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Magnetic flux transport by turbulent reconnection in astrophysical flows

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Abstract
The role of magnetohydrodynamics (MHD) turbulence in astrophysical environments is still highly debated. An important question that permeates this debate is the transport of magnetic flux. This is particularly important, for instance, in the context of star formation. When clouds collapse gravitationally to form stars, there must be some magnetic flux transport. Otherwise, the newborn stars would have magnetic fields several orders of magnitude larger than the observed ones. Also, the magnetic flux that is dragged in the late stages of the formation of a star can remove all the rotational support from the accretion disc that grows around the protostar. The efficiency of the mechanism that is often invoked to allow transport of magnetic fields at different stages of star formation, namely ambipolar diffusion, has recently been put in check. We discuss here an alternative mechanism for magnetic flux transport which is based on turbulent fast magnetic reconnection. We review recent results from three-dimensional MHD numerical simulations that indicate that this mechanism is very efficient in decoupling and transporting magnetic flux from the inner denser regions to the outskirts of collapsing clouds at different stages of star formation. We discuss this mechanism also in the context of dynamo processes and speculate that it can play a role both in solar dynamo and in accretion disc dynamo processes.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Astrophysical flows are known to be turbulent and magnetized. The specific role played by magnetohydrodynamics (MHD) turbulence in different astrophysical flows is still highly debated. One question that frequently permeates these debates is the diffusion of the magnetic field. The conductivity is high enough to make the Ohmic diffusion negligible on the scales typically involved in most of the astrophysical fluids. This means that the ideal MHD (or 'frozen-in') approximation is appropriate for most of these environments. However, without considering diffusive mechanisms that can violate the magnetic flux freezing, one faces several problems. For instance, simple estimates show that if all the magnetic flux were brought together with the material that collapsed to form a star in a molecular cloud, then the magnetic fields in proto-stars should be several orders of magnitude larger than the observed ones. This is often referred to as the 'magnetic flux problem' in star formation. Magnetic flux transport is also known to be a necessary ingredient in dynamo processes.

We discuss here a *new* mechanism for magnetic flux transport that is based on turbulent fast magnetic reconnection. In section 2, we summarize the theoretical grounds of this transport mechanism. In section 3, we review recent results on this mechanism applied to star formation. Then, in section 4, we speculate that this mechanism might also play a role in dynamo processes, both in accretion discs

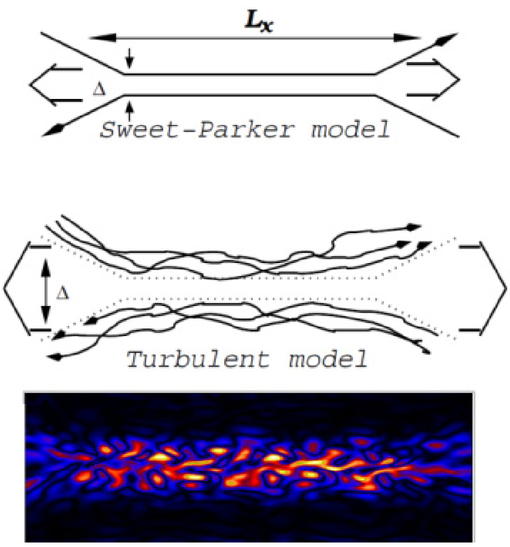

Figure 1. Magnetic reconnection models. Top panel: the S–P model of reconnection. The outflow is limited by a thin slot Δ determined by Ohmic diffusivity. The other scale is an astrophysical scale $L_x \gg \Delta$. Middle panel: fast reconnection model in the presence of turbulence according to Lazarian and Vishiniac (1999) (extracted from Lazarian *et al* 2004). Bottom panel: 3D MHD numerical simulation of fast turbulent reconnection (from Kowal *et al* 2009).

and in the solar dynamo, and in section 5 we present our conclusions.

2. Turbulent magnetic reconnection: theoretical grounds

The magnetic diffusion mechanism that we will address is a process deeply rooted in the microphysics behavior of the magnetic fields in highly conductive flows. Textbooks characterize these flows by the Lundquist number $S = L_X V_A/\eta$, where η is the Ohmic diffusivity, L_X is a typical scale of the system and V_A is the Alfvén velocity, For astrophysical systems, L_X is in general very large and therefore $S \gg 1$, which makes magnetic diffusion negligible. However, one may ask: does the magnetic field remain absolutely frozen-in within highly ionized astrophysical fluids? The answer to this question depends on magnetic reconnection.

Magnetic reconnection occurs when two magnetic fluxes of opposite polarity encounter each other. In the presence of finite magnetic resistivity, the converging magnetic lines annihilate at the discontinuity surface and a current sheet forms there. In the standard Sweet–Parker (S–P) model the velocity at which the two converging fluxes reconnect is given by $v_{rec} \approx v_A S^{-1/2}$, where in this case L_X gives the length of the reconnection layer (see figure 1). Because S is large for Ohmic resistivities (e.g. for the interstellar medium (ISM), $S \sim 10^{16}$), the S–P reconnection is very *slow*. In other words, since all the matter moving with the speed V_{rec} over the scale L_X must be ejected with the Alfvén velocity through a thin slot (Δ), the disparity between the typical scales L_X and the outflow thickness Δ, which in turn is determined by microphysics, i.e. the resistivity, makes the S–P reconnection rate negligibly small.

However, observations indicate that magnetic reconnection must be *fast* in some circumstances (e.g. solar flares). Lazarian and Vishniac (1999) proposed a model for fast reconnection that is independent of the resistivity. The model appeals to the ubiquitous astrophysical turbulence as a universal trigger of fast reconnection. When turbulence is present within the current sheet, the outflow region Δ gets determined by magnetic field wandering and therefore becomes independent of the resistivity (see figure 1, middle panel). It allows the formation of a thick volume filled with several reconnected small magnetic fluctuations that make the reconnection fast. This model has been successfully tested numerically by Kowal *et al* (2009) (see figure 1, bottom panel). This challenges the well-rooted concept of magnetic field frozenness for the case of turbulent fluids and provides an interesting way of removing magnetic flux out of astrophysical flows, e.g. star formation regions (Lazarian 2005, Santos-Lima *et al* 2010, 2012, Gouveia Dal Pino *et al* 2011, Lazarian 2011), accretion discs or the solar dynamo.

It must be remarked that numerical effects are always a concern when dealing with numerical simulations involving reconnection and magnetic field diffusion. However, the high-resolution numerical tests of magnetic reconnection performed by Kowal *et al* (2009) showed that in the presence of turbulence the local nonlinear enhancements of resistivity are not important. This confirms that the turbulent reconnection diffusion that we observe in our simulations (see below and also Santos-Lima *et al* 2010, 2012) is a real effect and not a numerical artefact. Analytical studies summarized by Eyink *et al* (2011) also support the notion that magnetic fields are generically not frozen-in when conductive fluids are turbulent. From these studies, we can conclude that the concept of reconnection diffusion looks very natural and ubiquitous.

In the following sections, we will review recent numerical studies of the application of this diffusion mechanism to star and protostellar disc formation, and also discuss its application to dynamo processes in accretion discs and the sun.

3. The magnetic flux transport problem in star formation

To address the magnetic flux transport problem in the framework of star formation, researchers usually invoke the ambipolar diffusion (AD) mechanism (e.g. Mestel and Spitzer 1956, Mouschovias 1979, Li *et al* 2008). In principle, AD allows magnetic flux to be redistributed during the collapse in low-ionization regions as a result of differential motion between the ionized and the neutral gas. Recent advances in the theory, however, have been putting in check the efficiency of this diffusion process in real systems. Shu *et al* (2006), for instance, explored the accretion phase in low-mass star formation and concluded that there should exist an effective diffusivity more than three orders of magnitude larger than the classic Ohmic diffusivity in order to allow efficient magnetic flux transport to occur. They found that AD could work in principle, but only under special circumstances, considering specific dust grain sizes. In other words, there is still no consensus if AD alone is high enough to solve the magnetic flux transport problem in collapsing flows. (See also alternative views in Shu *et al* (2011).)

3.1. Magnetic flux transport by turbulent reconnection in the early stages of star formation

We have recently explored the role of turbulent reconnection in the transport of magnetic field flux from the central, denser regions of a molecular cloud to outside, in order to follow the cloud gravitational collapse (Santos-Lima *et al* 2010).

Molecular clouds are known to be turbulent and magnetized. They have a variety of structures on all scales and turbulence rules their structuring and fragmentation and probably plays an important role during most of the different stages of star formation (Mac Low and Klessen 2004, Vazquez-Semadeni *et al* 2005, McKee and Ostriker 2007). A dominant source of turbulence injection is possibly supernova shocks (see Melioli *et al* 2006, Leão *et al* 2009 and references therein).

We performed 3D MHD simulations of ISM clouds considering a central gravitational field provided by embedded stars and introducing forced turbulence. We used a shock-capturing Godunov-type code with a Harten-Lax–van Leer–Einfeldt (HHL) solver to integrate the fluxes and a second-order Runge–Kutta to integrate in time (Kowal *et al* 2007, Santos-Lima *et al* 2010, 2012). We considered an isotropic, non-helical, solenoidal, delta correlated in time turbulent forcing. This forcing acts in a thin shell around the wave number $k = 2.5(2\pi/L)$, so that the scale of turbulence injection $l_{\rm inj}$ is about 2.5 times smaller than the computational domain size L. In all the examples below, transonic, sub-Alfvénic turbulence with an rms velocity around unity was injected in the system, which was then allowed to evolve.

When compared with MHD simulations without turbulence, those with turbulence revealed a decrease of the magnetic flux to mass ratio as the density at the center of the gravitational potential increases. The magnetic flux is transported to the outskirts of the cloud by turbulent reconnection. We observed this effect both when starting with initial equilibrium distributions of gas and magnetic field and when following the evolution of dynamically unstable configurations. Thus, the process of turbulent magnetic field removal is applicable both to quasi-static subcritical molecular clouds and to collapsing supercritical ones. The increase of the gravitational potential, as well as the decrease of magnetization of the gas, showed an increase of the decoupling between the mass and the magnetic flux in the saturated final state of the simulations, supporting the notion that turbulent diffusivity relaxes the magnetic field+gas system in the gravitational field to its minimal energy state (Santos-Lima *et al* 2010).

More recently, we have been exploring more realistic systems including the effects of the self-gravity of the gas in the clouds. The stability of a cloud supported by magnetic pressure may be quantified by the mass to magnetic flux ratio, $M/\Phi \sim N/B$, where M is the cloud mass, Φ is the magnetic flux, B is the magnetic field and N is the column density. This ratio defines to what extent a static magnetic field can support a cloud against gravitational collapse (e.g. Nakano and Nakamura 1978, Crutcher 2008). When this ratio exceeds a critical value above which gravity overpasses the magnetic and turbulent forces, the cloud or cloud core is able to collapse.

We considered an initially spherical cloud clump with a central gravitational potential that mimics a small group of embedded stars. It was put in the middle of a homogeneous magnetized background, then a violent initial contraction of the gas takes place for a short period of time (of the order of the free-fall time), after which due to the presence of the magnetic field and the turbulence injected, the system evolves more smoothly. The system is simulated inside a cubic domain with periodic boundaries. The existence of several clumps in the interior of a typical giant molecular cloud allows us to use periodic boundaries for our setup. For the sake of simplicity, we employ an isothermal equation of state, with a single temperature for the whole system (for more details see Leão *et al* (2012)).

Figure 2 shows examples of this sort of simulation considering the conditions appropriate for molecular clouds. The left panels show logarithmic density maps of the central slices of the simulated models after 100 Myr. The middle column panels compare the time evolution of the magnetic field to density ratio, normalized by the average value of this ratio, inside a central sphere with radius $r = 0.3$ pc which represents the core of the cloud, both for the models with turbulence (red dashed line) and for the ones without turbulence (black solid line). After an initial rapid decrease caused by the relaxation of the system, the magnetic field to density ratio remains nearly constant in the laminar cases (i.e. without turbulence)[4], while in the cases with turbulence there is a clear decrease of it. This result indicates that there was magnetic flux transport from the denser, more massive central regions to the less dense regions outside the cloud cores. This effect is particularly more pronounced in the bottom panel model which has a larger initial gas density than the other models and is therefore under the influence of a larger self-gravity. Comparing the top and middle models which have the same initial gas density, the one with larger stellar potential (top model) shows a larger decoupling between the magnetic flux and the mass density. All the models above are initially subcritical clouds; that is, they have an initial mass to flux ratio that is smaller than the critical value necessary for the cloud to collapse gravitationally. We have also computed the time evolution of this ratio for the three turbulent models and found that the one with larger initial density (bottom model) is the only one that becomes supercritical and therefore able to continue the collapse to form stars, whereas the one with a larger stellar gravitational potential (top model) has only approached the critical value.

The results above suggest that the inflow associated with self-gravity has an important effect as it facilitates the gas infall and therefore the decoupling of the magnetic field that is more easily removed to the outer regions of the collapsing cloud core. The results also suggest that an

[4] We note that the oscillations observed in these plots (which are slightly stronger in the laminar models) are acoustic oscillations of the cloud due to the fact that the virialization time of these systems is larger than the simulated period.

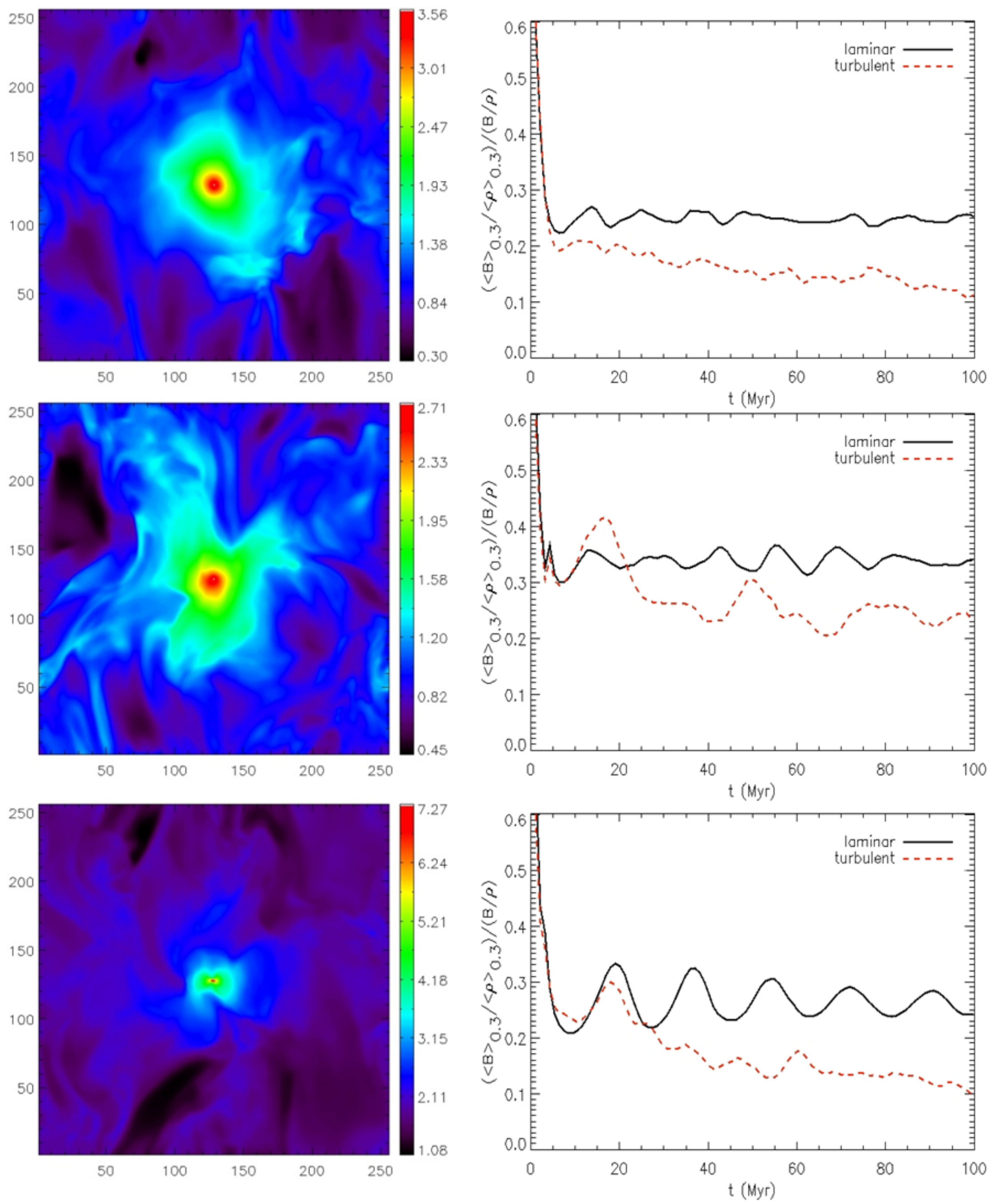

Figure 2. Magnetic flux transport in a collapsing interstellar cloud. The left panels show density maps of the central slices of the cloud evolution for turbulent models at $t = 100$ Myr. The right panels show the temporal evolution of the magnetic field to density ratio in the cloud core region (within a radius of 0.3 pc) normalized by the average value in the system, both for turbulent (red dashed lines) and laminar (black continuous lines) models. The top model has a stellar potential of $M_{\rm pot} = 61.1$ solar mass. The middle and bottom models have $M_{\rm pot} = 40.7$ solar mass. The top and middle models have initial densities $n = 10\,{\rm cm}^{-3}$, and the bottom model has $n = 90\,{\rm cm}^{-3}$. All models have a thermal to magnetic pressure ratio $\beta = 3.0$ (see also Leão *et al* 2012).

increase in self-gravity is more important than an increase in the stellar gravitational potential in causing magnetic flux transport by turbulent reconnection. However, we found that turbulence is able to remove magnetic flux from collapsing, self-gravitating clouds and make them supercritical within a narrow range of densities (for clouds with ∼50 solar mass, $10 < n < 100\,{\rm cm}^{-3}$; see Leão *et al* (2012) for more details). At the same time, this result is compatible with the known low efficiency of star formation in the Galaxy.

3.2. Magnetic flux transport by turbulent reconnection in the late stages of star formation

The late stages of star formation are not fully understood either (see Krasnopolsky *et al* 2011 for a recent review). Previous studies have shown that the observed embedded magnetic field in molecular cloud cores (Troland and Crutcher 2008) is high enough to inhibit the formation of rationally supported discs during the main protostellar accretion phase of low-mass stars if ideal MHD applies.

This has been known as the magnetic *braking* problem (see, e.g., Galli *et al* 2006, Price and Bate 2007, Hennebelle and Fromang 2008, Mellon and Li 2008). For realistic levels of core magnetization and ionization, recent work has shown that again AD does not seem to be sufficient to weaken the magnetic braking in order to allow rotationally supported discs to form. In some cases, the magnetic braking has been found to be even enhanced by AD (Basu and Mouschovias 1995, Krasnopolsky and Königl 2002, Hosking and Whitworth 2004, Duffin and Pudritz 2009, Mellon and Li 2009, Li *et al* 2011). These findings motivated Krasnopolsky *et al* (2010) (see also Li *et al* 2011) to examine whether Ohmic dissipation could be effective in weakening the magnetic braking. They claimed that in order to enable the formation of rotationally supported discs during the protostellar mass accretion phase, an enhanced resistivity a few orders of magnitude higher than the classic Ohmic resistivity would be required (Krasnopolsky *et al* 2010). On the other hand, Machida *et al* (2010) (see also Inutsuka *et al* 2010, Machida *et al* 2011) performed core collapse three-dimensional (3D) simulations and found that with just the Ohmic resistivity, a massive, rotationally supported disc can form but the process is slow and one has to wait for over 10^5 years for this to occur.

While this question of the effectiveness of Ohmic diffusion in disc formation still requires further testing, considering the success of the turbulent magnetic reconnection discussed above for removing magnetic flux in the early stages of star formation, we have also investigated this mechanism during the late phases of the protostellar disc formation. We showed by means of 3D MHD simulations that the diffusivity arising from turbulent magnetic reconnection is able to transport magnetic flux to the outskirts of the (cloud core) disc progenitor at time scales compatible with the collapse. In just a few 10^4 years, a rotationally supported disc forms around the protostar of dimensions $\sim$100 au, with a nearly Keplerian profile as required by observations. Since MHD turbulence is expected to be present in protostellar discs, this is a natural mechanism for removing magnetic flux excess and allowing the formation of these discs (de Gouveia Dal Pino *et al* 2011, Santos-Lima *et al* 2012).

4. The role of turbulent reconnection magnetic flux transport in dynamo mechanisms: future prospects

In this section, we discuss the potential role of the turbulent reconnection mechanism in dynamo processes, both in accretion discs and in the sun, on a preliminary basis. In future work, we will explore quantitatively the predictions made herein.

4.1. In the framework of the solar dynamo

It is well known that turbulent motions in the convective layer are a key ingredient in the solar dynamo. Therefore, besides the inductive role that helical turbulence might play in amplifying the solar magnetic field, it is natural to expect that the mechanism of turbulent reconnection transport of magnetic flux discussed above can also play an important role in the solar dynamo cycle.

For many years, it was thought that the sunspots migration pattern observed at the solar surface corresponds to the propagation of a dynamo wave. This requires negative kinetic helicity in the Northern Hemisphere (as observed) and a radial differential rotation profile increasing towards the center of the Sun. However, helioseismology found that in the bulk of the convection zone the radial profile of the differential rotation is almost flat, but rapidly decreases in the inner interface (named tachocline) between the convective and the radiative layers. The migration pattern of a dynamo wave with such characteristics fails to reproduce the observations. Today, it is known that near the solar surface there is a thin layer where there is a negative velocity shear (i.e. the velocity increases inwards). This layer alone could give a proper surface shape to a dynamo wave generated by turbulence in the entire convection zone (Brandenburg 2005). Another class of dynamos assumes that the magnetic field observed in the sunspots is formed at the tachocline. Since the shear there at lower latitudes is negative, these models rely on the meridional circulation (a large-scale flow occurring in the r and θ directions) to explain the observed sunspots migration. Nevertheless, observations indicate that this flow is rather incoherent, changing from one solar cycle to the next and even during the same cycle. Global numerical simulations have not succeeded either in obtaining a well-defined meridional circulation flow. Guerrero and de Gouveia Dal Pino (2008) proposed that turbulent pumping could be the mechanism responsible for the transport of the magnetic flux in the observed directions. Turbulent pumping is an advective transport coefficient of the electromotive force in the mean-field MHD model. The role that turbulent magnetic reconnection may play in this process remains to be understood.

In the upper layers near the solar surface, it might be examined whether turbulent reconnection combined with latitudinal (and radial) shear motions can help in the deposition of magnetic flux near the equator, as observed. Its contribution to the deeper convective layers where turbulent convection is mostly anisotropic must also be tested, particularly in order to understand its behavior towards the pumping and storage of magnetic field in the tachocline.

The suppression of turbulence and hence of magnetic diffusivity (as well as other turbulent processes) with an increase of magnetic field (the so-called η-quenching) is another interesting issue to be explored in depth (e.g. Rüdiger *et al* 1994, Tobias 1996, Guerrero *et al* 2009).

4.2. In the framework of accretion discs

The application of the reconnection diffusion concept to protostellar disc formation (section 3.2) and, in a more general framework, to accretion discs is natural, as the discs are expected to be turbulent. In fact, the well-investigated magneto-rotational instability (MRI; Chandrasekhar 1960, Balbus and Hawley 1991) is effective not only in the transport of angular momentum in the disc, but also in triggering turbulence. This, in turn, may help in the amplification of the magnetic fields in the disc in a dynamo process (Livio *et al* 2003). However, once a large-scale magnetic field is established it may be strong enough to inhibit the MRI, which then stops operating.

On the other hand, as discussed before in the process of disc formation, if turbulence is still present, this large-scale magnetic field can be efficiently removed from the inner, denser regions of the accretion disc to the outer regions by the action of turbulent reconnection transport and then the MRI instability can be resumed, initiating a new phase of the dynamo process. This interplay between the MRI and the turbulent reconnection transport of magnetic flux in accretion discs in a dynamo process by means of fully 3D MHD simulations will be explored elsewhere. Nonetheless, it should be noted that previous studies of the injection of turbulence in accretion discs have shown that turbulence may be ineffective in diffusing magnetic flux outwards (Rothstein and Lovelace 2008).

5. Summary and conclusions

We have reviewed recent results on the transport of magnetic flux in astrophysical conducting flows in the presence of turbulence. We have discussed a new transport mechanism that is based on the fact that, in the presence of turbulence, magnetic reconnection becomes fast and therefore very effective in diffusing magnetic flux (Lazarian and Vishniac 1999, Kowal *et al* 2009).

We investigated this turbulent reconnection mechanism in the context of star formation by means of high-resolution 3D MHD numerical simulations, from the early stages of molecular cloud gravitational collapse to the late stages when a Keplerian accretion disc grows around the protostar. We found that this mechanism is very efficient in transporting the magnetic flux excess from the inner denser regions to the outskirts of the collapsing system on time scales compatible with the gravitational collapse (Santos-Lima *et al* 2010, 2012, de Gouveia Dal, Pino *et al* 2011, Leão *et al* 2012). Since turbulence is present in these systems, this mechanism provides a natural way to transport magnetic flux. Besides, it dismisses the necessity for postulating an artificial hypothetical increase of the Ohmic resistivity, as discussed in the literature, and calls for reconsidering the relative role of AD in the processes of star and planet formation.

Finally, we have argued that turbulent fast reconnection may also play a role in the development of dynamo processes, both in the more general framework of accretion discs and in the solar dynamo. In our future work, we intend to study in depth these ideas, particularly by means of fully 3D MHD numerical studies employing the same numerical tools and codes as described in the previous sections, including all the essential ingredients, such as stratification and differential rotation, in addition to injection of forced turbulence in order to control the flux transport and the magnetic field amplification.

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