Interaction of the Dark-Matter Cusp with the Baryonic Component in Disk Galaxies

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Abstract—The influence of the formation and evolution of a (disk) galaxy on the matter distribution in the dark-matter halo is considered. Calculations of the evolution of an isolated dark-matter halo were carried out with and without including a baryonic component. N-body simulations (for the dark-matter halo) and gas-dynamical numerical simulations (for the baryonic gas) were used for this analysis. Star formation, feedback, and heating and cooling of the interstellar medium were taken into account in the gas-dynamical calculations. The results of these numerical simulations with high spatial resolution indicate that 1) including the star formation resolves the so-called cusp problem (according to CDM cosmological models, the density distribution in the central regions of the dark-matter halo should have a distinct peak (cusp), which is not shown by observations); 2) the interaction of the dark matter with dynamical substructures of the stellar–gas galactic disk (spiral waves, a bar) affects the shape of the dark-matter halo. In particular, the calculated dark-matter distribution in the plane of the disk is more symmetric when the baryonic component is taken into account.

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1. INTRODUCTION

On the whole, progress in our understanding of the formation and (early) evolution of galaxies has led to a fairly clear picture (see, e.g., [1–3]). According to modern CDM cosmological models, the development of density fluctuations resulted in the formation of gravitationally bound objects, the ensemble of which evolved hierarchically, i.e., in a “bottom-up” fashion. First, objects with the smallest masses were formed, with more massive structures then forming via the merging and accretion of these objects. These objects were formed from dark matter (DM), whose average density exceeded the density of the baryonic component by approximately a factor of ten. As a result, a large number of gravitationally bound objects (often called “dark matter halos”) with a wide range of masses were formed. The baryonic matter gradually collected in the potential wells formed by the gravitational effect of the DM halo and accumulated there, and it is precisely in these potential wells that the protogalaxies and first stars (Population III) formed, changing the chemical composition of the gas and enriching it in metals.

Because of the relatively small spatial scales of the Universe in early stages of its evolution (z = 10–30), the DM halos and baryonic gas in their central regions merged fairly rapidly, forming more and more large-scale structures. Later (z = 1–10), galaxies formed. Mergers of galaxies with similar sizes and masses (major mergers) occurred mainly up to z ~ 1–2. By approximately the same time, the “acquisition” of rotational angular momentum by galaxies had generally finished. Further, as a rule, if galaxies were in dense environments, they could experience only minor mergers with satellites having masses less than 10% of the galaxy’s mass. However, in spite of the obvious success of the theoretical approach (the construction of adequate models for the formation and evolution of galaxies), many questions arising from disagreements between theoretical conclusions (models) and the observed characteristics of galaxies remain unsolved. We list below some problems typical for cosmological models for the formation and evolution of disk galaxies.

- The DM density in the central regions of galaxies given by calculations is much higher than the observed density (the central cusp problem) [4].
- The mass–size relation derived in models of galaxies is considerably less well defined than the relation obtained from observations [5].
- In models, in general, galaxies without a central spheroid (bulge) are not formed [6].
Galaxies in models are only partially balanced by their rotation [7].

The number of satellites (small-mass galaxies in groups) derived from calculations is considerably higher than the observed value [8].

These problems are apparently connected partly with the fact that the typical spatial scale of processes determining the evolution of the baryonic matter (galaxies) is smaller than the scales on which the DM halos evolve ($\sim 10^2$–$10^3$ kpc), by several orders of magnitude. For a coherent approach, we must study the evolution of both the baryons and DM halo with the same (currently unachievably high) spatial resolution. It is impossible to use methods (grid, SPH, etc.) that are adequate for including processes such as the star formation, chemical enrichment of the interstellar gas, supernova explosions, heating and cooling of the gas, etc., even for galactic disks (scales of $\sim$10 kpc), since spatial scales of these processes generally do not exceed several parsecs. Therefore, modeling must be carried out in a “subgrid physics” approximation. In any case, enhancement of the resolution in models is an important means of refining the theoretical approach.

In our study, we considered the influence of formation and evolution of a (disk) galaxy on the matter distribution in a DM halo, paying special attention to the so-called cusp problem and the influence of the baryonic matter on the shape of the DM halo during the formation of the disk galaxy.

The central cusp problem is known to anyone who has tried to numerically model the evolution (of clumps) of DM and the formation of baryonic structures in these clumps. The heart of the problem is that the density $\rho$ goes to infinity at the halo center in numerical models, forming the so-called central cusp, but such cusp-like density distributions do not appear in observations. The density profile of the DM halo is described by the approximation $\rho \propto r^\alpha$ at $-1.5 < \alpha < -1$. For example, we have for the most commonly used NFW profile [9]

$$\rho \propto \frac{\rho_0}{(r/r_s)[1 + (r/r_s)^2]}$$  \hspace{1cm} (1)

where $r$ is distance from the center, $\rho_0$ and $r_s$ are parameters describing a specific halo, and $\alpha = -1$. However, the observed density distribution of stars corresponds to the density distribution in a DM halo with $\alpha > -1$, called a core-type distribution.

For comparison with observations, data on rotation curves (or velocity dispersions) in the central regions of dwarf galaxies are usually used (see, e.g., [10]). Dwarf galaxies are convenient objects for determining the density distribution of the DM halo, which dominates even in the central regions of these systems. However, observations also indicate core-type density distributions of the DM halos of more massive galaxies. For example, detailed rotation curves were constructed in [11] using the results of an Hα kinematic survey of 36 nearby spiral galaxies. Decomposition of the rotation curves of these galaxies favors a quasi-isothermal density distribution for the DM halo ($\alpha$ is closer to 0 than to $-1$, the value for the NFW distribution).

Of course, much research has gone into work on the cusp problem. Two basic types of approaches have been applied. In the first, the cusp problem is solved by taking the properties of DM into account. It was shown in [4, 12] that cosmological random motions of a matter “heat up” DM particles in the collapsing protohalos, leading to the suppression of cusp-like density profiles inside the forming halos and favoring the formation of DM cores in galaxies, making it possible to explain the difference between the galactic rotation curves that are observed and obtained in numerical simulations. It is noted in [4, 12] that the analytical conclusions made in this approach must be confirmed by numerical $N$-body models, which is possible when the spatial resolution of the central regions of the halo is enhanced.

The CDM model is treated as an ensemble of elementary particles with flavor mixing in [13], and computer modeling of the formation of the large-scale structure of the Universe carried out. It is shown that a mixed particle (i.e., a particle comprising a mixture of several flavors, such as a neutralino, for example) can gradually “evaporate” from a potential well, and that this type of DM model can simultaneously solve two serious problems of the standard CDM cosmology: the cusp problem and the lack of satellite galaxies.

In another (more widespread) approach, the influence of baryons accumulated in a potential well (due to DM) on the distribution and kinematics of the DM is considered. A number of authors [14, 15] have considered the post-evolution of DM under the influence of baryons in the $\Lambda$CDM approach. The baryonic matter affects the DM distribution through the influence of supernovae and/or dynamical friction. Of course, some time (1–2 Gyr) after the formation of a galaxy is needed for the manifestation of these mechanisms. It is shown in [16] based on linear perturbation theory and $N$-body models that a bar in a galactic disk can transform a previously formed DM distribution with a central cusp into a core-type distribution. The scenario of interaction of the DM with gas flows caused by supernovae and active galactic nuclei, also involves smoothing of the density distribution of DM in massive galaxies (C. Ragone-Figueroa, G.L. Granato, M.G. Abadi, e-Print arXiv: 2012.1527v2 [astro-ph.CO] (2012)).