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MODELLING THE GENERAL STRUCTURE AND PHYSICAL DESCRIPTION OF CLUMPS IN STAR-FORMING MOLECULAR CLOUDS

TODOR VELTCHEV, ORLIN STANCHEV, LYUBOV MARINKOVA,
MARIYANA BOGDANOVA

Department of Astronomy

Тодор Велчев, Орлин Станчев, Любов Маринкова, Марияна Богданова. МОДЕЛИРАНЕ НА ОБЩАТА СТРУКТУРА И ФИЗИЧНО ОПИСАНИЕ НА СГЪСТЯВАНИЯ В ЗВЕЗДООБРАЗУВАЩИ МОЛЕКУЛЯРНИ ОБЛАЦИ

Правим обзор на текущата работа на групата по звездообразуване към Физическия факултет на Софийския университет. Тя е фокусирана върху структурата и физиката на молекулярните облаци. Разработваме два основни подхода: i) моделиране на общата структура на облака, проследена на различни абстрактни пространствени скали или описана чрез статистически величини; и ii) отделяне и физичен анализ на свързани обекти/структури като сгъстявания, ядра и влакнести структури. Освен това моделираме масовото разпределение на сгъстяванията и изучаваме възмосжните връзки с началната функция на звездните маси.

Todor Veltchev, Orlin Stanchev, Lyubov Marinkova, Mariyana Bogdanova. MODELLING THE GENERAL STRUCTURE AND PHYSICAL DESCRIPTION OF CLUMPS IN STAR-FORMING MOLECULAR CLOUDS

We review the current research of the Star formation group at the Sofia University, Faculty of Physics. It is focused on the structure and physics of molecular clouds. Two main approaches are developed: i) modelling of general cloud structure as traced at various abstract spatial scales or described by statistical quantities; and ii) delineation and physical analysis of contiguous objects/substructures like clumps, cores and filaments. Additionally, we model the mass distribution of clumps and study its possible link to the stellar initial mass function.

Keywords: star formation, molecular clouds, clumps, scaling relations, density distribution
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For contact: Lyubov Marinkova, Department of Astronomy, Faculty of Physics, Sofia University “St. Kliment Ohridski”, 5 James Bourchier Blvd., Sofia 1164, Phone: +359 2 8161414, E-mail: ln@phys.uni-sofia.bg

1. INTRODUCTION

Contemporary theory of star formation (SF) is supported by observational and numerical studies of the interstellar medium (ISM) in the Galaxy. Of crucial significance is to understand the formation and evolution of molecular clouds (MCs). Observational evidence testifies that stars are born in MCs whose sizes and mean densities vary in large ranges 0.1–100 pc and 1–10^5 cm^{-3}, respectively. Typical sites of star formation (SF) are dense regions in MCs [1], [2], often associated with young stellar objects, wherein local gravitational instability leads to collapse and/or fragmentation and formation of protostellar cores. According to the modern paradigm in the SF theory, such condensations result from shocks, generated by supersonic turbulent flows (see [3], for a review).

The early MC evolution, prior to subsequent processes of active star formation, allows for simplified physical modelling due to lack of feedback from the emerging stars. Recent numerical simulations shed light on this epoch [4], [5]. Its characteristic stages could be summarized as follows: (i) convergent flows in the warm neutral medium lead to local compressions and non-linear instabilities; (ii) turbulent domains (clouds) of cold molecular gas form in the dense regions; (iii) self-gravity in the cloud takes slowly over and local sites of gravitational collapse emerge, and (iv) global contraction of the cloud starts (for a review, see [3], [6]). Thus the main contributors to the energy budget of evolving MCs are gravity and turbulence while magnetic fields and thermal pressure may play also a significant role in some cases.

We apply two main approaches for physical investigation of MCs. The first one focuses on their *general structure* as traced at various abstract spatial scales or described by statistical quantities. The second approach deals with *contiguous objects/substructures* (e.g. clumps, cores, filaments) in MCs and derivation of their physical characteristics: size, mass, velocity dispersion etc.

Often used tools for description of cloud's general structure are scaling relations of basic physical quantities. The one of velocity dispersion results from the theory of incompressible turbulence, developed by Kolmogorov [7]. Hierarchy of scales and cascade of the kinetic energy in them, predicted in the Kolmogorov's theory, are present in the cold ISM. As early as four decades ago, Larson [8] found scaling relation of velocity and mean density of MCs and their fragments, called 'Larson's first and second laws:

$$u \sim L^{\beta}\ , \tag{1}$$

$$<n> \sim L^{\alpha}, \tag{2}$$

where L is the spatial scale (or, effective size of the fragment), u is the *rms* velocity dispersion and $<n>$ is the mean density. Typical values are: $\beta \sim 0.41$–0.43 and $\alpha \sim -1$. Another indicator of the general MC structure is the probability density function (pdf) of density (ρ-pdf) and column density (N-pdf). Its typical shape at an early stage of cloud evolution is lognormal, conditioned mainly by turbulence [9], whereas a power-law (PL) tail develops as gravity is taking over in the denser zones/cores of the cloud [10].

Clump-finding algorithms have been put to test with the advance of numerical simulations of MC evolution. Clump properties depend essentially on how the entire population is considered: as a set of independent entities or as a hierarchy in the *position–position–position* (PPP) / *position–position–velocity* (PPV) space. A widely used technique for non-hierarchical clump extraction is CLUMPFIND [11]. One hierarchical method for clump delineation is the DENDROGRAM technique [12], which traces the segmentation of cloud structures as one increases the threshold intensity. Yet projection effects can be misleading in studies of cloud hierarchy. One can reduce them by the use of the clump-extraction technique GAUSSCLUMPS [13]. This approach is neither purely hierarchical, nor purely non-hierarchical, but inherits advantages of both approaches.

The mass distribution of clumps called clump/core mass function (CMF) is considered as a clue to the longstanding problem of the stellar initial mass function (IMF). Indeed, the correspondence between the CMF and the IMF is well established from observations of nearby star-forming regions. It is well known that the high-mass IMF slope, originally estimated to be Γ=–1.3 [14], seems to be universal with variations within ±0.5 in some regions of active star formation (see [15] for a review).

2. DESCRIPTION OF GENERAL STRUCTURE OF MCs

The existence of mass–density relationship $n \sim m^x$ in molecular cloud condensations (clumps) was first suggested in [16]. It has been studied in [17] and [18], considering various equipartition relations between their gravitational, kinetic, internal and magnetic energies. Due to the turbulence and the dynamics of the ISM, such a relationship has a statistical significance and therefore a statistical approach was chosen – clumps are described statistically, with a density distribution that reflects a lognormal probability density function in turbulent cold interstellar medium. The clump mass–density exponent x derived at different scales L varies in most of the cases within the range $-2.5 \leq x \leq -0.2$, with pronounced scale dependence and in consistency with observations. When derived from the global size–mass relationship for set of clumps, generated at all scales, the clump mass–density exponent has typical values $-3.0 \leq x \leq -0.3$ that depend on the forms of energy, included in the equipartition relations, and on the velocity scaling law, whereas the description of clump geometry is important when magnetic energy is taken into account.

Another approach to describe the general structure of MCs at early evolutionary stages in terms of their mass–size relationship $M \propto L\gamma$ was proposed in [19]. Sizes are defined through threshold levels at which equipartitions between gravitational, turbulent and thermal energy $|W| \sim f(E_{kin} + E_{th})$ take place, adopting interdependent scaling relations of velocity dispersion and density and assuming a lognormal density distribution at each scale.

Ballesteros-Paredes [20] demonstrated that in case of equipartition between gravitational and kinetic energy the scaling indices α and β are interdependent:

$$\beta = \frac{\alpha + 2}{2} \quad (3)$$

Variations of the equipartition coefficient $1 \leq f \leq 4$ allow for modelling of star-forming regions at scales within the size range of typical MCs (4 pc). Best fits are obtained for regions with low or no star formation (Pipe, Polaris) as well for such with star-forming activity but with nearly lognormal distribution of column density (Rosette). An additional numerical test of the model suggests its applicability to cloud evolutionary times prior to the formation of first stars.

When mass–size relationships are derived through imposing extinction or column density thresholds, the plausible slopes at small scales are ≤ 2, in view of the properties of the extinction/column density pdf [21]. This is illustrated also by observational mass–size relationships for a region with (Rosette, Pipe) and without star-forming activity (Polaris). Such slopes can be reproduced by models with β = 0.33 as shown in fig. 1.

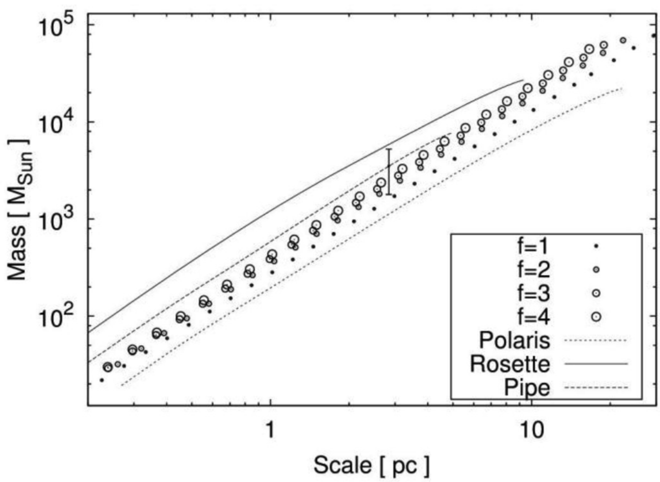

Fig. 1. Mass–size relationships from models with β = 0.33 [19] compared with those of 3 Galactic star-forming regions, derived from Planck observations. Typical uncertainties of the mass estimates due to uncertainties or gradients of distance to/within given region are shown

Stanchev et al. [22] presents an analysis of N-pdfs in different zones of the star-forming region Perseus and its diffuse environment based on the map of dust opacity at 353 GHz available from the Planck archive. The pdf shape can be fitted by a combination of a lognormal function and an extended power-law tail at high densities, in zones centered at the molecular cloud Perseus. A linear combination of several lognormal fits very well the N-pdf in rings surrounding the cloud or in zones of its diffuse neighborhood. Analysis shows that the slope of the mean-density scaling law $\langle\rho\rangle_L \propto L^{\alpha}$ is steep ($\alpha = -1.93$) in the former case and rather shallow ($\alpha = -0.77 \pm 0.11$) in the rings delineated around the cloud (fig. 2).

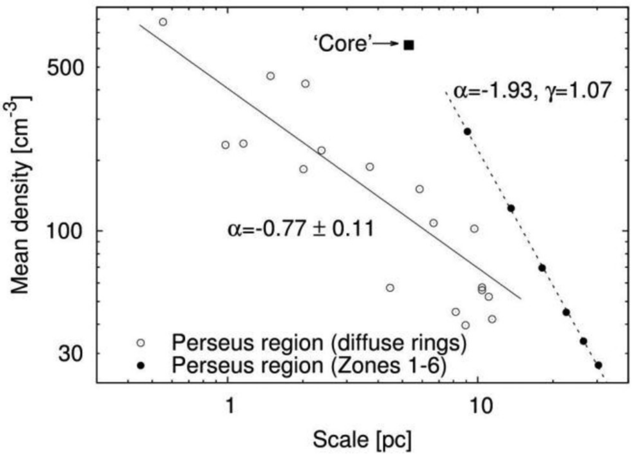

Fig. 2. Power-law scaling of mean density in the Perseus region and in its diffuse rings, obtained in [22]. The slope in the former case was derived excluding the cloud 'core' (square)

The paper interprets these findings as signatures of two distinct physical regimes: (i) a gravoturbulent one which is characterized by nearly linear scaling of mass and practical lack of velocity scaling; and (ii) a predominantly turbulent one which is best described by steep velocity scaling and by invariant for compressible turbulence $\langle\rho\rangle_L u_L^3/L$, describing a scale-independent flux of the kinetic energy per unit volume through turbulent cascade. The gravoturbulent spatial domain can be identified with the molecular cloud Perseus while a relatively sharp transition to predominantly turbulent regime occurs in its vicinity.

The concept of a class of equivalence of molecular clouds represented by an abstract spherically symmetric, isotropic object is introduced in [23]. This novel notion allows one to study a set of clouds (possibly with different morphology and physics), characterized by a single pdf of density, single total size, single size of the dense cloud core, density of the core and density at the cloud's edge. This object is described by use of abstract scales in respect to a given ρ-pdf. Mass and average density are ascribed to each scale and thus are linked to the density distribution: a power-law type and an arbitrary continuous one. In the latter case, a differential relationship is derived between the mean density at a given scale and the structure parameter that defines the mass-density relationship. The two-dimensional (2D) projection of the cloud along the line of sight is also investigated. Scaling relations of mass and mean density are derived in the considered cases of power-law and arbitrary continuous distributions. The paper obtains relations between scaling exponents in the 2D and 3D cases. The proposed classes of equivalence are representative for the general structure of real clouds with various types of column-density distributions: power law, lognormal or combination of both.

The proposed MC classes of equivalence as characterized by the scaling of the structure parameter x are representative for the general structure of real clouds with various types of N-pdfs: PL, lognormal or combination of both. In the case of PL pdf, the predicted values of x lead to mass functions of prestellar cores with slopes larger than the Salpeter value (−1.35) but close to it within the observational uncertainties.

3. PHYSICAL STUDY OF SUBSTRUCTURES IN MCs

Contiguous substructures of MCs are delineated on maps from several observational tracers: molecular-line emissions, dust-continuum emission and dust extinction. Spatial association of clumps from different tracers turns out to be a valuable tool to determine the cloud physical properties. Veltchev et al. [24] studies the spatial association between clump populations, extracted by use of the GAUSSCLUMPS technique from ^{12}CO (1–0) and ^{13}CO (1–0) line maps and *Herschel* dust-emission maps of the star-forming region Rosette, and analyse their physical properties. All CO clumps that overlap with another CO or dust counterpart are found to be gravitationally bound (fig. 3) and located in the massive star-forming filaments of the molecular cloud. They obey a single mass–size relation with $\gamma \sim 3$ (implying constant mean density) and display virtually no velocity–size relation. The interpretation is that their population represents low-density structures formed through compression by converging flows and still not evolved under the influence of self-gravity. The high-mass parts of their clump mass functions are fitted by a power law $dN_{cl} / d \log M_{cl} \propto M_{cl}^{\Gamma}$ and display a nearly Salpeter slope $\Gamma \sim -1.3$. On the other hand, clumps extracted from the Herschel map exhibit a shallower mass–size relation with $\gamma = 2.5$ and mass functions with very steep slopes $\Gamma \sim -2.3$ even if associated with CO clumps. They trace density peaks of the associated CO clumps at scales of a few tenths of pc where no single density scaling law should be expected.

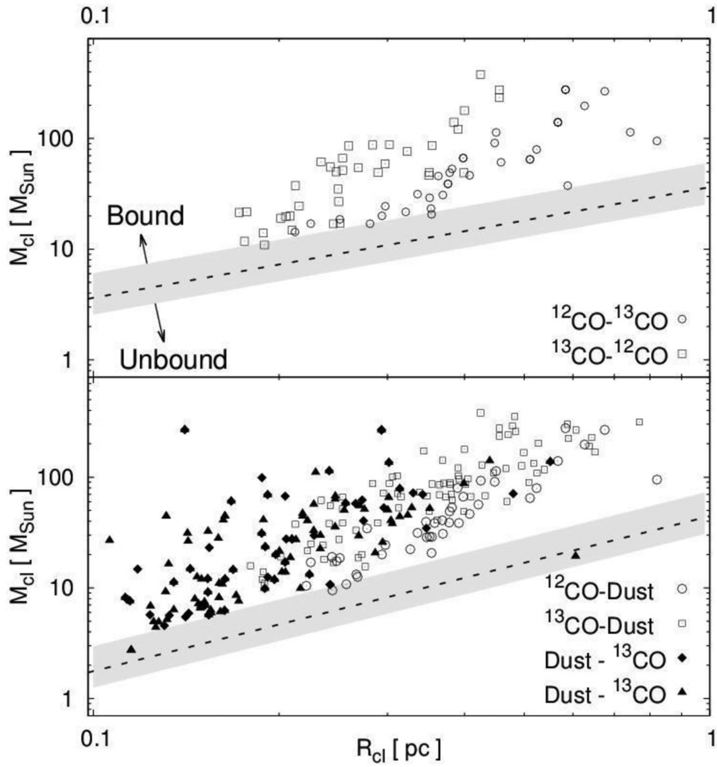

Fig. 3. Virial analysis of the associated populations from mass–size diagrams [24]

4. SEMI-ANALYTICAL MODELLING OF THE CMF AND ITS RELATION TO THE IMF

The mass function of clumps formed through a turbulent cascade over a range of spatial scales $L \leq 20$ pc during early, predominantly turbulent evolution of a MC is derived in [25]. Clumps are considered as ensembles of objects in a state of equipartition between gravity and other forms of energy and obeying a power-law mass–density relationship $n \propto m^x$ (Section 2) with a scale dependence of the exponent x. The functional form $x = x(L)$ is determined by the chosen equipartition relation and the free parameters of the model: velocity scaling index $0.33 \leq \beta \leq 0.65$ (eq. 1) and turbulent forcing parameter $0.33 \leq b \leq 0.55$ [26]. The clump mass distribution at a fixed scale was obtained from the assumed lognormal density distribution and then the composite CMF was derived by superposition of the clump mass distributions generated at the various different scales, assuming self-similar cloud structure. The derived CMF could be represented by series of two or three power laws, depending on the chosen equipartition relation, the velocity scaling index and the type of turbulent forcing. The high-mass CMF can be fitted by a power law of average slope $\Gamma \sim -1$, typical for fractal clouds [27], with some variations when magnetic energy is included in the energy balance of the clumps. When derived from a 'virial-like' equipartition between the gravitational ($|W|$) and turbulent energy (E_{kin}) without ($|W| \sim 2E_{kin}$) or with accounting for the thermal component of the velocity ($|W| \sim 2E_{kin} + 2E_{th}$), the intermediate-mass CMF could be represented by a single power law of slope $\Gamma \sim -0.65$, in agreement with some observational CMFs. Increase of the contribution of turbulent ($|W| \sim 4E_{kin}$) or magnetic energy ($|W| \sim 2E_{kin} + E_{mag}$) against gravity in the clump energy balance leads to an intermediate-mass CMF which is a combination of two power laws, except in the case of large velocity scaling index ($\beta > 0.50$). The slope of the steeper part varies in a narrow range $-0.7 > \Gamma > -0.9$ depending on the adopted equipartition. The other power law tends to flatten in case of purely solenoidal turbulent forcing ($b = 0.33$) and even has a positive slope when the equipartition $|W| \sim 2E_{kin} + E_{mag}$ is adopted.

The statistical approach for CMF derivation from [25] is put to observational test through comparison with mass distributions of clumps from molecular emission and dust continuum maps of Galactic cloud complexes, obtained by various authors. The results indicate gravitational boundedness of the dominant clump population, with or without taking into account the contribution of their thermal and magnetic energy. The CMF can be presented by combination of two-power-law functions separated by a characteristic mass from about ten to hundreds of solar masses. The slope of the intermediate-mass (IM) CMF is shallow and nearly constant ($-0.25 > \Gamma_{IM} > -0.55$) while the high-mass (HM) part is fitted by models that imply gravitationally unstable clumps and exhibit slopes in a broader range ($-0.9 > \Gamma_{HM} > -1.6$), centered at the value of the stellar initial mass function ($\Gamma_{HM} > -1.3$, $\Gamma_{HM} < -1.3$).

An example of good fit of observational HM CMF through the model of [25] is shown in fig. 4. Nonweighted CMFs obviously fail to reproduce the observational one although the HM slope $\Gamma \sim -0.7$ is close to the estimate of [13]. The model is not applicable to fit the IM CMF because of the high lower mass limit of confidence.

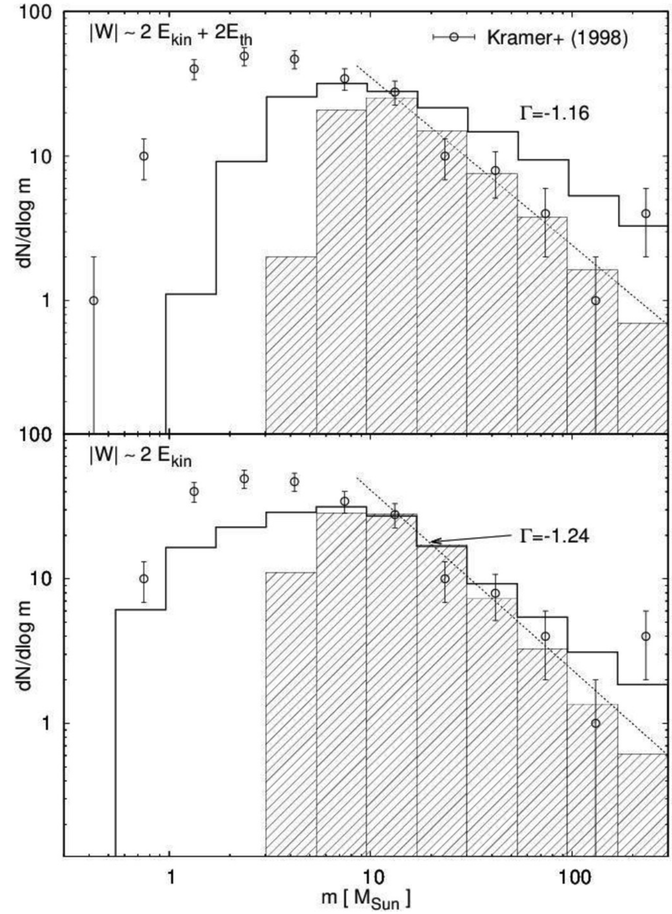

Fig. 4. Observational CMF of the Orion B complex [13] compared with the model of [18] for all (solid lines) and gravitationally unstable (hatched areas) clumps

The stellar IMF was derived in [16] from the superposition of mass distributions of dense cores, generated through gravoturbulent fragmentation of unstable clumps in MCs and growing through competitive accretion. MCs are formed by the turbulent cascade in the interstellar medium at scales L from 100 down to ~0.1 pc. Their internal turbulence is essentially supersonic and creates clumps with a lognormal distribution of densities n. Our model is based on the assumption of a power-law relationship between clump mass and clump density: $n \propto m^x$, where x is a scale-free parameter. Gravitationally unstable clumps are assumed to undergo isothermal fragmentation and produce protostellar cores with a lognormal mass distribution, centered around the clump Jeans mass. Masses of individual cores are then assumed to grow further through competitive accretion until the rest of the gas within the clump is being exhausted. The observed IMF is best reproduced for a choice of $x = 0.25$, for a characteristic star formation time-scale of $\sim$5 Myr and for a low star formation efficiency of $\sim$10 per cent.

5. SUMMARY

We developed a semi-analytical model of the IMF that takes into account the basic mechanisms in the SF process: gravoturbulent fragmentation and subsequent accretion on the pre-stellar cores. Then we built a theoretical substantiation of the clump mass–density relationship $n \propto m^x$ and for a plausible estimation of its exponent x.

By use of a statistical approach, we derived mass functions of condensations (clumps) which were formed through a turbulent cascade over a range of spatial scales $L \leq 20$ pc during the early MC evolution. The clump mass distribution at a fixed scale was obtained from the assumed lognormal density distribution and then the composite ClMF was derived by superposition of the clump mass distributions generated at the various different scales, assuming self-similar cloud structure.

We compared ClMFs from molecular line and dust continuum studies of Galactic cloud complexes with ones derived from our model applying alternative fitting criteria: fitting the structure $x(L)$ of individual complexes (when additional dust extinction data are available) or direct fitting of the observational ClMF.

Also, we proposed an approach to describe the general structure of MCs through a statistical object, labelled „class of equivalence“. This novel notion allows one to study a set of clouds (possibly with different morphology and physics), characterized by a single PDF of density, single total size, single size of the dense cloud core, density of the core and density at the cloud’s edge.

We presented an analysis of the column-density pdfs in the star-forming region Perseus and its diffuse environment using the dust opacity map at 353 GHz available from the Planck archive.

And finally, we studied clump populations extracted from ^{12}CO, ^{13}CO, and Herschel dust-emission maps of the RMC using the clump-extraction algorithm GAUSSCLUMPS. By performing a cross-identification (association) between the populations from different tracers and subsequent physical analysis, we can derive essential properties of the cloud structure.

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