New Astronomy 67 (2019) 89–96

Contents lists available at ScienceDirect

New Astronomy

journal homepage: www.elsevier.com/locate/newast

On the role of magnetic fields in star formation

C.J. Nixon*[,a], J.E. Pringle[a,b]

[a] Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK
[b] Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

ARTICLE INFO

Keywords:
Accretion
accretion discs
Dynamo
Magnetic fields
Magnetohydrodynamics (MHD)
Planets and satellites: formation
Stars: formation

ABSTRACT

Magnetic fields are observed in star forming regions. However simulations of the late stages of star formation that do not include magnetic fields provide a good fit to the properties of young stars including the initial mass function (IMF) and the multiplicity. We argue here that the simulations that do include magnetic fields are unable to capture the correct physics, in particular the high value of the magnetic Prandtl number, and the low value of the magnetic diffusivity. The artificially high (numerical and uncontrolled) magnetic diffusivity leads to a large magnetic flux pervading the star forming region. We argue further that in reality the dynamics of high magnetic Prandtl number turbulence may lead to local regions of magnetic energy dissipation through reconnection, meaning that the regions of molecular clouds which are forming stars might be essentially free of magnetic fields. Thus the simulations that ignore magnetic fields on the scales on which the properties of stellar masses, stellar multiplicities and planet-forming discs are determined, may be closer to reality than those which include magnetic fields, but can only do so in an unrealistic parameter regime.

1. Introduction

In two papers, Mestel (1965a,b) argued for the importance of the role of magnetic fields in star formation. He pointed out that an average region of the interstellar medium (ISM) containing a stellar amount of mass cannot simply collapse to stellar densities, because it contains too much angular momentum. He argued that magnetic fields are likely to play a vital role in removing that angular momentum. At the same time, he pointed out that the average region of interstellar medium containing a stellar mass also contains too much magnetic flux for it to be able to collapse to stellar densities. Therefore the magnetic field has to find a balance between enabling the removal of angular momentum, and itself escaping from the collapsing material. He proposed that ambipolar diffusion might provide such a mechanism (see also Mestel and Spitzer, 1956).

In contrast, Bate (2012) started with a self-gravitating, turbulent cloud core of mass $M = 500M_\odot$, density and temperature $T = 10\,\mathrm{K}$, and followed the subsequent evolution. He was able to reproduce the observed initial mass function, and also the observed properties of binary and multiple stars, for stars less than around a solar mass. Similar results were obtained by Krumholz et al. (2012) using a grid based code. Moreover, Bate (2018) has shown that his simulations also produce plentiful and massive discs around his protostars, of the kind required for planet formation (Nixon et al., 2018) and beginning to be seen around the youngest (Class 0 and I) protostars (e.g. Tobin et al., 2015; Pérez et al., 2016). None of the simulations by Bate (2012) and Krumholz et al. (2011, 2012) included magnetic fields.

In the light of all this McKee (Reipurth, 2017) commented: “*How is that possible when it is known that magnetic fields... have a major effect in extracting angular momentum from the accreting gas? In fact, in our current understanding, magnetic fields are so effective at extracting angular momentum that many simulations of the formation of protostellar disks fail to produce disks nearly as large as observed.*”

In fact, McKee’s comments illustrate very well the problem with magnetic fields. If we do not put them into the simulations, then we can get results quite close to the observations. But if we include magnetic fields, then we do not. Application of Occam’s Razor suggests a simple conclusion. But the question then is: how do we reconcile this with the observed presence of magnetic fields in and around regions of star formation (see the review by Crutcher, 2012)? It is this apparent contradiction that we address in this paper.

2. Do we need magnetic fields?

The presence and influence of magnetic fields has been thought to play a major role in two aspects of the star formation process. First magnetic fields are able to transfer angular momentum efficiently and so are a potential solution of Mestel’s angular momentum problem.

---

* Corresponding author.
E-mail address: cjn@leicester.ac.uk (C.J. Nixon).

https://doi.org/10.1016/j.newast.2018.09.007
Received 21 August 2018; Accepted 14 September 2018

Second, magnetic fields are able to provide additional support to cloud material against gravitational collapse, and so can mediate, and in particular reduce, the rate at which star formation can proceed in dense interstellar material. We discuss each of these in turn.

2.1. Is there an angular momentum problem?

The picture of star formation envisaged by Mestel was that of the formation of a single star, such as the Sun, from the monolithic gravitational collapse of an amount of interstellar material. This concept was later developed in more detailed form, with single core, monolithic collapse calculations leading to the view of star formation summarized in the review by Shu et al. (1987) (and also promulgated in reviews by Stahler and Palla, 2005, and by McKee and Ostriker, 2007). It is clear that if one views the star formation process in terms of forming one star at a time from the interstellar medium which is of necessity rotating, then the need for the removal of angular momentum from the forming protostar becomes paramount.

The problem with this approach from the point of view of star formation is that it always leads to the formation of single stars. This is not a good result for typical solar mass stars of which only 50 ± 10 per cent are single (Raghavan et al., 2010).

In view of this it is possible to make the case (Pringle, 1989; 1991; Clarke and Pringle, 1991; Reipurth and Clarke, 2001) that, contrary to the single core collapse picture, the formation of binary (and multiple) stars is in fact the way to understand the formation of all stars. The point is that in order to account for the occurrence of numbers of binary and multiple systems it is necessary that essentially all stars have to form in the presence of companions. If all stars form in groups, then many of these will be ejected as single stars (see the reviews by Zinnecker, 2001; Reipurth et al., 2014). And given that single stars are in a minority, it follows that most stars must form in groups. The observational case for the veracity of this conclusion is reviewed by Lada and Lada (2003). This leads to the current model of chaotic star formation crystallized by Bate (2012).

In this picture, it is to be expected that the angular momentum problem is to a large extent overcome by gravitational interactions alone (e.g. Larson, 2010), and this expectation is confirmed by the simulations. Thus it is clear that while magnetic fields may be present, they are not required to solve Mestel's fundamental angular momentum problem of removing angular momentum from the interstellar medium.

Note, however, that the presence of magnetic fields is likely required at some level in the very late stages in order to help drive the final stages of disc evolution and the formation of jets, although Hartmann and Bae (2018) make the case that the importance of disc magnetic winds may have been overestimated. The early stages of disc evolution occur while the disc is self-gravitating (e.g. Nixon et al., 2018) and around 90 percent of the stellar mass is accumulated in this way. However, the late stages, involving angular momentum from the last few per cent of the stellar mass, and the inner disc regions, from where the proto-stellar jets are driven, both involve discs that are ionized enough to support dynamo activity (MRI). However, the magnetic fields in these instances are unlikely to have been dragged in by accreting material (Lubow et al., 1994). Local dynamo activity, acting on seed fields, is capable of generating the necessary viscosity through MRI, as well as generating larger scale, sufficiently ordered fields, that can drive dynamic outflows (Tout and Pringle, 1996; Fendt and Gaßmann, 2018).[1]

We conclude that the problem of removing angular momentum from interstellar material in order to allow the formation of stars does not require a significant presence of large-scale magnetic fields. Indeed, it has been widely demonstrated (Li and McKee, 1996; Myers et al., 2013; 2014; Li et al., 2014; Tomida et al., 2015; Hennebelle et al., 2016; Masson et al., 2016; Küffmeier et al., 2017; 2018; Küffmeier and Nauman, 2018; Gray et al., 2018) that introducing additional angular momentum transport (by introducing magnetic fields to the calculations) leads to the two major problems mentioned by McKee:

(i) it is difficult to reproduce the observed number of stars that are in binary and multiple systems, let alone the properties of the systems, and

(ii) it is difficult to produce the fraction of stars with massive enough discs to give rise to planet formation. Winn and Fabrycky (2015) find that at least one half of solar-type single stars have planetary systems; and to form planets the disc masses need to be well above the minimum mass solar nebula of around $\sim 0.01 M_\odot$ (Nixon et al., 2018).

2.2. Is there a star formation rate problem?

The original perception of molecular clouds was that they are self-gravitating, isolated long-lived entities (e.g. Solomon et al., 1987; Blitz, 1991; 1993). In that picture the observed supersonic turbulent support of the cloud was necessary in order to prevent the high star formation rate that would result from the gravitational contraction of the cloud on its free-fall or dynamical timescale. Moreover, it was thought that the turbulence needed to be strongly magnetic in order to cushion the shocks and so prevent rapid dissipation of the turbulence (Arons and Max, 1975; Lizano and Shu, 1989; Bertoldi and McKee, 1992; Allen and Shu, 2000). However, it turned out that inclusion of magnetic fields has a minimal effect on the dissipation rate of the turbulence (Ostriker et al., 1999; Mac Low et al., 1998). This idea that magnetic intervention is required in molecular clouds in order to slow the rate of star formation is indeed still prevalent (Ballesteros-Paredes et al., 2005; Vázquez-Semadeni et al., 2005; Padoan and Nordlund, 2011; Federrath and Klessen, 2013; Myers et al., 2014; Padoan et al., 2014; Federrath, 2016).

In recent times, this picture of molecular clouds has given way to a realisation that molecular clouds are much more transient entities.

First, Elmegreen (2000), and others (for example Beichman et al., 1986; Lee et al., 1999; Jessop and Ward-Thompson, 2000; Ballesteros-Paredes et al., 1999) have given cogent observational arguments that the star formation within a giant molecular cloud (GMC) occurs within one or two crossing times of its formation, that is within a few Myr. Similarly comparisons of the ages of young clusters and their association with molecular gas both in our Galaxy (Leisawitz et al., 1989) and in the Large Magellanic Cloud (Fukui et al., 1999) indicate that the dispersal of a cloud in which star formation has occurred takes a timescale of only $5-10$ Myr.[2] Thus, molecular clouds are far more ephemeral than was previously postulated, and therefore the rate of star formation within them cannot be as high as previously envisaged.

Second, it has become apparent that GMCs as a whole are not self-gravitating (Heyer et al., 2009; Dobbs et al., 2011b).[3] Numerical simulations of the evolution of the interstellar medium within disc galaxies show that the denser regions (the giant molecular clouds) are

---

[1] An important distinction here is that in contrast to hydrodynamic turbulence, MHD turbulence can give rise to an inverse cascade whereby it is able to generate magnetic fields on lengthscales much larger than the driving lengthscale of the turbulence.

[2] Incidentally, it follows from these observations that, contrary to what is often assumed (Walch and Naab, 2015; Padoan et al., 2016; Körtgen et al., 2016) since the vast majority of massive main-sequence lifetimes of stars that give rise to supernovae, ie $M \geq 8 M_\odot$, are $\geq 5-10$ Myr (Crowther, 2012), supernova explosions cannot provide an internal source of turbulent energy in GMCs. It has also been shown that supernova explosions cannot provide an external source of turbulent energy either (see for example Seifried et al., 2018).

[3] This implies that the discussion of the properties of such clouds in terms of "free-fall times" (e.g. Padoan et al., 2014) not only has no meaning, but stems from the previous outdated physical picture (see also Kennicutt and Evans, 2012).