DYNAMICS OF COSMIC BODIES IN THE OPEN UNIVERSE

A.V. Kudinova[1], M.V. Eingorn[2], A.I. Zhuk[3]

[1] Department of Theoretical Physics, Odessa National University, st. Dvoryanskaya 2, 65082 Odessa, Ukraine, *autumnforever1@gmail.com*

[2] Department of Theoretical and Experimental Nuclear Physics, Odessa National Polytechnic University, Shevchenko av. 1, 65044 Odessa, Ukraine, *maxim.eingorn@gmail.com*

[3] Astronomical Observatory, Odessa National University, st. Dvoryanskaya 2, 65082 Odessa, Ukraine, *ai.zhuk2@gmail.com*

ABSTRACT. As it has been recently demonstrated, the mathematical model with the hyperbolic space (or, in other words, with the negative spatial curvature) is the most appropriate one for describing the inhomogeneous Universe at late stages of its evolution in the framework of the theory of scalar perturbations. In this model we develop a dynamic approach and investigate nonrelativistic motion of two, three and even more cosmic bodies against the cosmological background, perturbed locally by density inhomogeneities (namely, galaxies). For arbitrary initial conditions, we get solutions of equations of motion (trajectories), demonstrating the most important features of cosmological expansion, only slightly restrained by gravitational attraction. We use our methods for indirect observations of dark energy in the Local Group, analyzing the relative motion of the Milky Way and Andromeda galaxies. The numerical estimation of the time before their collision is obtained. Besides that we consider the Hubble flows anisotropy caused by the non-point mass distribution.

Key words: inhomogeneous Universe, Local Group, Hubble flows.

1. Introduction

In this paper we consider the Universe at the late stages of its evolution deep inside of the cell of uniformity. On these scales (less than $300Mpc$) the hydrodynamic approach of the cosmic bodies motion description is inappropriate, because the space is filled with discrete structures, such as galaxies, clusters of galaxies. The background metrics is Friedmann-Robertson-Walker (FRW) metrics:

$$ds^2 = a^2\left(d\eta^2 - \gamma_{\alpha\beta}dx^\alpha dx^\beta\right) =$$
$$= a^2\left(d\eta^2 - \frac{\delta_{\alpha\beta}dx^\alpha dx^\beta}{\left[1+\frac{1}{4}K\left(x^2+y^2+z^2\right)\right]^2}\right),$$

where $K = -1, 0, +1$ for open, flat and closed Universes, respectively. This isotropic and homogeneous background is perturbed by the discrete mass sources.

When analyzing the motion of non-relativistic objects we can write the expression for the perturbed metrics this way:

$$ds^2 \approx \left(1+\frac{2\varphi}{ac^2}\right)c^2dt^2 - a^2\gamma_{\alpha\beta}dx^\alpha dx^\beta .$$

For every $i-$th mass of the system the Lagrange function can be written:

$$L_i = -\frac{m_i\varphi_i}{a} + \frac{m_i a^2 v_i^2}{2},$$

where φ_i is the gravitational potential, and v_i is the comoving peculiar velocity. The gravitational potential is taken in the Newtonian approximation:

$$\varphi_i = -G_N\sum_{j\neq i}\frac{m_j}{|\mathbf{r}_i-\mathbf{r}_j|} .$$

Based on these expressions, we can analyze the motion of objects of arbitrary mass systems.

2. Cosmological "molecular" dynamics

In this section we will apply our mechanical approach to mass systems of different number of particles. We can build the system of Langrange equations. Adding the known initial conditions we can solve such systems numerically and analyze the trajectories of the cosmic bodies' motion in the case of the background cosmological receiding.

To start with, we consider the system of three test particles. The solution of the corresponding Lagrange equations can be visualized on the scheme.

Let us suppose the following initial conditions: $m_A = m_B = m_C = \overline{m}$ and $\tilde{X}_A|_{\tilde{t}=0} = 0$, $\tilde{Y}_A|_{\tilde{t}=0} = -1.5$,

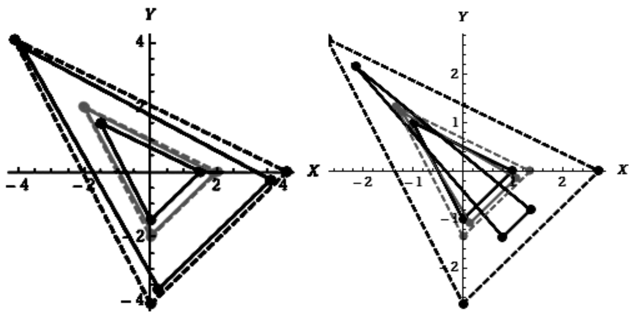

Figure 1: Dynamics of three points motion.

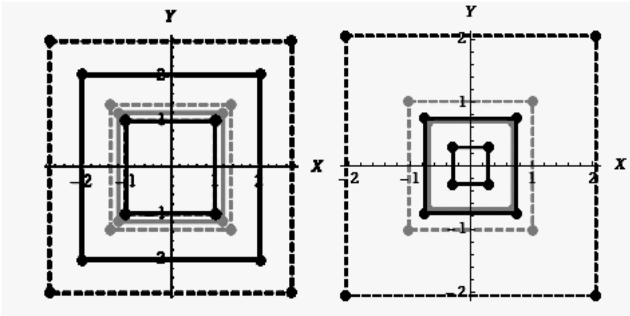

Figure 2: Dynamics of four points motion.

$\tilde{X}_B|_{\tilde{t}=0} = 1.5$, $\tilde{Y}_B|_{\tilde{t}=0} = 0$, $\tilde{X}_C|_{\tilde{t}=0} = -1.5$ $\tilde{Y}_C|_{\tilde{t}=0} = 1.5$, $d\tilde{X}_i/d\tilde{t}|_{\tilde{t}=0} = 0$, $d\tilde{Y}_i/d\tilde{t}|_{\tilde{t}=0} = 0$.

The red triangle with vertices $(0, -1.5)$, $(1.5, 0)$ and $(-1.5, 1.5)$ (see Figure 1, left part) showes the initial position of particles (at $\tilde{t} = 0$). Smooth (where both cosmological expansion and gravitational attraction are taken into account) and dashed (only cosmological expansion) green triangles illustrate the position of particles at $\tilde{t} = 1$, blue ones – at $\tilde{t} = 2$. Two different peculiarities of the motion can be seen on the above mentioned diagrams: smooth triangles are enclosed in the corresponding dashed triangles, meaning that gravitational interaction inhibits expansion. The second feature is that in the case of attraction absence the points A and B, located on the axes of coordinates, recede along the axes (point C recedes along the direction of its initial radius vector). This fact is confirmed by the constructed dashed triangles; in the presence of attraction the points do not recede along the coordinate axes (or along the initial radius vectors), which is confirmed by the smooth triangles.

If we change the initial conditions for the following $\tilde{Y}_A|_{\tilde{t}=0} = -1$, $\tilde{X}_B|_{\tilde{t}=0} = 1$, $\tilde{X}_C|_{\tilde{t}=0} = -1$ and $\tilde{Y}_C|_{\tilde{t}=0} = 1$, the test points will get closer to each other at $\tilde{t} = 0$, and the diagrams will take the form of the right part of Figure 1.:

There is a distinction in kind between these two situations. Gravitational attraction of points A and B predominate cosmological expansion between them, so they start to close in and will collide in the future. At the same time point C becomes gravitationally unbound, so it starts to move off.

The same procedure can be applied to the case of four test masses.

We make an assumption that $m_A = m_B = m_C = m_D = \overline{m}$ and $d\tilde{X}_i/d\tilde{t}|_{\tilde{t}=0} = 0$, $d\tilde{Y}_i/d\tilde{t}|_{\tilde{t}=0} = 0$. On the left side of the diagram (see Figure 2) at $\tilde{t} = 0$ the points form the square with verteces $(1, 1)$, $(1, -1)$, $(-1, -1)$ and $(-1, 1)$, on the right side of the diagram – with verteces $(0.75, 0.75)$, $(0.75, -0.75)$, $(-0.75, -0.75)$ and $(-0.75, 0.75)$.

The squares can be rebuilt with the different initial conditions.

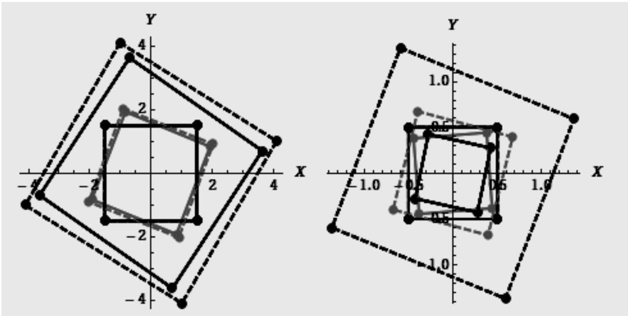

Figure 3: Dynamics of four points with initial non-zero velocities.

In this case the test points have the initial non-zero velocities. On the left side of the diagram (srr Figure 3) the points form the square with verteces $(1.5, 1.5)$, $(1.5, -1.5)$, $(-1.5, -1.5)$ and $(-1.5, 1.5)$ at $\tilde{t} = 0$, their velocities are $(0, -1)$, $(-1, 0)$, $(0, 1)$ and $(1, 0)$ correspondingly, on the right side of the diagram the verteces' coordinates are $(0.5, 0.5)$, $(0.5, -0.5)$, $(-0.5, -0.5)$ and $(-0.5, 0.5)$, velocities take the following values: $(0, -0.25)$, $(-0.25, 0)$, $(0, 0.25)$ and $(0.25, 0)$.

3. The collision between the Milky Way and Andromeda

Besides the illustrative examples we can apply our approach to some real mass systems. One of the most convenient and informative system of gravitating sources we can observe and analyze is the Local Group containing out galaxy, the Milky Way, Andromeda galaxy and some dwarf galaxies. Building the system of Lagrange equations for the system of two bodies, particularly, for M31 and M33 galaxies, we can describe the dynamics of the Milky Way and Andromeda collision and obtain the numerical estimation of the time before their collision. In the centre-of-mass system we can get the equation of motion in the following form:

$$\ddot{L} = -G_N \frac{m_A + m_B}{L^2} + \frac{M^2}{\mu^2 L^3} + \frac{\ddot{a}}{a} L$$

where L is the absolute value of the distance between the galaxies' centres.

The following plot illustrates the dynamics of the galaxies' approach:

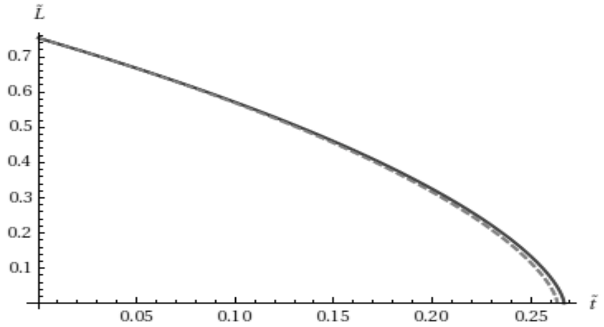

Figure 4: Dynamics of The Milky Way and Andromeda galaxies approach.

The collision of the Milky Way (of the mass $10^{12}\, m_\odot$) and Andromeda (of the mass $1.6 \times 10^{12}\, m_\odot$), located on the "physical" distance of 0.78 Mpc at the present time and approaching with the "physical" velocity 120 km/s, will occure in 0.2670 of Hubble time, i.e. 3.68 billion years. Without the gravitational attraction this collision will occure in 0.48 of Hubble time, i.e. 6.6 billion years. On the contrary, without taking into account the cosmological expansion, the collision will occur in 0.2636 of Hubble time, i.e. 3.63 billion years. Relative deviation of this estimation from the previous one is about 1,5 percent.

4. Hubble flow anisotropy

Dwarf galaxies in the Local Group form Hubble flows around the massive giant galaxies, the Milky Way and Andromeda. But the distance between these galaxies is significant enough to cause the flows anisotropy. We can consider the system of these two gravitating masses and analyze the acceleration of the test bodies in the resulting gravitational field.

We have built the 3D plot of the acceleration (see Figure 5). At the fixed moment of time it illustrates the spatial distribution of the acceleration value. Gravitating masses, the Milky Way and Andromeda galaxies, are placed in the centres of the plot peaks.

Besides that, we can visualize the localization of the zero-acceleration points (see Figure 6). Analysis indicates that there are no surfaces of zero-acceleration, but only the finite number of points of zero-acceleration. The yellow line on the plot shows

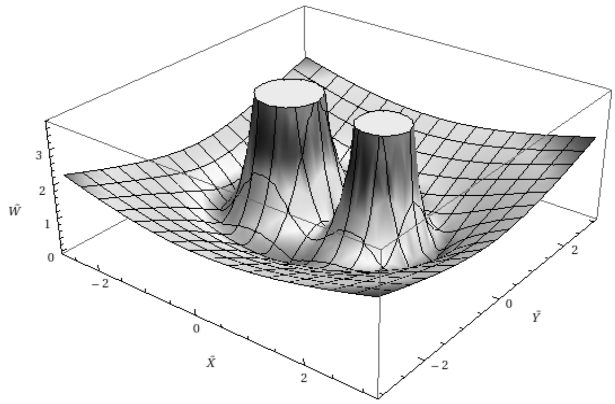

Figure 5: 3D-plot of the acceleration value in the Local Group.

the lines of the zero x-component of acceleration, the green line shows the line of the zero y-component of acceleration. Points of their intersection define the points of zero acceleration. Black points on the plot indicate the positions of the gravitating masses.

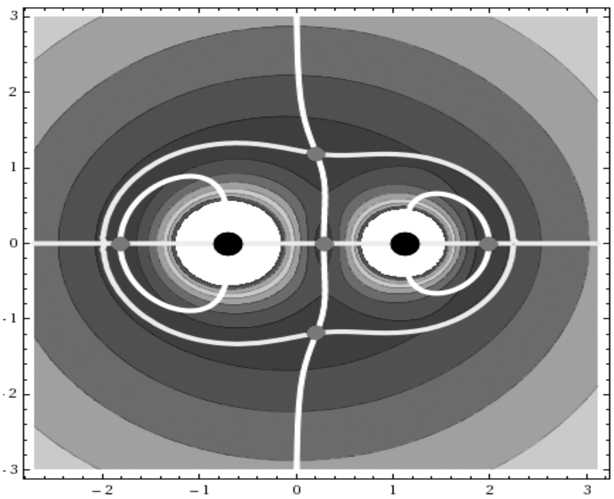

Figure 6: Points of the zero acceleration.

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