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Magnetohydrostatic structures of magnetically-supported filaments and their stability

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Abstract. Polarization of dust thermal emissions shows that the dense filaments are extending perpendicular to the interstellar magnetic field. Magnetohydrostatic structures of such filaments are studied. The magnetically-supported maximum line mass increases in proportion to the magnetic flux per unit length threading the filament. Comparison is made with 3D clouds. Stability of these magnetized filaments is studied using time-dependent 3D MHD simulations to discuss star formation in the filaments.

Key words. Stars: Formation – Interstellar: magnetic fields – Interstellar: matter

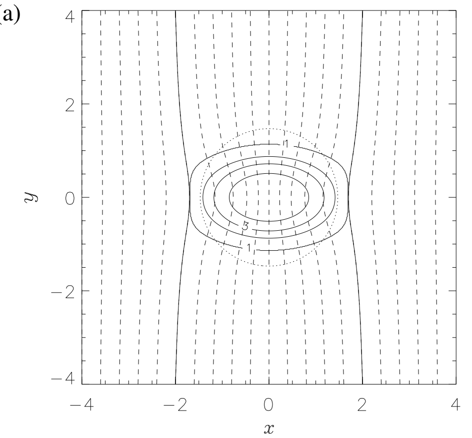
1. Introduction

Interstellar filaments are gathering much attention, since Herschel Space Observatory found many filamentary structures in the molecular clouds (André et al. 2010). They claimed that the line-mass (mass per unit mass), λ, of a filament is a crucial parameter which controls the star formation in the filament. That is, the filament with $\lambda > 2c_s^2/G \equiv \lambda_{\rm cr,0}$ indicates star formation signature, where c_s and G represent, respectively, the isothermal sound speed and the gravitational constant and this $\lambda_{\rm cr,0}$ is the maximum line-mass of isothermal filaments in hydrostatic balance without magnetic field (Stodółkiewicz 1963). However, observation of interstellar extinction in near IR (Sugitani et al. 2011; Palmeirim et al. 2013) reveled that interstellar magnetic field is running perpendicular to such filaments. Further more, polarization of thermal emissions from interstellar dust indicates the same trend (Planck Collaboration Int. XXXV 2016). We have to consider the effect of magnetic field which is running perpendicular to the filament. In a case of magnetic fields (B_0) parallel to the filament, the critical line mass increases as $\lambda_{\rm cr,\parallel} = \lambda_{\rm cr,0}(1 + \beta^{-1})$, where $\beta \equiv c_s^2\rho/(B_0^2/8\pi)$ = const represents the plasma beta (Stodółkiewicz 1963). However, observed filaments have perpendicular magnetic fields.

2. Magnetohydrostatic structure

Structure of the filament is calculated under the assumption of magnetohydrostatics. We solved two simultaneous partial differential equations in second-order by the self-consistent field method (Tomisaka 2014). The one equation is the Poisson equation of the gravitational potential Ψ. The other is the Grad-Shafranov equation of the magnetic potential Φ. The solution has 3 parameters after natural normalization: R_0, β_0, and ρ_c. Figure 1 shows typi-

(a)



(b)

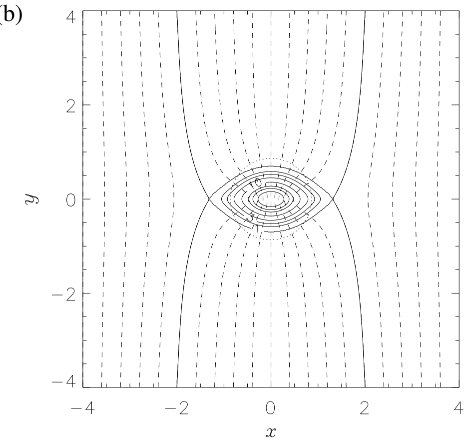


Fig. 1. Examples of magnetohydrostatic filaments. Global magnetic field is running in y-direction (dashed line). The solid closed lines indicate isodensity contours. These models have the same parameters of $R_0 = 2$ and $\beta_0 = 1$. These two models have different line-mass λ_0 and the central density ρ_c as (a: $\rho_c = 10$, $\lambda_0 = 21.6$) and (b: $\rho_c = 300$, $\lambda_0 = 28.4$).

cal structures of filaments. These two models have the same plasma beta far from the filament (β_0) and the radius of a hypothetical "parent" cloud from which the filament is made under the magnetic flux freezing (R_0). Since magnetic flux per unit length, $\Phi_{\rm cl}$, is given by $R_0/\beta_0^{1/2}$, the two models have the same magnetic flux but different center-to-surface density ratios (ρ_c). For a given $\Phi_{\rm cl}$, the line-mass is an increasing function of the central density,

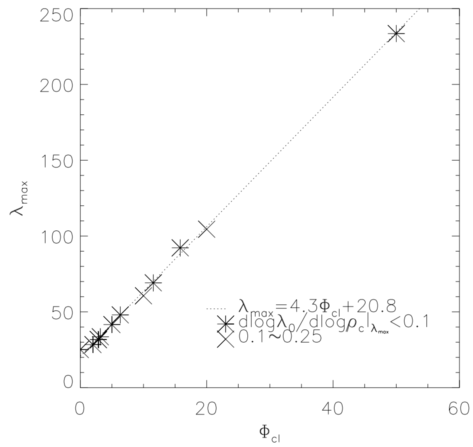


Fig. 2. The line-mass which can be supported by a given magnetic flux $\Phi_{\rm cl}$ is plotted against $\Phi_{\rm cl}$.

ρ_c. The maximum line-mass $\lambda_{\rm max}$ supported by a $\Phi_{\rm cl}$ is obtained by extrapolation of $\rho_c \to \infty$. As shown in Figure 2, the maximum line-mass increases as the magnetic flux per unit mass $\Phi_{\rm cl}$ increases. From this figure, an empirical formula is obtained for the critical line-mass supported by a lateral magnetic field as

$$\begin{aligned}
\lambda_{{\rm cr},B} &\equiv \lambda_{\rm max}(\Phi_{\rm cl}) \\
&\simeq 0.24\Phi_{\rm cl}/G^{1/2} + 1.66c_s^2/G, & (1) \\
&\simeq 22.4M_\odot\left(\frac{R_0}{0.5{\rm pc}}\right)\left(\frac{B_0}{10\mu{\rm G}}\right) & (2) \\
&\quad +13.9M_\odot\left(\frac{c_s}{190{\rm m\,s^{-1}}}\right)
\end{aligned}$$

in the dimensional form, in which the first term in the right-hand side represents the magnetic effect and the last represents the thermal one. This shows us that the filament with the magnetic flux of $\geq 5\mu$G pc is mainly supported by the magnetic field.

The axisymmetric cloud has also a critical mass supported by the magnetic field as

$$M \simeq \Phi_{\rm cl,\,2D}/2\pi G^{1/2}, \quad (3)$$

where $\Phi_{\rm cl,\,2D}$, of which the unit is μG pc^2, represents the magnetic flux threading the cloud. Comparing equations (1) and (3), a similarity exists between the two ($1/2\pi \simeq 0.16$).

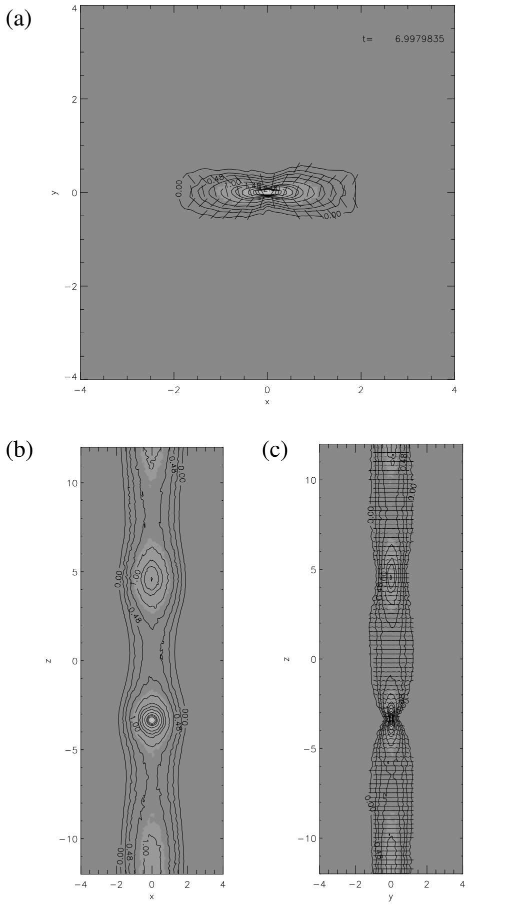


Fig. 3. Structure of the fragmented filaments with parameters $R_0 = 2$, $\beta_0 = 1$ and $\rho_c = 10$. Cross-cut views by *xy*- (a), *xz*- (b), and *yz*-planes (c). Solid contour lines indicate density distribution. Short bars in (a) and (c) represent the magnetic field.

3. Stability analysis

To study the stability of such filaments, we performed 3D MHD simulations (Tomisaka & Matsumoto 2017) with AMR code SFUMATO (Matsumoto 2007)[1].

We added density perturbation to each cell (x_i, y_j, z_k)

$$\rho(x_i, y_j, z_k) = \rho_0(x_i, y_j) + \delta\rho(x_i, y_j, z_k), \tag{4}$$

where $\rho_0(x_i, y_j)$ is given from the magnetohydrostatic solution above and the z-axis is directed to the axis of the filament. The density perturbation is assumed as follows: $\delta\rho/\rho$ is chosen to follow a Gaussian distribution with $\overline{\delta\rho/\rho} = 0$ and the standard deviation $\delta = 0.1$. The range of the numerical box is $-4 \le x \le 4$, $-4 \le y \le 4$, and $-12 \le z \le 12$. Although the fixed boundary condition is applied to the x- and y-boundaries, the periodic boundary condition is applied to the z-direction. Figure 3 shows a snapshot at $t = 7$ of a filament shown in Figure 1(a) ($\lambda \le \lambda_{\rm cr,\mathit{B}}$). This shows clearly that the filament breaks into 3 high-density clumps and the most unstable wavelength is $\simeq 8$. The clump is contracting and has a shape of a thick disk whose minor axis coincides with the magnetic field direction (y-direction). In the perpendicular direction to the magnetic field (x- and z-directions), the clump has larger scalelength than y-direction, which is typical structure of a magnetized pseudo-disk (Tomisaka 1995). This shows us that even a subcritical filament ($\lambda \le \lambda_{\rm cr,\mathit{B}}$) is gravitationally unstable and fragments into clumps in which star formation begins.

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[1] Linear stability analysis has been done for a simplified setup assuming uniform magnetic field, in which uniform perpendicular field does not play a role in the hydrostatic structure of the filament but is important to stabilize the gravitational instability of the filament (Hanawa, Kudoh, & Tomisaka 2017).

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