Structure and Critical Mass of Filamentary Isothermal Cloud Threaded by Lateral Magnetic Field

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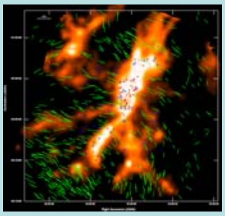
Herschel observation has recently revealed that interstellar molecular clouds consist of many filaments. Polarization observations in optical and infrared wavelengths indicate that the magnetic field is often running perpendicular to the filament. In this paper, the magnetohydrostatic configuration of isothermal gas is studied, in which the thermal pressure and the Lorentz force are balanced against the self-gravity and the magnetic field is globally perpendicular to the axis of the filament. The model is controlled by three parameters: center-to-surface density ratio (ρ_c/ρ_s), plasma β of surrounding interstellar gas (β_0) and the initial radius of the filament normalized by the scale-height (R'_0), although there remains a freedom how the mass is distributed against the magnetic flux (mass loading). In the case that R'_0 is small enough, the magnetic field plays a role in confining the gas. However, the magnetic field has generally an effect in supporting the cloud. There is a critical line-mass (mass per unit length) above which the cloud is not supported against the gravity. Comparing with the critical line-mass of non-magnetized cloud ($2c_s^2/G$, where c_s and G represent respectively the isothermal sound speed and the gravitational constant), the critical line-mass of the magnetized filament is larger than the non-magnetized one. The critical line-mass is numerically obtained as

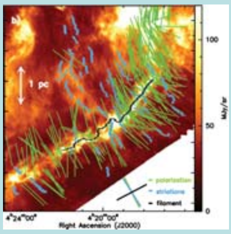
$$\lambda_{\max} \approx 0.24\Phi_{cl}/G^{1/2} + 1.66c_s^2/G$$

where Φ_{cl} represents one half of the magnetic flux threading the filament per unit length. It is shown that the critical mass of the filamentary cloud is much affected by the effect of the magnetic field when the magnetic flux per unit length exceeds $\Phi_{cl} \sim 3$ pc μG.

Introduction

Molecular clouds consist of many filaments.
Magnetic field lines are perpendicular to the main filament.





Left: Serpens South Cloud by Sugitani et al (2011), right: Taurus Cloud (B211/213) by Palmeirim et al. (2013)

Isothermal cylinder has a density distribution as

$$\rho(r) = \rho_c\left(1+\frac{r^2}{8H^2}\right)^{-2}$$
$$H = c_s/(4\pi G\rho_c)^{1/2}$$

(Stodolkiewicz 1963; Ostriker 1964)

Line-mass (mass per unit length)

$$\lambda(R) \equiv \int_0^R 2\pi r\rho(r)dr = \frac{2c_s^2}{G}\frac{R^2/8H^2}{1+R^2/8H^2}$$

controls the stability of the filament;

$$\begin{cases} \lambda > 2c_s^2/G & \text{dynamical contraction,} \\ \lambda < 2c_s^2/G & \text{hydrostatic,} \\ \lambda = 2c_s^2/G & \text{critical line-mass.} \end{cases}$$

How about Magnetized Cloud?

Filament with B_z with constant beta
$\lambda = \left(2c_s^2/G\right)(1+\beta^{-1})$ (Stodolkiewicz 1963)

Filament with B_z with constant B_z/ρ ratio
increases the line-mass (Fiege & Pudritz 2000a,b).

However, magnetic field and filaments are perpendicular each other.

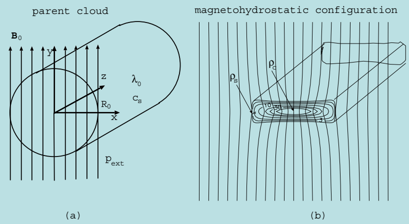
We study the magnetohydrostatic configuration of a magnetized cloud threaded by lateral magnetic field and obtain the critical line-mass of the filament.

Method

Basic Equations:
Using flux function Φ and gravitational potential Ψ, basic equations are:

$$\Delta_2\Phi = 4\pi\frac{dq}{d\Phi}\exp\left(-\frac{\psi}{c_s^2}\right) \quad \leftarrow \text{Grad-Shafranov eq.}$$
$$\Delta_2\psi = 4\pi G\frac{q(\Phi)}{c_s^2}\exp\left(-\frac{\psi}{c_s^2}\right) \quad \leftarrow \text{The Poisson eq.}$$
$$\Delta_2 \equiv \partial^2/\partial x^2 + \partial^2/\partial y^2$$

This nonlinearly coupled partial differential equation system is solved by the self-consistent field method.

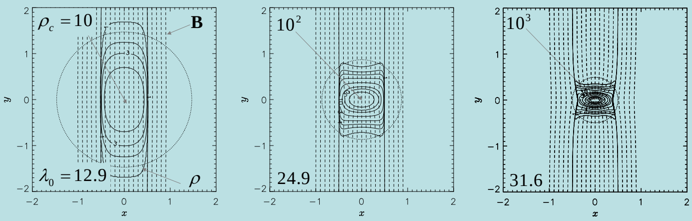


Mass Loading:
Mass distribution against magnetic flux is given as the same as the parent cloud, which is a hypothetical cylindrical cloud with uniform density and uniform magnetic field.

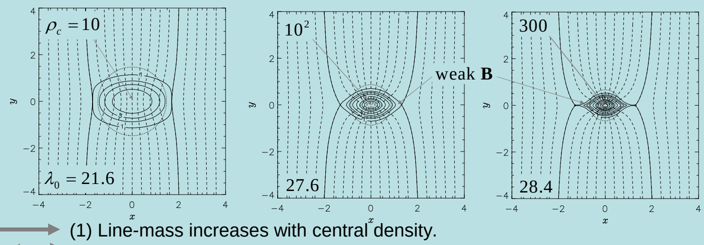
Three Parameters to Specify a Solution:
- R_0 Radius of the parent cloud
- $\beta_0 \equiv p_{ext}/(B_0^2/8\pi)$ Plasma β of the external medium far from the filament
- λ_0 Line-mass ➔ ρ_c Central density

Result

(a) Small R_0 model ($R_0 = 0.5, \beta_0 = 0.03$)

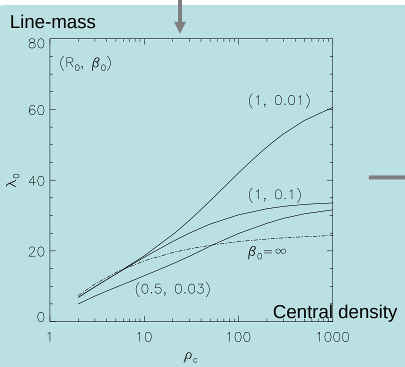


(b) Standard model ($R_0 = 2, \beta_0 = 1$)

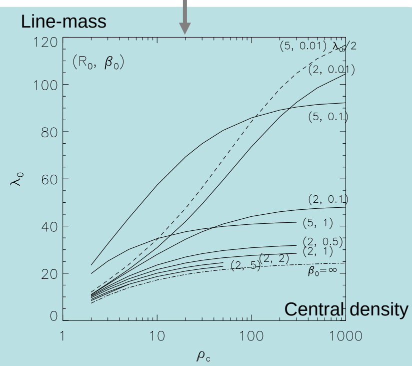


(1) Line-mass increases with central density. ⟷ (1) Line-mass increases with central density.
(2) Low central density: Major axis of density distribution is parallel to the magnetic field. ⟷ (2) Major axis is along the perpendicular direction of the magnetic field.
(3) High central density: Major axis is along the perpendicular direction to the magnetic field. (3) B-field is weak around the mid-plane.

Line-Mass – Central Density Relation



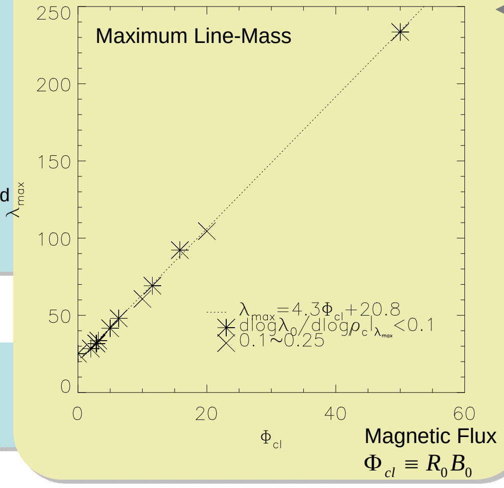
(1) Line-mass is smaller than that of the non-magnetized filament.
(2) B-field plays a role in confining the filament for low central density.



(1) Line-mass is larger than that of the non-magnetized filament.
(2) B-field plays a role in supporting the filament against the gravity.

Maximum Line-Mass – Flux Relation

$$\lambda_{\max} \approx 0.24\Phi_{cl}/G^{1/2} + 1.66c_s^2/G$$



Magnetic field plays a role in supporting the filament.

Critical mass depends mainly on B_0 for $\Phi_{cl} > 3$ pc μG.