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GRAVITY-BASED STRUCTURAL ANALYSIS OF THE MOLECULAR CLOUDS PERSEUS AND ORION A

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Abstract. This paper presents an analysis of the structural characteristics of the giant molecular clouds Perseus and Orion A using the gravity-based method G-virial applied to ^{13}CO(1-0) data cubes. The method utilizes a physical quantity called gravitational boundedness and through it defines gravitationally coherent regions. To define the gravitationally coherent regions we used the Dendrogram method. The results from our analysis reveal four things: the studied gravitationally coherent regions follow Larson-type relations, the gravitational boundedness rises towards the centers of these structures, cluster-forming regions generally have higher values of gravitational boundedness, and Orion A is characterized with higher values of gravitational boundedness than Perseus.

1. INTRODUCTION

Molecular clouds (MCs) represent the densest components of the interstellar medium where star formation takes place. Observations and simulations reveal that MCs exhibit highly complex, filamentary structures driven by the interplay of gravity, turbulence, and magnetic fields (Schneider & Elmegreen 1979; Menshchikov et al. 2010). Gravity plays an important role in MC evolution on multiple physical scales (Heyer et al. 2009; Kauffmann et al. 2013) and is particularly significant, as it governs the formation and growth of dense gas structures. However, quantifying its influence is not straight forward, as is also the case for the rest of the factors that contribute to the dynamics and kinematics of MCs. Observational data alone isn't enough to provide a clear picture of the role of gravity. Observational constraints, projection effects, and theoretical obstsacles call for the development of better methods for analysis of the data (Beaumont et al. 2013).

In this paper we use the G-Virial method (Guang-Xing Li et al., 2015) to analyze the structures of two prominent MCs: Perseus and Orion A. Our goal is to reproduce the results of Guang-Xing Li et al. (2015) for some of the regions in Perseus and apply the method to a set of entirely new regions for which the method has not been tested. We aim to quantify the gravitational bounedness of said regions and to establish whether these gravitationally coherent structures follow Larson's relations.

The structure of the paper is as follows: Section 2 details the G-Virial method, Section 3 describes the data we have used, Section 4 discusses the results, and Section 5 provides a summary.

2. THE METHOD G-VIRIAL

Up until now the analysis of gravity in MCs has been done via the virial parameter (α_{vir}) as defined by Bertoldi & McKee (1992). It is derived from the Virial Theorem and is a measure of the balance between gravitational potential energy and kinetic energy for a given region. The most common form of the equation is:

$$\alpha_{vir} = \frac{Gm}{5\sigma_v^2 r}$$

where G gravitational constant; m mass of the system of particles; σ_v the velocity dispersion; r size of the system.

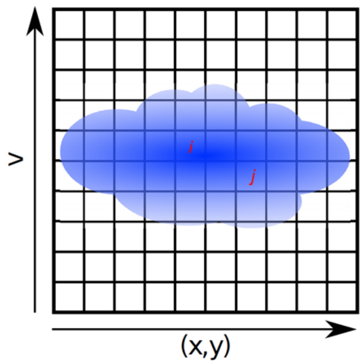

Figure 1: (x,y) represents the spatial dimensions and v represents the velocity dimension. The mass distribution is represented in blue. For each voxel i its total gravitational boundedness can be determined by adding up the gravitational boundedness to all the voxels j (not excluding i). Source: Guang-Xing Li et al. (2015)

There are two main issues with this approach: (1) the virial parameter is defined locally, so it provides no information on the effect the surrounding medium has on the region; (2) it requires geometric assumptions about the size and shape of the region which then inform how we determine its mass and velocity dispersion.

The G-Virial method provides an approach to overcome these and other challenges by calculating the gravitational boundedness between voxels in a 3D Position-Position-Velocity (PPV) data cube (Figure 1), resulting in a 3D map of the gravitational boundedness which allows one to define gravitationally coherent regions (GCRs). In essence, it aims to redefine what a region is, based on the gravitational interaction.

The gravitational boundedness of voxel i with respect to voxel j is defined as:

$$I_{j\to i} = \frac{Gm_j}{\delta r_{ij}\, \delta v_{ij}^2}$$

where G gravitational constant; m_j mass of the j-th voxel in the PPV space; δv_{ij} the velocity difference between voxels i and j; δr_{ij} distance between voxels i and j.

The G-Virial parameter is the total gravitational boundedness. For a discrete density distribution it is defined as:

$$\alpha^{i}_{G-virial} = \sum_j I_{j\to i} = G\sum_j \frac{m_j}{\sqrt{(x_i-x_j)^2+(y_i-y_j)^2\,(v_i-v_j)^2+c_0^2}}.$$

This sets up the G-Virial parameter as a generalized version of the the virial parameter.

The method has three main aims: (1) to provide a new way of selecting regions within MCs; (2) to provide a quantitative analysis of the global gravitational boundedness of MCs within a PPV space without assuming any geometry; (3) to provide a quantitative analysis of the properties of GCRs within MCs.

For more information we refer the reader to the original paper (Guang-Xing Li et al., 2015).

3. DATA USED

For this study, we utilized ^{13}CO maps from the COMPLETE survey (Ridge et al., 2006) and Bell Laboratories (Bally et al., 1987) for two MCs: Perseus and Orion A. These regions were selected due to their well-studied properties. Additionally, Perseus was selected due to it being one of the original MCs that Guang-Xing Li et al. (2015) applied the method to. Table 1 provides key physical information for the MCs and technical details of the observational data.

Table 1: Basic Parameters and Observational Data for Perseus and Orion A

	Perseus	**Orion A**
Data source	COMPLETE Survey	Bell Laboratories
Instrument	FCRAO Radio Telescope (14 m)	7m Telescope
Beam FWHM	46 arcsec	60 arcsec
Spectral Resolution	0.067 km/s	0.27 km/s
Studied subregions	B1, B3, NGC 1333, IC348, etc.	M42, L1640, NGC 1918, etc.
Distance	250 pc	400 pc
Mass	$10^4\,M_\odot$	$10^5\,M_\odot$

4. RESULTS AND DISCUSSION

To identify GCRs, the Dendrogram method (Rosolowsky et al. 2008) was applied. This algorithm is well-suited for a hierarchical contour-based region segmentation. It enables us to isolate gravitationally coherent clumps in the G-Virial map. Figure 2 shows a panel of the ^{13}CO maps with the dendrogram-derived regions highlighted.

4. 1. G-VIRIAL

The first result is shown in Figure 3 (left). The graph reveals the amount of mass enclosed within a contour of a given threshold of gravitational boundedness. A clear

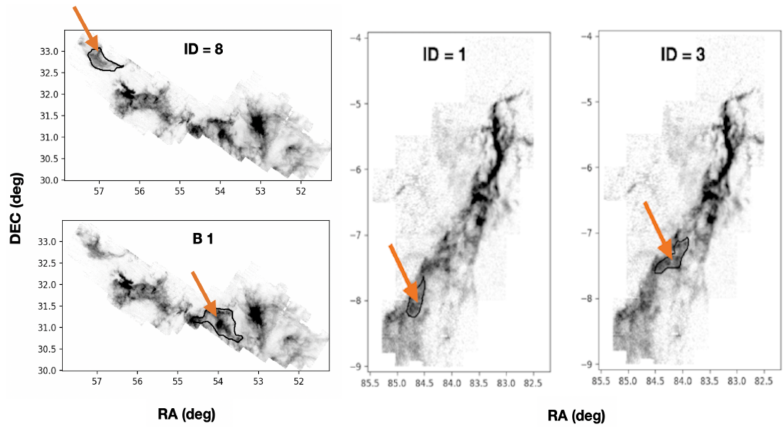

Figure 2: GCRs in the MCs Perseus (left) and Orion A (right), obtained by applying the dendrogram method to the maps of gravitational boundedness. The 2D projections of these regions are outlined with contours on the integrated ^{13}CO(1-0) map. Arrows indicate the contour boundaries of the dendrogram objects.

trend emerges: for smaller values of gravitational boundedness, the contours enclose increasingly larger amounts of mass. This result is entirely expected, as greater mass should naturally imply a more pronounced role of kinetic energy that resists gravity and upholds the structure. In other words, Larson's relations begin to appear here, even if not explicitly demonstrated. We also find that Orion A is characterized with higher values of boundedness than Perseus due to its cluster forming subregions.

The next result (Figure 3, right) concerns the profiles of gravitational boundedness. The G-Virial parameters radial gradient reflects increasing gravitational significance toward the centers of GCRs. Once again, the results are as expected gravitational boundedness decreases with increasing size. This is again an indication of adherence to Larson's relations. Here there are a few interesting lines of thought that would be valuable to explore in future studies. For different curves, it seems possible for one to define asymptotes, which can be interpreted as the maximum size of the gravitationally coherent region. Some curves show a distinct plateau, indicating a regime of constant gravitational boundedness, followed by the beginning of a decline. The start of this decline might be interpreted as a cut-off radius - the point where the surrounding medium begins to have a significant effect. Naturally, these are speculations and will require further verification.

4. 2. LARSON-TYPE RELATIONS

A crucial aspect of MC structure analysis lies in investigating mass-radius and velocity dispersion-radius scaling - Larson's empirical relations. In Figure 4 we explicitly verify whether the identified regions adhere to these relations. We have plotted Larsons relations as formulated by Larson himself and by Kauffmann, who suggested an adjustment to the power-law index for more massive objects.

It is clear that the identified regions follow Larsons relations, as expected from general physical considerations. The differences result from the differing methods

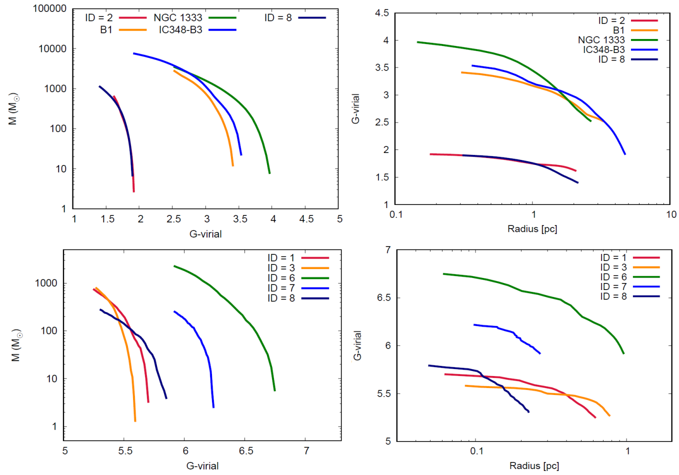

Figure 3: Amount of mass enclosed within a contour with the corresponding threshold value of the gravitational boundedness (left) and profile of the gravitational boundedness (right) in Perseus (top panel) and Orion A (bottom panel).

used to define the regions. In our case, we are examining GCRs that consider only the role of gravity.

5. SUMMARY

This study of Perseus and Orion A confirms that the G-Virial method effectively maps GCRs and complements traditional virial parameter calculations. The G-Virial method successfully circumvents the need for geometric assumptions and gives us the ability to coherently study the role of gravity in MCs on a global scale.

Our analysis reveals that: (1) for all GCRs the gravitational boundedness increases towards the center; (2) GCRs associated with star clusters are characterized with higher values of gravitational boundedness; (3) GCRs in both clouds obey the Larson relations; (4) Orion A is characterized with higher values of boundedness than Perseus.

Future work could extend this analysis to a broader range of MCs across the galaxy and a broader range of characteristics.

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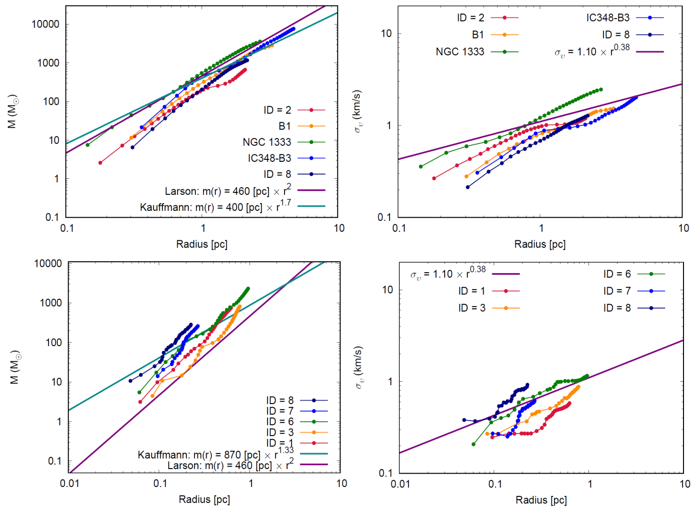

Figure 4: Mass-size relation (left) for the GCRs identified in Perseus (top) and Orion A (bottom). Larson's (1981) and Kauffmann et al. (2010b) scaling relations are added. Velocity dispersion-size relation (right).

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