Mem. S.A.It. Vol. 88, 864

Memorie della

Stabilizing Population III accretion disks with magnetic fields

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Abstract. Population III accretion disks are prone to gravitational instabilities that can cause them to fragment. Studies of present-day star formation find that magnetic fields can help to stabilize protostellar accretion disks and suppress fragmentation. However, the role of magnetic fields during Pop III star formation is uncertain. The small-scale dynamo (SSD) can amplify weak seed fields to dynamically significant values, but it is unclear whether the resulting field is strong enough to suppress fragmentation. Here, we use an extended Toomre criterion to estimate the critical field strength $B_{\rm crit}$ needed for disk stabilization. We compare this with estimates of the field strength produced by the SSD, $B_{\rm sat}$. We show that in general, $B_{\rm crit} > B_{\rm sat}$, implying that the magnetic field produced by the small-scale dynamo is too weak to fully stabilize the disk.

1. Introduction

Numerical simulations of Population III (Pop III) star formation show that the protostellar accretion disks that form around the first Pop III protostars are prone to gravitational fragmentation (see e.g. Clark et al. 2011; Greif et al. 2012). This can reduce the amount of mass reaching the central star, and also provides a mechanism for forming low-mass Pop III stars that may survive until the present day. However, most simulations of Pop III accretion disks have neglected the effects of the strong, tangled magnetic field generated in the gravitationally collapsing gas by the turbulent dynamo (Kulsrud et al. 1997). In this contribution, we estimate the strength of this tangled field on the scale of the disk and compare it to an estimate of the field strength required to stabilize the disk against gravitational fragmentation.

2. Our model

2.1. Extended Toomre criterion

We use an extended version of the Toomre criterion (Toomre 1964) in order to estimate a minimum magnetic field strength, $B_{\rm crit}$, which is needed to keep a typical Population III accretion disk stable. We assume that the magnetic field is highly tangled with little large-scale coherence, and hence that we can account for its effects simply by modifying the effective speed of sound used in the Toomre criterion (see e.g. Kim & Ostriker 2001). We therefore have

$$Q = \frac{\kappa\,(c_{\rm s}^2 + v_{\rm A}^2)^{1/2}}{\pi\, G\, \Sigma}, \quad (1)$$

where $c_{\rm s}$ is the speed of sound, $v_{\rm A}$ is the Alfven velocity, κ is the epicyclic frequency, G is the gravitational constant and Σ is the disk

Table 1. Values of $B_{\rm crit}$, $B_{\rm sat,c}$ and $B_{\rm sat,s}$ computed using values at the indicated radius for the Pop III accretion disks modelled in Clark et al. (2011) and Greif et al. (2012). For the latter, we indicate which realization is referred to by using the same MHn identifier as in Greif et al. (2012)

	R [AU]	$B_{\rm crit}$ [G]	$B_{\rm sat,c}$ [G]	$B_{\rm sat,s}$ [G]
C11	20	3.1	0.5	2
G12-MH1	10	1.8	0.6	2
G12-MH2	1	260	40	140
G12-MH2	10	3.2	0.6	2
G12-MH3	1	440	60	180
G12-MH3	10	6.1	0.8	3
G12-MH4	1	480	70	230
G12-MH4	10	6.9	0.8	3

References: C11 Clark et al. (2011); G12 Greif et al. (2012).

surface density. If κ, $c_{\rm s}$ and Σ are known then we can solve for the value of $v_{\rm A}$ necessary to ensure that $Q > 1$. $B_{\rm crit}$ then follows as

$$B_{\rm crit} \gtrsim \frac{c_{\rm s}}{Q_{\rm hyd}} \sqrt{4\pi\rho\,(1 - Q^2_{\rm hyd})}, \tag{2}$$

where $Q_{\rm hyd}$ is the value of Q in the absence of the magnetic field. We take representative values of $c_{\rm s}, \rho$ and $Q_{\rm hyd}$ from Clark et al. (2011) and Greif et al. (2012).

2.2. Saturation field strengths of the small-scale dynamo

The SSD (e.g. Kazantsev 1968) rapidly amplifies initially weak magnetic seed fields to dynamically significant values during the gravitational collapse of primordial gas (see e.g. Schober et al. 2012). The final saturation field strength is not known precisely and so we make the following ansatz:

$$\frac{B^2_{\rm sat}}{8\pi} = \frac{1}{2}\,\epsilon\,\rho\,u^2_{\rm turb}. \tag{3}$$

Here, $u_{\rm turb}$ is the turbulent velocity and ρ is the disk density. The efficiency factor ϵ accounts for the back-reaction from the field on the turbulence. Its value depends on the nature of the turbulence, and so following Federrath et al. (2011), we adopt $\epsilon_s \approx 0.3$ for solenoidal turbulence and $\epsilon_c \approx 0.03$ for compressive turbulence. We also assume, following Clark et al. (2011) and Greif et al. (2012), that the turbulence in the disk is transonic, so that $u_{\rm turb} \sim c_{\rm s}$.

2.3. Results

In Table 1, we present our estimates of $B_{\rm crit}$, $B_{\rm sat,s}$ and $B_{\rm sat,c}$, where the latter two quantities are the saturation field strength for purely solenoidal or purely compressive turbulence, respectively. We see that in almost all cases, $B_{\rm crit} > B_{\rm sat}$, regardless of the nature of the turbulence, implying that in general the magnetic field is not strong enough to stabilize the disk. The only case in which the field is strong enough to provide stabilization (run MH1 in Greif et al. 2012) is unusual in that the disk is already very close to stability ($Q_{\rm hyd} \sim 0.9$), and so only a little extra support is needed to provide complete stabilization.

3. Conclusions

Our simple estimates show that small-scale dynamo action alone does not seem to be able to produce a strong enough magnetic field to stabilize a Pop III accretion disk, unless the disk is already very close to stability. However, we find that in many cases, $B_{\rm sat}$ is close to $B_{\rm crit}$, demonstrating that the effects of the field cannot be completely neglected. Also, as the disk evolves, it is possible that the small-scale field will be further amplified and evolved into a large-scale, coherent field via the α-Ω–dynamo (Steenbeck & Krause 1966).

Acknowledgements. We thank Daniel Seifried and Jennifer Schober for useful discussions. KMJW, SCOG and RSK acknowledge support from the ERC Advanced Grant 'STARLIGHT: Formation of the First Stars' (project number 339177). VB is supported by NSF grant AST-1413501.

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