Structure and Stability of Prestellar Cores

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Abstract

Following an approach initially outlined by McKee & Holliman [5], we investigate the structure and stability of dense, starless molecular cloud cores. We model those as spherical clouds in hydrostatic equilibrium and supported against gravity by thermal, turbulent, and magnetic pressure. We determine the gas pressure by solving for thermal equilibrium between heating and cooling, while the turbulent and magnetic pressures are assumed to obey polytropic equations of state. In comparing the models to observed cloud cores we find that the observed peak column densities often exceed the limit for stable equilibria supported by thermal pressure alone, suggesting significant non-thermal pressure if the cores are to be stable. Non-thermal support is also needed to stabilize cores embedded in molecular clouds with high average pressures. Since the observed molecular linewidths of cores suggest that the turbulent pressure is lower than the thermal pressure, magnetic field are likely a dominant pressure component in many such cores.

1 Hydrostatic equilibrium models

To model a gas cloud in hydrostatic equilibrium we make the simplified assumption that the gas pressure consists of the sum of thermal (subscript “th”), turbulent wave (“w”), and magnetic (“m”) pressure components,

\[ P = P_{th} + P_w + P_m. \] (1)

We compute the thermal pressure through a detailed thermal equilibrium calculation, but the wave and magnetic pressures are assumed to obey a polytropic equation of state,

\[ P_w \propto \rho^{\gamma_{P,w}}, \quad P_m \propto \rho^{\gamma_{P,m}}, \] (2)

i.e. the pressure only depends on density, and \( \gamma_P \), the polytropic exponent, is constant in a given object. Given the thermal and non-thermal gas pressure, it is possible to construct hydrostatic equilibria for any surface pressure.
and central to surface density contrast. We assume spherical symmetry for simplicity.

Whether a given hydrostatic equilibrium model cloud is gravitationally stable depends on its response to perturbations in pressure or density. Different equations of state apply for such perturbations. For example, if the perturbation occurred on a time scale shorter than the cooling time, the scaling of the thermal pressure with density would be stiffer than if the perturbation would be allowed to reach thermal equilibrium. To analyze the stability we make the simple assumption that the perturbation obeys a polytropic equation of state, but with some different “adiabatic index”, $\gamma$:

$$\frac{\delta P_w}{P_{w,0}} \propto (\delta \rho/\rho_0)^{\gamma_w}, \quad \frac{\delta P_m}{P_{m,0}} \propto (\delta \rho/\rho_0)^{\gamma_m},$$

(3)

where $\delta$ are infinitesimal perturbations, and the subscript “0” refers to values before the perturbation.

A hydrostatic equilibrium cloud is stable against spontaneous contraction or expansion when at any point in the cloud, the pressure increases during a compression or decreases during an expansion, i.e.,

$$\frac{\delta P}{\delta r} < 0$$

(4)

where $r$ is the radius from the cloud center. Marginally stable equilibria have $\delta P/\delta r = 0$ at some point in the cloud.

1.1 Thermal Pressure

At any radial point in the cloud we solve the coupled thermal balance for the gas and dust. We adopt the gas heating and cooling rates and thermal gas-dust coupling from Goldsmith [4], and the dust heating and cooling rates for the solar neighborhood from Zucconi et al. [8]. The heating is due to cosmic rays and the interstellar radiation field, for which we allow some shielding, $A_{V,0}$, due to the material surrounding the core. When analyzing the stability, we assume that the heating or cooling due to a perturbation is negligible. The heating and cooling rates themselves however change, as they depend on the perturbed density and visual extinction.

1.2 Turbulent and Magnetic Pressure

We treat the kinetic pressure due to non-thermal motions, which we call turbulence, in the very simplifying framework of Alfvén waves. The pressure due to Alfvén waves can be described by a polytropic exponent $\gamma_{P,w} = 1/2$, and an adiabatic exponent $\gamma_w = 3/2$ for the case where no energy flow occurs [6, 3]. If we allow for a flow of the turbulent energy between the core and its surroundings during perturbations, then the adiabatic exponent would be equal to the polytropic one, i.e. $\gamma_w = 1/2$. This requires that the heat flows are faster than the duration of the perturbation.
Fig. 1. Observed column densities of prestellar cores (symbols) and upper limits for stable equilibria (lines). The lower line applies for pure thermal support, the one above for an equal thermal and magnetic pressure in the cloud center, the one above that for equal thermal and turbulent, the top one for equal thermal, magnetic and turbulent pressures in the cloud center. Dotted lines connect independent measurements of the same object by different authors.

The magnetic pressure due to the average magnetic flux threading the cloud depends on the distribution of field lines in the cloud, which is a result of how the cloud has formed while the gas was frozen to the field lines. A somewhat more realistic case was adopted for the 2-dimensional hydrostatic equilibria computed by Tomisaka et al. [7]: here a cloud was assumed to initially have been spherical and at uniform density within a uniform magnetic field. We examined these 2-D equilibria to determine the magnetic field – density scaling, finding $\gamma_{P,m} = 0.9$. The magnetic adiabatic exponent adopted in our work, $\gamma_m = 1.2$, is chosen such that the critical density contrasts of Tomisaka et al. [7] are reproduced. We adopt these values for our idealizing spherical model to study the behavior of 2-D magnetized equilibria.
2 Results & Conclusion

In our yet preliminary study we have looked at clouds with a particular ratio between the non-thermal and thermal pressure at the cloud center: we investigated clouds with \((P_{w}/P_{th})_{r=0} = 0\) or 1, and with \((P_{m}/P_{th})_{r=0} = 0\) or 1, which is meant to give a first impression on the effect of non-thermal pressure support on the cloud stability. We adopt an extinction due to material surrounding the clouds of 5 magnitudes in the visual.

As a function of cloud mass we computed the maximum central column density for a stable hydrostatic equilibrium. These are plotted in Figure 1 for clouds with and without non-thermal pressure. A comparison with the column densities measured for all starless low-mass cores we found in the literature shows that some of the more massive cores have column densities which are larger than what could be accounted for by a stable cloud with pure thermal pressure support.

With a magnetic or turbulent pressure at least comparable to the thermal pressure in the cloud center, higher central condensations comparable to those observed would be possible for stable clouds. If this non-thermal pressure were due to turbulent motions, then the observed cores’ non-thermal velocity dispersions should be comparable to the sound speed, but observations typically show smaller non-thermal linewidths [1]. Thus turbulence is unlikely to be the dominant support in such cores, and magnetic fields remain as the stabilizing force.

A second argument for the need of non-thermal support in the more massive low-mass cores derives from their maximum possible surface pressure. A core of given mass in a stable hydrostatic equilibrium can only exist if the kinetic surface pressure due to thermal and turbulent particle motions is below some critical value. Significant non-thermal pressure is necessary to stabilize the more massive cores \((M > 2 \text{ to } 3 \, M_{\odot})\) in such environments.

To summarize, our preliminary analysis of the stability of dense, self-gravitating cores and our comparison with observed cores and their environments suggests the need for non-thermal pressure support, most likely provided by magnetic fields of less than 100 µG.

References

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