FRAGMENTATION IN KINEMATICALLY COLD DISKS

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Abstract

Gravity is scale free. Thus gravity may form similar structures in self-gravitating systems on different scales. Indeed, observations of the interstellar medium, spiral disks and cosmic structures, reveal similar characteristics. The structures in these systems are very lumpy and inhomogeneous. Moreover some of these structures do not seem to be of random nature, but obey certain power laws.

Models of slightly dissipative self-gravitating disks show how such inhomogeneous structures can be maintained on the kpc-scale. The basic physical processes in these models are self-gravity, dissipation and differential rotation. In order to explore the structures resulting from these processes, local simulations of self-gravitating disks are performed in 2D and 3D. We observe persistent patterns, formed by transient structures, whose intensity and morphological characteristic depend on the dissipation rate.

Key words: Methods: numerical – Galaxies: structure, ISM – ISM: structure

1. Introduction

Molecular clouds reveal hierarchical structures, obeying power laws over several orders of magnitude in scale. Observations suggest, that the hierarchical structure of kinematically cold media is not only present in Milky Way molecular clouds, but is also found in other systems and on larger scales. Vogelaar & Wakker (1994) found, e.g., perimeter-area correlations in high-velocity clouds. Power-law power spectra were found in the Small and the Large Magellanic Cloud by Stanimirovic et al (1999) and Elmegreen et al. (2001), respectively. Furthermore, measurements of the HI distribution in galaxies of the M81 cluster reveal fractal structures on the galaxy disc scale (Westpfahl et al. 1999). The matter on cosmic scales is also hierarchically organized. A common feature of the ISM and the cosmic structure is, that the matter distribution can be characterized by a comparable fractal dimension. All this suggests, that a general scale free factor is mainly responsible for the matter distribution and the dynamics of cosmic structures, disks and molecular clouds. There is only one factor being able to have a dominant influence on all these scales, namely gravity. The local shearing sheet experiments of Toomre & Kalnajs (1991, hereafter TK) show that gravity in combination with shearing and dissipation can develop long-range correlations and maintain the system out of equilibrium. In order to study in detail the structures resulting from these processes on the kpc scale, we perform local simulations of self-gravitating disks in 2D and 3D. The third dimension becomes important as soon as a strong matter clumping causes a tight coupling of self-gravitating forces in the 3D equations of motion.

2. Local Model

2.1. Principle

In local models of disks, everything inside a box of a given size is simulated and more distant regions in the plane are represented by replicas of the local box. In such a model the orbital motion of the particles is determined by Hill's approximation of Newton's equation of motion (Hill 1878). In 3D they read

$$\begin{array}{lcll} \ddot{x} - 2\Omega_0\,\dot{y} &=& 4\Omega_0 A_0 x &+ F_x(x,y,z) \\ \ddot{y} + 2\Omega_0\,\dot{x} &=& & F_y(x,y,z) \\ \ddot{z} &=& -\nu^2 z &+ F_z(x,y,z)\,, \end{array} \qquad (1)$$

where $A_0 = -\frac{1}{2}\mathcal{R}_0(d\Omega/d\mathcal{R})_{\mathcal{R}_0}$ is the Oort constant of differential rotation and ν is the vertical epicycle frequency. F_x, F_y and F_z are local forces due to self-gravitating particles.

The local system is periodic in the y-direction and isolated in the z-direction. If we use an affine coordinate system whose pitch angle changes with time then the system is also in the y-direction periodic (Huber & Pfenniger 1999, 2001). Thus we can calculate the forces with the convolution method using the FFT algorithm. Thereby the computation time is reduced to be proportional to $N_\mathrm{c}\log(N_\mathrm{c})$, where N_c is the number of cells, taken here as proportional to the number of particles.

2.2. Weak Friction

To counteract the particle dynamical heating, TK proposed to add an ad-hoc friction term playing the role of the dissipative factors at work in the interstellar gas. Following TK we include linear friction terms as well. The friction terms should be weak in order to keep a quasi-Hamiltonian system. Indeed at the kpc scale the physics

Proc. Symposium *'The Promise of the Herschel Space Observatory'* 12–15 December 2000, Toledo, Spain
ESA SP-460, July 2001, eds. G.L. Pilbratt, J. Cernicharo, A.M. Heras, T. Prusti, & R. Harris

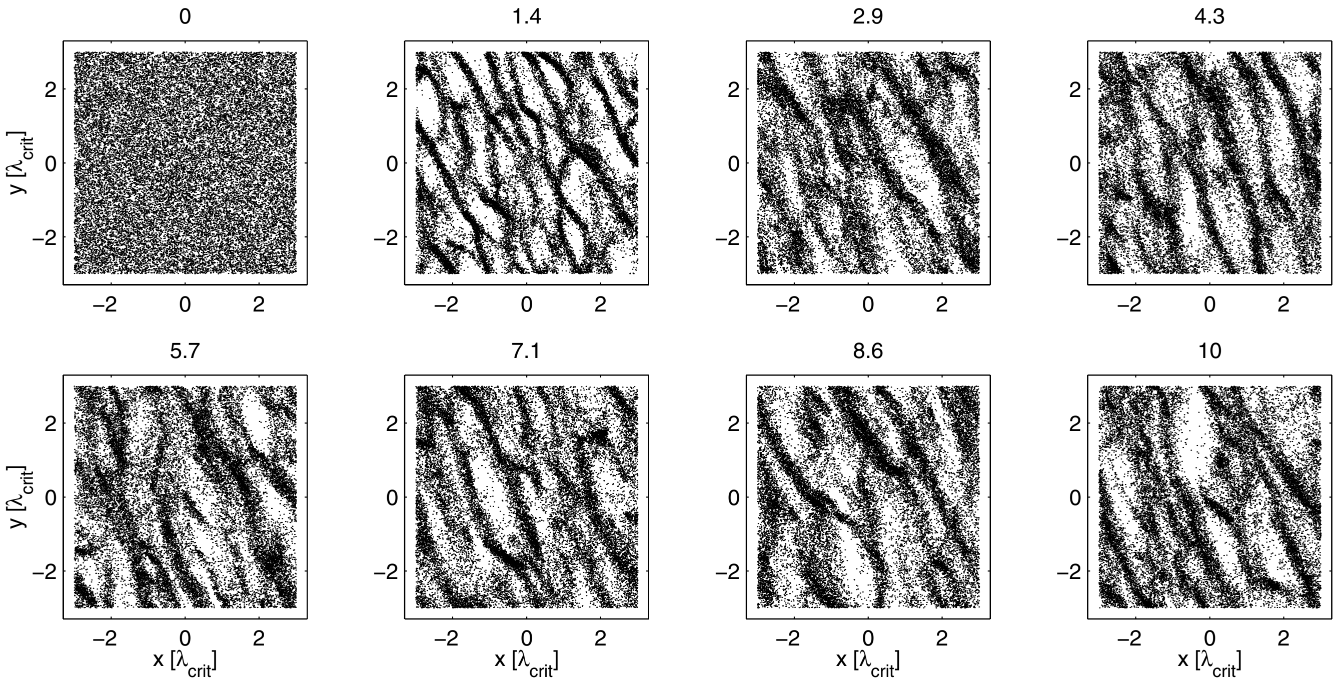

Figure 1. The evolution of the particle positions seen from above the galaxy plane. The structures result from a 3D simulation with a "weak" dissipation.

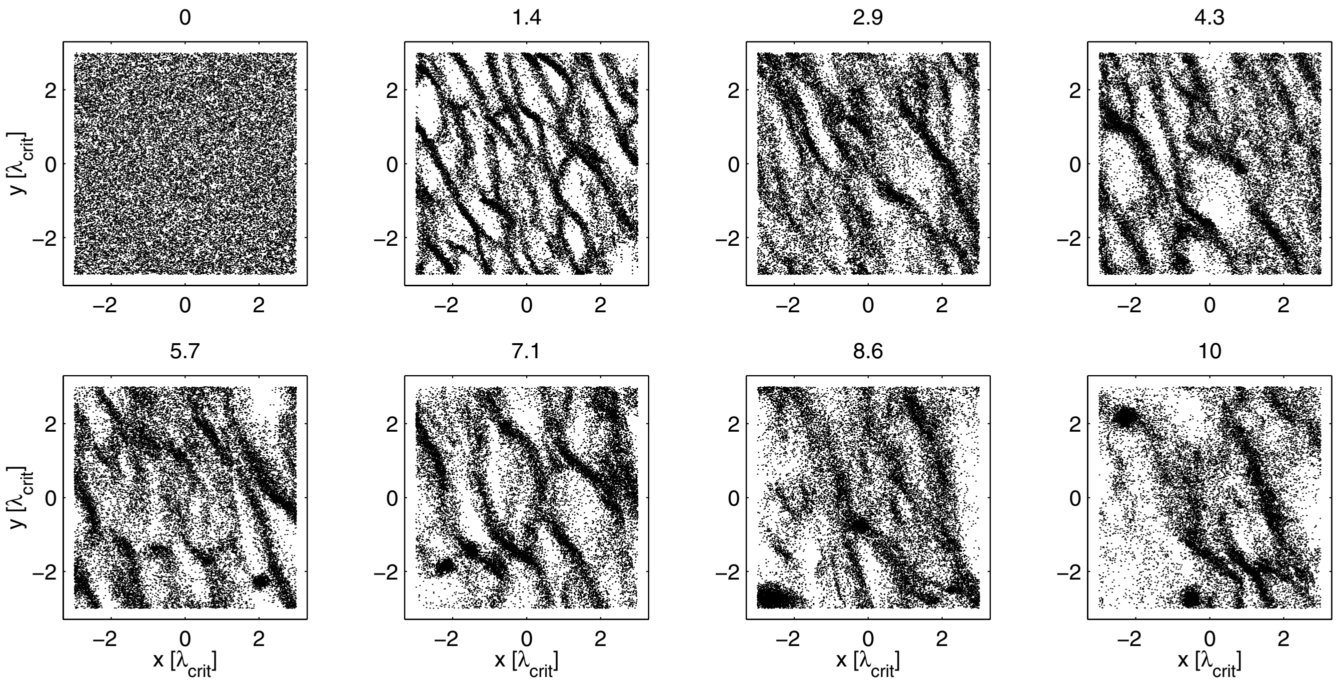

Figure 2. The evolution of the particle position, resulting from a simulation with a "middle" dissipation.

is still dominated by gravitational dynamics and its concrete behavior should be weakly dependent on the particular dissipative factors.

The linear friction terms $-C_x\dot{x}$ and $-C_z\dot{z}$ added to the radial resp. vertical forces (F_x, F_z) control the particle motions via Equation 1. There is no azimuthal friction in order to be consistent with a global angular momentum conservation.

2.3. Initial Conditions

We are interested in the secular time behavior of the galaxy disk. Thus we perform simulations for $t = 10$ galactic ro-

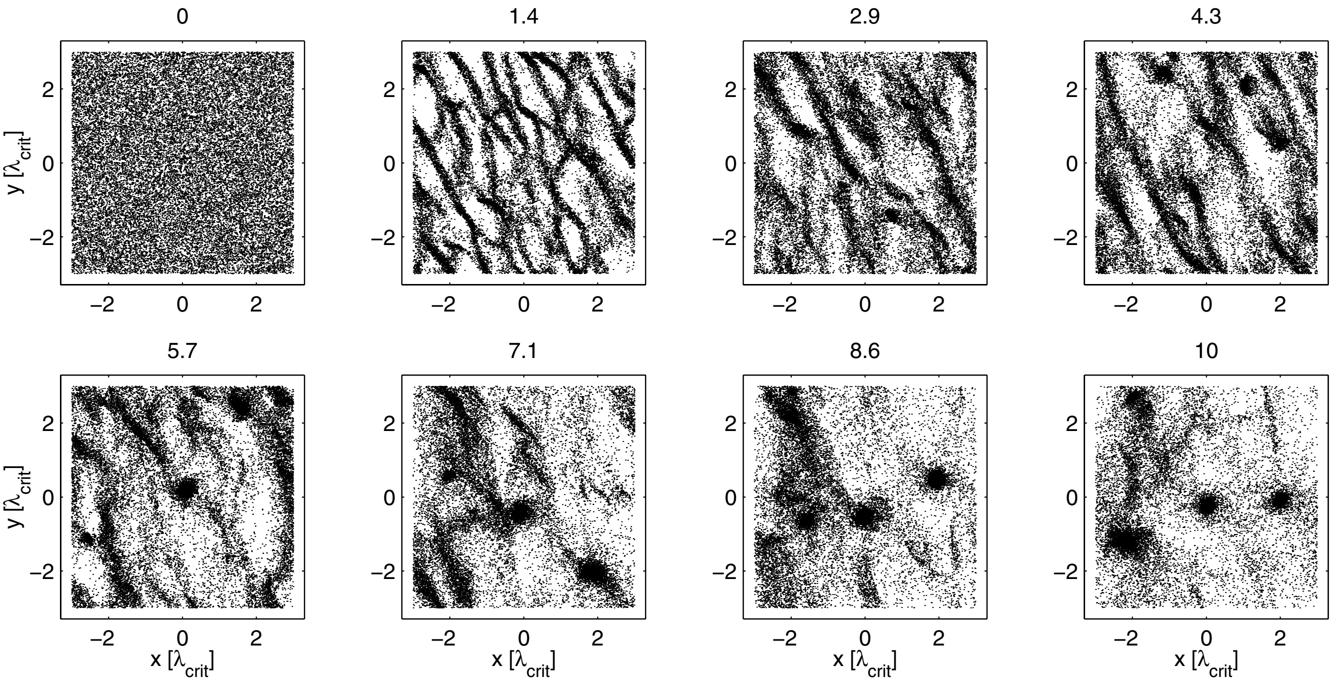

Figure 3. The evolution of the particle position, resulting from a simulation with a "strong" dissipation.

tations. In the initial state at $t = 0$ the particles are distributed uniformly in the x-y-plane. In the z-direction the particle distribution follows an isothermal law

$$\rho \propto \operatorname{sech}^2(z/z_0)\,, \tag{2}$$

where ρ is the density and z_0 is the disk scale height. The velocities at $t = 0$ are determined by the shear

$$\dot{x} = 0\,, \quad \dot{y} = -2A_0 x\,, \quad \dot{z} = 0 \tag{3}$$

and the Schwarzschild velocity ellipsoid

$$\begin{aligned} \sigma_x &= \frac{3.36 G \Sigma_0 Q}{\kappa} \\ \sigma_y &= \frac{\sigma_x \kappa}{2\Omega_0} \\ \sigma_z &= \sqrt{\pi G \Sigma_0 z_0}\,, \end{aligned} \tag{4}$$

where the Safronov-Toomre stability criterion is $Q \geq 1$.

3. Results

We present here some preliminary results of an extended study to this subject (Huber & Pfenniger 2001).

3.1. 3D shearing boxes

The structures resulting from shearing box simulations depend a lot on the relative strength of the competing gravitational and dissipation processes. Gravitational instabilities lead to a conversion of directed kinetic energy (shear-flow) into random thermal motion. In this way the disk is heated up. If the dissipation is too weak then initially arised structures can not be maintained and smear out quickly. If the dissipation is increased, a filamentary structure can be maintained in a statistical equilibrium. If we continue to increase the dissipation the filaments become denser and denser and clumps in filaments may be formed. If finally the dissipation dominates completely the heating process hot clumps, collecting almost all the matter of the simulation zone are formed out of the filaments. The change of the structure morphology for an increasing dissipation is showed in Figures 1-3. For convenience we call the dissipation strengths, leading to the presented structures, "weak", "middle"and "strong". The relative cooling times corresponding to these dissipation strengths are: $\tau_{\rm cool,1} : \tau_{\rm cool,2} : \tau_{\rm cool,3} : \tau_{\rm osc} = 16 : 15 : 14 : 1$, where $\tau_{\rm osc}$ is the period of the unforced epicyclic motion.

The simulations are carried out with 131040 particles, corresponding to a surface number density of $n = 3640\,\lambda_{\rm crit}^2$. The dynamical range is 1.8 dex. Only each forth particle is shown.

3.2. Mass-Size Relation

In order to characterize the structures resulting from the shearing box experiments, we determine the mass-size relation. We choose a representative set of particles and count for each particle the number of neighboring particles $N(R)$ inside a certain radius. If we repeat this for other values of R we can find the structure dimension $D(R)$ via

$$D(R) = \frac{d\ln(N)}{d\ln(R)}(R)\,, \tag{5}$$

where R denotes the scale. The mass-size relation is then

$$N(R) \propto M(R) \propto R^{D(R)}\,. \tag{6}$$

If the structure dimension is independent of the scale, $D = D_f$, i.e., if D is constant or oscillates around a mean value, then the mass-size relation is a power law,

$$M \propto R^{D_f} \ . \tag{7}$$

If furthermore D_f is non-integer, the structure is fractal. If however the structure dimension depends on the scale $D = D(R)$, the structure dimension may simply be regarded as a statistical measure describing the clumpiness at the corresponding scale.

In order to asses the general relevance of the underlying physical processes we check the structure for self-similarity, i.e., we check if $D = D_f$ for a certain scale range. However, one has to take into account that the structures result form a finite simulation, modeling a finite physical system. Thus the system can not be fractal beyond an upper and lower cutoff. An upper cutoff is given by the scale at which the system become periodic. A lower scale limit is due to the finite resolution of the simulation mesh.

Figure 4 shows the structure dimension of the mass distribution presented in Figures 1-3. The longer term evolution of the structure may be superimposed by fluctuations on time-scales of the order of $\sim 1/2\ \tau_{\rm rot}$, where $\tau_{\rm rot}$ is the time for a rotation around the galaxy center. In order to eliminate these fluctuations we indicate in this paper mean values of the structure dimension D determined during the last two rotations.

The structure dimensions are not constant over the corresponding dynamical range and are thus not fractal. However the structure dimension resulting from the simulation with the "middle" dissipation has a structure dimension $1.5 < D < 1.8$ over the whole dynamical range and remains smaller than 2 also on scales where the disk thickness becomes important. Thus the corresponding matter distribution can approximately be described by a power-law for the considered scale range. The structure dimension has a minimum at $R = 0.25\ \lambda_{\rm crit}$. The increase of the structure dimension at $R >| 0.25\ \lambda_{\rm crit} \mid$ may then be due to the lower and upper cutoff. A larger dynamical range may thus flatten the curve depicting the structure dimension. This supposition is supported by low resolution simulations showing a steeper increase of D beyond the minimum.

4. Conclusions

The structure resulting from the local simulations of self-gravitating disks can be homogeneous, filamentary or clumpy depending on the relative strength of the competing gravitational and dissipation processes. As long as the structure is mainly filamentary self-gravitation and dissipation ensure a statistical equilibrium, i.e., persistent patterns consisting of transient structures are formed. If the dissipative processes begin to dominate the evolution, the structures turn from filamentary to clumpy. During

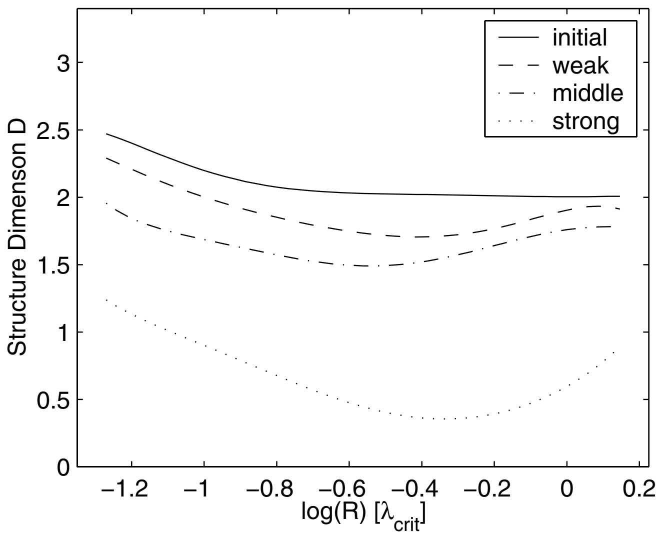

Figure 4. The structure dimension D of the mass distributions showed in Figures 1-3 as a function of the scale R. The corresponding simulations were carried out with a "weak", a "middle" and a "strong" dissipation, respectively. The solid line depicts the initial mass distribution. On large scales this state represents a 2D matter distribution, whereas on small scales it tends to $D = 3$.

the subsequent evolution the clumps become hotter and more massive. In general clumpy structures do not evolve towards a statistical equilibrium. However 2D simulations with a dynamical range of 2.5 dex show that it is also possible to establish persistent patterns formed by clumps.

A larger dynamical range produce in general a flatter structure dimension curve. However the scale range of the simulations is still too small to draw final conclusions about self-similarity in open, self-gravitating systems.

Acknowledgements

This work has been supported by the Swiss Science Foundation.

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