebedev et al. (2005), and it is inflated by the magnetic field and is not mechanically driven by wide-angle winds. At the base of the cavity the continuous generation of B_ϕ provides the Poynting flux powering an outflow which originates from the core and a region extending several au around it. Depending on the ejection efficiency, which is measured by the ejection index $\xi = \mathrm{d}\ln\dot{M}_a/\mathrm{d}\ln\varpi$ with $\dot{M}_a$ the mass accretion rate through the disc, this outflow can be described as either magnetocentrifugally driven or magnetic pressure driven (Ferreira & Pelletier 1995). As we shall see in the next section, the ejection efficiency increases with time and both launching regimes are attained during the simulations. The collimation of this 'disc' wind into a jet depends on the radial distribution of currents (e.g. Pudritz et al. 2006), and therefore on the width of the magnetic cavity itself, which takes up the 'return current' and the magnetic stresses associated with the B_ϕ component of the magnetic field (e.g. Spruit 2009). However, the collimation of the magnetic tower depends in turn on the distribution of gas and magnetic field in the surrounding environment, which is swept up into a shock layer delineating the walls of the expanding magnetic tower. Therefore the medium through which the magnetic tower expands plays as well an important role on the overall collimation of the outflow. Fig. 2 shows the outflows' three-dimensional structure for different α, indicating that increasing the misalignment leads to the narrowing and better collimation of the whole magnetic tower. This is due to the increasing scaleheight of the pseudo-disc with α, which provides confinement over a longer length of the magnetic tower. In addition, because the outflow is inclined with respect to the pseudo-disc, it tends to propagate into it, leading again to a better lateral confinement, albeit asymmetric. The difference between the aligned and misaligned cases is also evident in Figs 1(d) and (e), where the base of the magnetic cavity, which is still embedded in the pseudo-disc, is indeed narrower for the misaligned case.

The angle α has also a strong impact on the homogeneity of the outflows. We find that for misaligned configurations the outflows undergo precession around the z-axis and that this effect is smaller

for larger values of α, settling within ~2000 yr to an approximately constant angle θ, which we remind is initially zero. Nutation is very small, and the initial angle between the magnetic field and rotation axis, α, remains approximately constant. Typical values of (α, θ), for $\mu = 5$, are (20°, 60°), (45°, 25°), (70°, 20°) and (80°, 10°). In addition, while the magnetic tower is initially launched perpendicular to the pseudo-disc, thus approximately parallel to the magnetic field, the outflow is ejected parallel to the rotation axis of the precessing core/disc, resulting in asymmetric cavities as shown in Figs 1 and 2. At later times the spatial variability observed in the outflows is mainly the consequence of growing non-axisymmetric current-driven modes and episodic ejections. The unsteady behaviour appears to be related to the increasing mass ejection efficiency and build-up of B_ϕ in the core/disc (Anderson et al. 2005). The precession present in the misaligned models further helps to seed large kink-like perturbations in the jet body, thus promoting the growth of the instability, which is otherwise artificially suppressed in the aligned case. The presence of a kink-like instability is indeed expected in jets confined by a helical magnetic field, and in detailed three-dimensional simulations it was also seen to lead to considerable distortions of the jet body and its fragmentation (Moll et al. 2008). In our simulations we find that the outflows are above the Kruskal–Shafranov stability threshold, with typical values of the magnetic pitch evaluated along single field lines, $\varpi |B_Z|/|B_\phi| \lesssim 30$ au (e.g. Appl et al. 2000). Precession and instabilities therefore lead to the fragmentation of the outflow into clumps, which, together with the generation of episodic ejection, produce a series of nested cavities and internal shocks, such as those visible in Figs 1(e) and (f), where faster ejections plough through previously launched material. Scaled laboratory astrophysics experiments of compressible, super-magnetosonic MHD flows have also shown that although jets may be episodic and unstable, multiple ejections of magnetic cavities and jets can produce clumpy flows which remain well collimated (Ciardi et al. 2009).

2.3 Outflow suppression and mass accretion

We find that the general trend of mass ejection–accretion during the collapse of a pre-stellar core is a decrease in the mass ejection efficiency for increasing α, which leads to a corresponding increase in the total mass, $M_{\mathrm{core}}(t)$, accreted on to the central core. Fig. 3 shows the total mass in the core and outflow ($M_{\mathrm{out}} + M_{\mathrm{core}}$) as a function of time. The outflow is defined as the plasma with $v \cdot \hat{R} > 0.1$ km s^{-1}, where $\hat{R}$ is the unit spherical radius; the core is defined as the plasma with a particle number density $n > 10^9$ cm^{-3} and $v \cdot \hat{R} \le 0.1$ km s^{-1}. From mass conservation the sum $M_{\mathrm{out}} + M_{\mathrm{core}}$ is the total *infall mass*, M_{inf}, which at early times is seen to be approximately constant, and largely independent of both angle α and magnetization μ. Its value is consistent with that
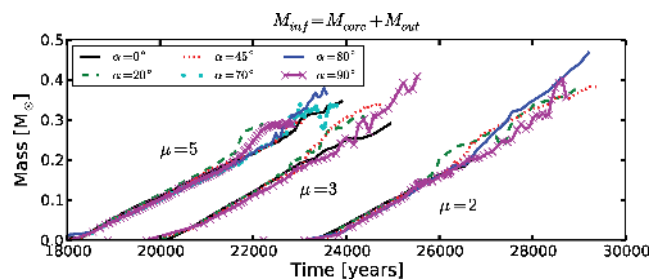

Figure 3. Total mass $M_{\mathrm{core}} + M_{\mathrm{out}}$ for different magnetizations μ and angles α.

given by Hunter (1977), who considered similarity solutions of the collapse of an unstable isothermal sphere. The relation between the accreted–ejected mass, and the misalignment of rotation axis and magnetic field, can be understood by considering the total mass outflow rate, $\int d\dot{M}_{out} = \int \rho \boldsymbol{v} \cdot d\boldsymbol{S}$. For steady-state axisymmetric flows it may be written as $\int d\dot{M}_{out} = \int \kappa d\Phi = \int \kappa \boldsymbol{B}_p \cdot d\boldsymbol{S}$, where $\kappa = 4\pi\rho v_p / B_p$ is the mass load per unit time, per unit poloidal magnetic flux, and may also be written in terms of the density, ρ_A, at the Alfvén surface as $\kappa = \sqrt{\rho_A}$ (Pelletier & Pudritz 1992). We make the simplifying assumptions that κ and $\boldsymbol{B}_p \cdot \hat{\boldsymbol{S}} \sim B_z \cos\alpha$ are constant over the surface (S) of the core, so that the integrated mass outflow rate can be approximated by $\dot{M}_{out} \sim \kappa\Phi \sim \kappa B_z \cos\alpha\, S$. We now proceed to establish a scaling relation between the mass ejection rate, $\dot{M}_{out}$, and the mass in the core, M_{core}. We assume that the core, of characteristic radius R, is in hydrostatic equilibrium, $GM_{core}/R \propto PR^{-3}$, and threaded by a constant magnetic flux, $\phi \propto BR^2 \sim$ const. The pressure P and density ρ scale as $P \propto \rho^\gamma$ and $\rho \propto M_{core}R^{-3}$, respectively, and combining these expressions one finds $R \propto M_{core}^{(2-\gamma)/(4-3\gamma)}$, $\rho \propto M_{core}^{-2/(4-3\gamma)}$, $S \propto R^2 \propto M_{core}^{(4-2\gamma)/(4-3\gamma)}$, $B \propto M_{core}^{(2\gamma-4)/(4-3\gamma)}$ and $\kappa \propto \rho^{1/2} \propto M_{core}^{-1/(4-3\gamma)}$. The relation obtained for κ is equivalent to assuming that the launching speed at the core/disc, v, scales with the Alfvén speed, $B/\sqrt{4\pi\rho}$. From these relations, the mass outflow rate is found to scale as a power of the total mass present in the core, $\dot{M}_{out} \propto M_{core}^{-1/(4-3\gamma)}$, which for the adiabatic core ($\gamma = 5/3$) gives the linear relation

$$\dot{M}_{out} = \eta M_{core}(t). \tag{1}$$

The characteristic accretion–ejection time-scale, $\eta^{-1} = \tau_{ae} = \tau_0/\cos\alpha =$ const, depends only on angle α, where τ_0 is the value corresponding to the aligned case ($\alpha = 0°$) which is to be determined numerically. We can then combine equation (1) with the expression for the mass conservation, $\dot{M}_{inf} = \dot{M}_{core} + \dot{M}_{out}$, to solve for the mass accreted on to the core as a function of time:

$$M_{core}(t) = \tau_{ae}\dot{M}_{inf}(1 - e^{-t/\tau_{ae}}) \tag{2}$$

and for the total ejected mass:

$$M_{out}(t) = \tau_{ae}\dot{M}_{inf}(e^{-t/\tau_{ae}} - 1) + \dot{M}_{inf}\,t. \tag{3}$$

Fig. 4 shows the simulated infall, core and outflow masses for the case $\mu = 5$ and for different angles α, together with the analytical solutions, which are strictly valid in the regime where $\dot{M}_{inf} =$ const. The results show that at early times the mass in the core is small, the ejection rate is negligible and mass accretion dominates, $\dot{M}_{core} = \dot{M}_{inf}e^{-t/\tau_{ae}}$, over the mass ejection, which is given by $\dot{M}_{out} = \dot{M}_{inf}(1 - e^{-t/\tau_{ae}})$. The model predicts that within a time-scale $\tau_{ae} = \tau_0/\cos\alpha$ the core accretes ~ 63 per cent of its 'final' mass, which is asymptotically given by $M_C = \tau_{ae}\dot{M}_{inf}$ (for $\alpha \neq 90°$). Since τ_{ae} increases with angle α, the initial misalignment between the rotation axis and magnetic field plays a fundamental role in determining the masses of the cores. The limiting case is for a perpendicular magnetic field and rotation axis ($\alpha = 90°$), where no mass is ejected from the core, and its growth is at the (time-dependent) mass infall rate $\dot{M}_{inf}$. This case is qualitatively similar to hydrodynamical simulations where no outflows are produced. The high ejection efficiency predicted by the model at late times is however not energetically favourable. A fraction of the outflow fails to become trans-Alfvénic and eventually falls back on to the core/disc before being reprocessed. By combining the mass conservation equation with the definition of ξ, the time when the limiting ejection efficiency occurs ($\xi = 1$ for jets with negligible enthalpy) can be estimated from the relation $(\varpi_i/\varpi_e)^\xi = 1 - \dot{M}_{out}/\dot{M}_{inf}$ (Ferreira & Pelletier 1995), where $\varpi_i \sim 10$–20 au corresponds to
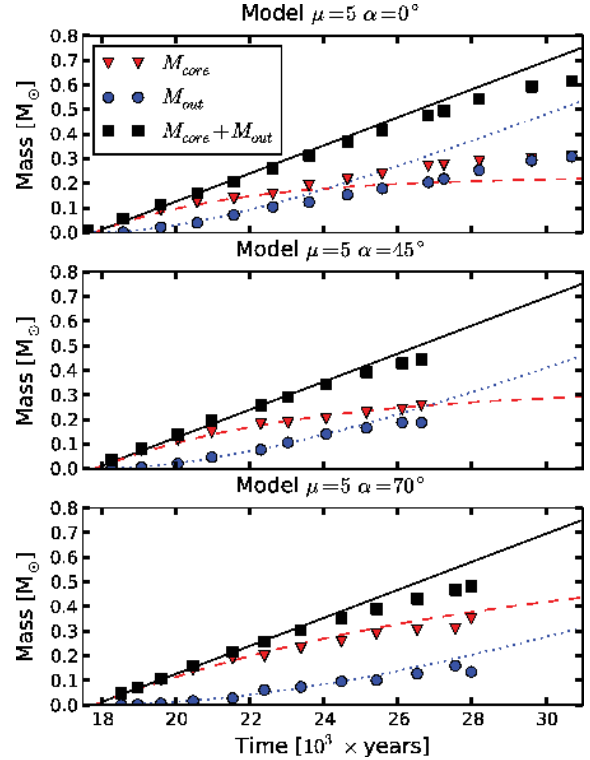

Figure 4. Total mass in the core (dashed) and outflow (dotted) for the analytical model, calculated using the nominal value of the mass infall (solid line) rate taken from Hunter (1977), $\dot{M}_{inf} = 36c_s^3/G = 5.7 \times 10^{-5}\,M_\odot\,yr^{-1}$, and the accretion–ejection time-scale from the aligned case $\tau_0 = 4000$ yr. The symbols are data from the simulations.

the core radius and $\varpi_e \sim 50$–100 au corresponds to the outer radius of the accretion–ejection structure, where $\dot{M}_{inf}$ is evaluated. For our model, $\xi = t\,[\ln(\varpi_e/\varpi_i)\,\tau_{ae}]^{-1}$, and the time when we expect the analytical model to overestimate the ejected mass is when $\xi \sim 1$, which gives $t \sim (1 - 3)\tau_{ae}$. This occurs for the aligned case, which is the only model to have reached a high ejection efficiency, at $\sim 24\,000$ yr, and it is consistent with our estimates. From inspection of the velocity fields, it is also evident that part of the outflow is failing to be ejected and falls back as a lower density envelope ($n < 10^{10}$ cm^{-3}). This material is visible in the first panel of Fig. 4 as an increase in the core's mass with respect to the analytical solution.

The results show that with increasing misalignment, the general trend of mass ejection–accretion in collapsing pre-stellar cores is to produce higher mass adiabatic cores, with lower ejection efficiency ($\xi \propto \cos\alpha$). Another consequence is an increase in the bulk speed of the outflow, defined as $v_b = \int dV\rho|\boldsymbol{v}|/\int dV\rho$, with the integral taken over the volume of plasma where $\boldsymbol{v} \cdot \hat{\boldsymbol{R}} > 0.1$ km s^{-1}. Typical values at $\sim 26\,000$ yr are $v_b(\alpha = 0°) = 1.17$ km s^{-1}, $v_b(\alpha = 45°) = 1.43$ km s^{-1} and $v_b(\alpha = 70°) = 1.76$ km s^{-1}, with their ratios consistent with the angle dependence obtained in the analytical model. This increase in the bulk speed can be understood by considering the expression for the asymptotic jet velocity $u_\infty = \Omega\varpi\sqrt{(2\lambda - 3)}$ (Blandford & Payne 1982). For misaligned collapsing pre-stellar cores, two factors contribute to the higher bulk speeds. The first is related to the magnetic lever arm λ, which depends on the ejection index through the relation $\lambda \simeq 1 + (1/2\xi)$ (Ferreira 1997); the second is related to the rotational speed, which scales with the core's mass, $\Omega\varpi \sim \sqrt{GM_{core}/R}$. Thus at a given time, the more massive cores obtained for larger α, and the corresponding lower ejection

efficiency, combine to eject faster outflows. Finally we note that following the initial launching of the magnetic tower, as ξ increases in time the outflow from the core/disc is first launched with a relatively large magnetic lever arm, and may be thought of as magnetocentrifugally driven; at later times, with increasing ξ, the lever arm is small and the outflow may be better described as magnetic pressure driven.

3 SUMMARY

We have presented three-dimensional simulations of the collapse of pre-stellar dense cores with misaligned magnetic field and rotation axis. Imposing non-axisymmetric initial conditions has several important effects on the formation of the first adiabatic core and its associated outflows. In particular an increasing angle α produces a decrease in the ejection efficiency, leading to the suppression of outflows for $\alpha \sim 90°$, and a corresponding increase of the mass of the cores. In addition we find that the misalignment of magnetic field and rotation axis produces precessing jets which are more susceptible to current-driven instabilities, leading to the formation of heterogeneous clumpy flows. These effects are visible even for small α, and indicate that aligned configurations may be too idealized and unable to capture the whole dynamics. To interpret the numerical results, we have developed a model which seems to capture the essential features observed in the simulations. In particular we find that for low ejection efficiencies the mass ejection rate, $\dot{M}_{\text{out}}$, is proportional to the mass of the core, and that the reduction of $\dot{M}_{\text{out}}$ with α is consistent with a decrease of the magnetic flux threading the (approximately constant) core's surface.

REFERENCES

Anderson J. M. et al., 2005, ApJ, 630, 945
Appl S. et al., 2000, A&A, 355, 818
Bacciotti F. et al., 2002, ApJ, 576, 222
Banerjee R., Pudritz R. E., 2006, ApJ, 641, 949
Blandford R. D., Payne D. G., 1982, MNRAS, 199, 883
Cabrit S., Bertout C., 1992, A&A, 261, 274
Ciardi A. et al., 2009, ApJ, 691, L147
Fendt C., 2006, ApJ, 651, 272
Ferreira J., 1997, A&A, 319, 340
Ferreira J., Pelletier G., 1995, A&A, 295, 807
Fromang S. et al., 2006, A&A, 457, 371
Hartigan P. et al., 1995, ApJ, 452, 736
Hennebelle P., Ciardi A., 2009, A&A, 506, L29
Hennebelle P., Fromang S., 2008, A&A, 477, 9
Hunter C., 1977, ApJ, 218, 834
Kudoh T. et al., 1998, ApJ, 508, 186
Lebedev S. V. et al., 2005, MNRAS, 361, 97
Lynden-Bell D., 2003, MNRAS, 341, 1360
Machida M. N. et al., 2006a, ApJ, 645, 1227
Machida M. N. et al., 2006b, ApJ, 647, L1
Machida M. N. et al., 2008, ApJ, 676, 1088
Matzner C. D., McKee C. F., 2000, ApJ, 545, 364
Mellon R. R., Li Z., 2008, ApJ, 681, 1356
Moll R. et al., 2008, A&A, 492, 621
Nakamura F., Li Z., 2007, ApJ, 662, 395
Ouyed R., Pudritz R. E., 1997, ApJ, 482, 712
Pelletier G., Pudritz R. E., 1992, ApJ, 394, 117
Price D. J., Bate M. R., 2007, MNRAS, 377, 77
Pudritz R. E., Norman C. A., 1983, ApJ, 274, 677
Pudritz R. E. et al., 2006, MNRAS, 365, 1131
Spruit H. C., 2009, in Belloni T., ed., Lecture Notes in Physics, Vol. 794, Theory of Magnetically Powered Jets. Springer-Verlag, Berlin, p. 233
Teyssier R., 2002, A&A, 385, 337
Uchida Y., Shibata K., 1985, PASJ, 37, 515
Ustyugova G. V. et al., 1999, ApJ, 516, 221
Wu Y. et al., 2004, A&A, 426, 503
Zanni C. et al., 2007, A&A, 469, 811

This paper has been typeset from a TEX/LATEX file prepared by the author.