Transition of Column Density Distribution in Molecular Clouds [2019]

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Keywords

- Molecular Clouds
- Column Densities
- Mass-to-Flux ratios

Background

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Column Density Probabilities Densities Functions (PDFs) can be effectively used to study the configurations of molecular clouds both observationally and theoretically.

Through numerical simulations we observed:

- For non-self-gravitating clouds driven by turbulence show log-normal PDF.
- While introducing gravity into simulations results in high-density power tail distributions

Observations also showed an underlying lognormal distribution followed by a power-law tail. The transitional point is called transitional column density.

In this paper, the transitional point has been studied for subcritical clouds (high magnetic fields) and how they handle large perturbations or disturbances to delay turbulence driven ambipolar diffusion resulting in a wider lognormal curve through numerical simulatons.

Introduction

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Lognormal shape :

It is linked to clouds with very less star-forming regions driven by supersonic turbulence and the width of the curve is linked to strength of Mach number.

But is considered more of a **general characteristic** present in supersonic clouds, gravitationally induced ambipolar diffusion and gravitational contraction.

Power-law tail shape :

It links to regions with active star-formation after a lognormal peak.

This is linked to gravitational contraction when the condensed cores are formed.

PDF $dN/d\log\Sigma \propto \Sigma^{-\alpha}$

This curve can be approximated for the power-law tails for isothermal gravitational contraction. (aplha is usally 2).

However, many observed sources had alpha > 3.

Influence of Magnetic Field:

Strong magnetic fields with low turbulence can result in steeper power-law tails as they can enhance contraction by ambipolar diffusion.

While strong turbulence in addition with magnetic fields can cause wider lognormal curves delaying the transition to power-law and keeps the steep 2.

PDF Parameters

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There are three main parameters of Column Density PDF graphs.

1. The Lognormal Part
   Its width is sometimes associated with initial Mach Number.

2. The slope of Power-Tail Part
   It develops when self-gravity is introduced in clouds driven by turbulence. As star-formation rates are quite low, this part has relatively less mass.

3. The transitional column density point
   Some theories have been made around it such as this point related to H1-H2 transition. As H1 clouds are known to be non-gravitating while molecular clouds do self-gravitate.

Transition Point:
Through observations it was found that the transition point is unique for each source.

Mainly, it is said to be related to cloud's initial conditions and other physical processes.

Numerical Simulations

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Time evolution of column density PDFs are studied for different 3D magnetohydrodynamic simulations with both initial turbulence and ambipolar diffusion.

Initial Conditions :

- Uniform density in x,y and stratified in z.
- Scale length calculated from sound speed and density
- Uniform vertical magnetic field
- Gaussian random velocity fluctuations in x and y components.

For more on initial conditions refer: https://doi.org/10.1088/0004-637X/728/2/123

Fitting Functions:

To estimate lognormal distribution the following function has been used:

$$f(\eta)_{\rm LN} = \log\left[A\frac{1}{\sqrt{2\pi\sigma^2}}\exp\left(-\frac{(2.3\eta-\mu)^2}{2\sigma^2}\right)\right], \qquad (2)$$

To model power-law tail a combination of both lognormal and power-law functions.

$$\begin{aligned} f(\eta)_{\rm LNPL} &= f(\eta)_{\rm LN}, \quad \text{if } \eta \leqslant \eta_{\rm TP}, \\ &= f(\eta_{\rm TP})_{\rm LN} + \alpha\eta, \quad \text{if } \eta > \eta_{\rm TP}, \end{aligned} \qquad (3)$$

Hence we have two fitting functions and four parameters μ (mean), α (index or slope of power law curve), sigma (standard deviation), the logarithmic transitional column density.

Fitting Simulation Data

How to decide when power-law-tail has started. It was done by taking values of PDFs by fitting both lognormal and hybrid function and comparing the values.

If hybrid function is 10% less than lognormal and alpha is less than 5 than it considered a power-law tail case.

Simulation Observations:

In the simulations, we saw that the transitional point **proportionally** depends on the product of initial Mach number squared and magnetic field strengths.

Package used:

Python Pymc package for Monte Carlo fittings.

Analytical Model

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The Conceptual understanding:

1. The cloud flattens along the z-direction and gets compressed in the x-y plane.
2. Magnetic fields are initially subcritical (until ambipolar diffusion dominates)
3. Turbulence transitions from subcritical at all regions to pockets of supercritical cores.
4. The magnetic pressures in these cores balances out the ram pressure and background magnetic pressure. (rebounds and oscillations)

$$H\frac{B^2}{8\pi} = H_0\left(\rho_0 v_{t0}^2 + \frac{B_0^2}{8\pi}\right), \qquad (4)$$

5. The half-thickness of the cloud is given by this relation.

$$H = \frac{c_s}{\sqrt{2\pi G\rho}} \qquad (5)$$

6. The integral of density over the scale height gives us the column density relations.

$$\Sigma = 2\rho H.$$

7. As ambipolar diffusion takes much more time than the initial compression, it can be assumed that flux freezes initially.

$$\frac{\Sigma}{\Sigma_0} = \left[v_{t0}^2\left(\frac{8\pi\rho_0}{B_0^2}\right) + 1\right]. \qquad (7)$$

8. The above equation can be transformed to the following equation considering that the turbulence and magnetic fields will turn weak.

$$\frac{\Sigma_{\rm TP}}{\Sigma_0} = a(\mathcal{M}_0^2\beta_0 + 1), \qquad (8)$$

This finally helps us get the transition point based on the initial magnetic field and Mach number values.

Discussions

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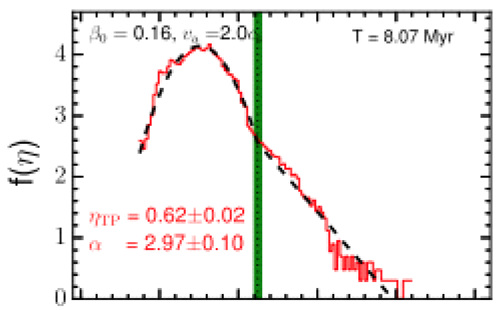
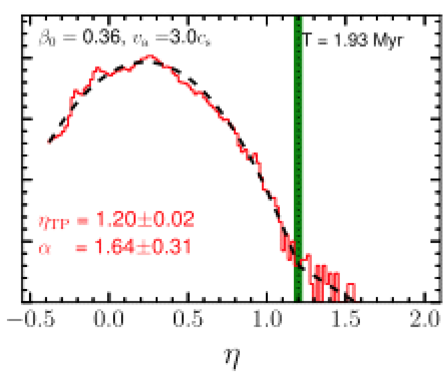
The literature was able to find a good analytical fit of logarithmic transitional column density with initial Mach Number and Magnetic field strength. The transitional point shifts linearly with increasng these two parameters.

Lowest initial values



Highest initial values



It also explains the physical aspects of transition point. The point majorly separates the subcritical turbulent regions from the compressed supercritical regions.

Or it is the critical point where mass to flux ratio reaches a point where gravitational collapse can initiate.

Note:
From the transitional point that we foresee in observations we can reverse engineer and get the initial values of magnetic fields and Mach numbers of a gass clouds

Any Future Work

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1. As of now observing the low density regions is quite difficult and the lognormal predictions are just to fit the missing parts of the observational data. Hence future work can involve working on new data sets if possible?

2. New work can be done to related the width of the lognormal curves with the initial Mach Numbers and Magnetic field strengths?

Questions?

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1. What is a column density?
   It is the number of atoms or molecules per cm^2 (area) along the line of sight.

   Refer: https://sentinelmission.org/astronomical-units-measurements-glossary/column-density/