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MODELS FOR DARK MATTER CORE FORMATION INDUCED BY FEEDBACK

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Abstract. Cold dark matter numerical simulations predict steep, 'cuspy' density profiles for dark matter haloes, while observations favour shallower 'cores'. The introduction of baryonic physics in simulations alleviates this discrepancy, notably as feedback-driven outflow episodes contribute to expanding the dark matter distribution. We present different theoretical models describing core formation in dark matter haloes. In the first one, small stochastic density fluctuations induced by stellar feedback in the interstellar medium dynamically heat up the halo, leading to the formation of a core. In the second one, sudden bulk outflows reorganise the halo mass distribution while it relaxes to a new equilibrium. In the third one, the combination of dynamical friction from incoming satellites with outflows speeds up core formation and enables the presence of cores early in the history of the universe.

Keywords: galaxies: evolution, galaxies: haloes, dark matter

1 Introduction

Within the cold dark matter (CDM) model of structure formation, 85% of the total matter content in the universe is assumed to be made of dark matter (DM), forming relatively diffuse haloes along the cosmic web. The remaining baryons, initially in the form of gas, can condense at halo centers, cool down, form stars, and lead to powerful *feedback* processes resulting from stellar evolution and active galactic nuclei (AGN). These feedback processes include stellar winds, radiation fields, supernova explosions, and AGN jets. They can heat up the surrounding gas and eject part of it.

The CDM model is extremely successful at describing the large scale structure of the universe, but it faces several challenges at galactic scales. In particular, CDM-only simulations predict steep, 'cuspy' central density profiles for DM haloes while observations favor 'cores' with a constant density towards the center (e.g., Oh et al. 2011). Within the CDM framework, the introduction of baryonic processes in simulations alleviates the tension by reproducing cored density profiles (e.g., Governato et al. 2012). However, hydrodynamical simulations do not necessarily isolate by themselves the physical mechanisms through which baryons affect the DM distribution. We propose here three different theoretical models describing core formation in DM haloes from first principles.

Baryons can affect DM through the gravitational potential in and around galaxies, where they locally dominate the mass budget. Baryons can lead to *adiabatic contraction* of the DM distribution when they accumulate towards the halo center and steepen its potential well (Blumenthal et al. 1986). Gas clumps or satellites can transfer part of their orbital energy to the DM background through *dynamical friction* (Chandrasekhar 1943) and thus dynamically heat the DM halo, which can contribute to core formation (El-Zant et al. 2001). Finally, *gas outflows* induced by the different feedback processes lead to mass and potential fluctuations that can also dynamically heat the DM distribution and form cores (Pontzen & Governato 2012).

2 Core formation from stochastic density fluctuations

Stellar feedback processes such as radiation, stellar winds and supernova explosions generate density fluctuations of variable size and amplitude in the different phases of the interstellar medium (e.g., Peters et al. 2017). Each of these fluctuations induces a small change in the gravitational potential, which can affect DM particles in the form of a force 'kick'. Each of these kicks is small, but their cumulative effect can induce the DM particles to slowly deviate from their initial trajectories, as in a diffusion process or two-body relaxation. As shown in El-Zant et al. (2016), this process can lead to DM core formation. It is illustrated in Fig. 1.

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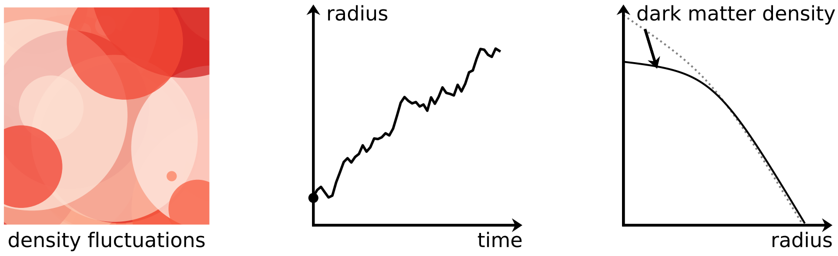

Fig. 1. Core formation from stochastic density fluctuations, as proposed in El-Zant et al. (2016): small density fluctuations of different size and amplitude resulting from feedback (left panel) induce 'kicks' to DM particles, slowly deviating them from their initial orbits as in a diffusion process (middle panel) and leading to DM core formation (right panel).

To describe this process, we assumed stochastic density fluctuations in a gaseous medium of mean density ρ_0 and Fourier-decomposed the density contrast $\delta(\vec{r}) = \rho(\vec{r})/\rho_0$ over a volume V,

$$\delta(\vec{r}) = \frac{V}{(2\pi)^3} \int \delta_{\vec{k}} e^{i\vec{k}.\vec{r}} d^3\vec{k}. \tag{2.1}$$

Each mode $\vec{k}$ induces a small force kick on the DM particles

$$\vec{F}_{\vec{k}} = 4\pi i \; G\rho_0 \; \vec{k} \; k^{-2} \; \delta_{\vec{k}}, \tag{2.2}$$

whose cumulative effect after a time T increases the velocity of the DM particles following

$$\langle \Delta v^2 \rangle = 2 \int_0^T (T - t) \, \langle F(0)F(t) \rangle \; dt, \tag{2.3}$$

from which we can derive an analytic expression for the relaxation time associated to the process (cf. El-Zant et al. 2016 and Freundlich et al. 2016 for more details, the latter providing a brief summary of the model).

This model and the resulting expression for the relaxation time were tested against collisionless simulations of a fiducial dwarf halo using the self-consistent field (SCF) method developed by Hernquist & Ostriker (1992). The potential fluctuations led to DM core formation within a timescale comparable to the relaxation time derived analytically (El-Zant et al. 2016). This model was also used to describe the effect of *fuzzy dark matter*[*] halo fluctuations on collisionless stellar systems by Marsh & Niemeyer (2019) and El-Zant et al. (2020a,b).

3 Core formation from bulk outflows

Feedback episodes induced by stellar evolution and AGN can launch massive gas outflows (e.g., Förster Schreiber & Wuyts 2020). Suddenly removing part of the gravitational pull at the center of the halo leads to its expansion and can hence form a core. This is the basis for the DM core formation model presented in Freundlich et al. (2020a), hereafter referred to as *CuspCore* (cf. also Freundlich et al. 2019 for a brief summary and Dutton et al. 2016, Section 4, for a preliminary version of the model). It is illustrated in Fig. 2.

The *CuspCore* model assumes a two-stage process where (1) the gravitational potential first adjusts instantaneously to the sudden mass loss while the DM velocities remain frozen to their initial values and (2) the halo then relaxes to a new equilibrium with no dissipation and no energy exchange between shells enclosing a given DM mass. The energy of such a shell, initially at radius r_i, can be written as

$$E_i(r_i) = U(r_i; p_i) + K(r_i; p_i) \tag{3.1}$$

where $U(r; p_i)$ and $K(r; p_i)$ are parametric expressions for the potential and kinetic energies, K being set by Jeans equilibrium. Such expressions, depending on parameters p_i, are notably available for the 'Dekel-Zhao' profile introduced by Dekel et al. (2017) and Freundlich et al. (2020b). We assume the shell energy to be

$$E_t(r_i) = U(r_i; p_i) - \frac{Gm}{r_i} + K(r_i; p_i) \tag{3.2}$$

[*]Fuzzy dark matter (or ultralight axions) is an exotic proposed form of DM where particles are so light that their de Broglie wavelength is of the order of a kpc, inducing quantum phenomena (such as density fluctuations) at galaxy and halo scales.

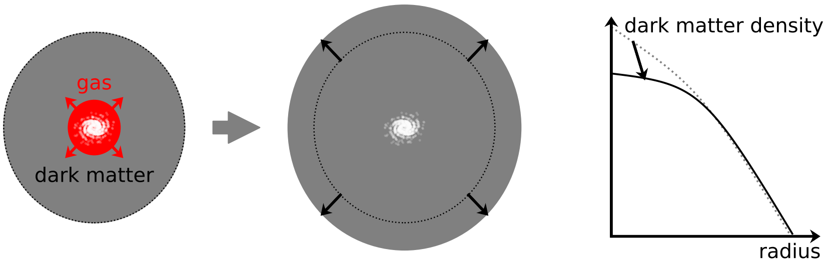

Fig. 2. Core formation from bulk outflows, as proposed in Freundlich et al. (2020a, *CuspCore* model): a sudden gas outflow instantaneously changes the gravitational potential at fixed velocities (left panel) and leads to halo expansion when the system relaxes to a new equilibrium (middle panel), thus leading to core formation (right panel).

right after a central mass loss m, and the system to subsequently relax to a new equilibrium where the shell initially at r_i has moved to r_f. Using the same parametric expressions for U and K, the final energy of the shell is written

$$E_f(r_f) = U(r_f; p_f) - \frac{Gm}{r_f} + K(r_f; p_f, m), \tag{3.3}$$

where parameters p_f describe the new mass distribution. Eqs. (3.1), (3.2), and (3.3) can be generalised to account for multiple halo components and a radius-dependent mass loss. The energy conservation assumption yields $E_f(r_f) = E_t(r_i)$ for each shell, which can be solved numerically to obtain the final parameters p_f. Radius r_f is indeed set for given parameters p_f, since the enclosed DM mass within each shell is conserved.

This model has been tested against successive outputs of cosmological zoom-in simulations, where it successfully predicted the evolution of the inner DM profile in about 75% of the cases, failing mainly in merger situations (Freundlich et al. 2020a). We are currently testing it using ideal N-body simulations, yielding an excellent agreement in the mass range where core formation occurs (François et al., in prep.).

4 Core formation from dynamical friction and AGN outflows

Recent observations have reported low DM fractions at the center of massive high-redshift galaxies (Wuyts et al. 2016; Genzel et al. 2017, 2020; Sharma et al. 2021), possibly indicating the presence of cored DM distributions three billion years after the Big Bang. To explain these early massive cores, we propose in Dekel et al. (2021) a hybrid scenario combining dynamical friction from merging satellites with AGN outflows when each of the two processes may not be sufficient by itself: dynamical friction first heats up the inner DM halo, which boosts the effect of AGN outflows with respect to core formation, as illustrated in Fig. 3.

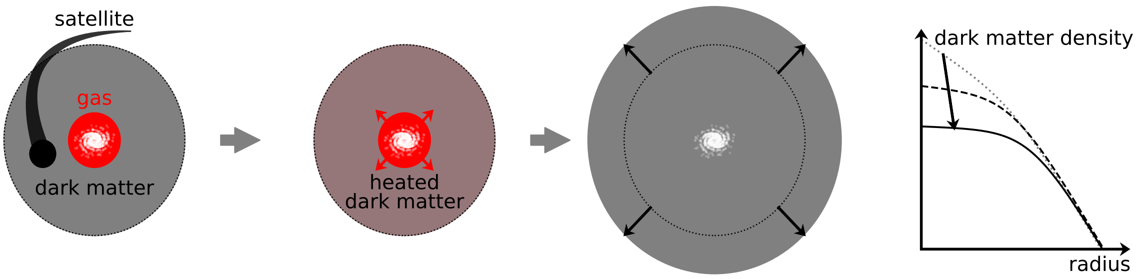

Fig. 3. Core formation from the combination of dynamical friction and AGN feedback, as proposed in Dekel et al. (2021): dynamical friction from a merging satellite (left panel) dynamically heats the DM halo (middle left panel), which increases the effect of the subsequent AGN outflow towards expanding the DM distribution and forming cores (right panels). Although not represented here, the energy deposited by dynamical friction can also contribute to expanding the DM distribution.

We first use analytical arguments and the *SatGen* semi-analytical model (Jiang et al. 2021) to assess the energy deposited in the halo through dynamical friction by single satellites, of different concentrations and orbits, and by a cosmological sequence of satellites. This energy heats up the halo and can already contribute to flattening its central cusp. If we assume an instantaneous energy deposition followed by relaxation to a new equilibrium and energy conservation for shells enclosing given DM masses, we can adapt the different steps of the *CuspCore* model (outlined in the previous Section) to describe how the DM halo can flatten from the heating. Namely, the transitional shell energy right after the energy deposition would be

$$E_t(r_i) = U(r_i; p_i) + K(r_i; p_i) + W(r_i), \tag{4.1}$$

where W is the energy input from dynamical friction, and the final shell energy

$$E_f(r_f) = U(r_f; p_f) + K(r_f; p_f, m), \tag{4.2}$$

where the energy input has been absorbed to transform the DM mass distribution. Again using the *CuspCore* model to describe the effect of a sudden bulk AGN outflow on the pre-heated or already-flattened halo, we show that the combination of dynamical friction and outflows enables particularly efficient core formation.

5 Conclusion

We presented three theoretical models for core formation in dark matter haloes induced by baryonic processes: a model invoking the small density fluctuations induced by stellar feedback in the interstellar medium, a model invoking bulk gas outflows, and a model invoking the combination of dynamical friction from merging satellites with AGN outflows in early massive galaxies. Each of these models provides a physical understanding of core formation within the cold dark matter framework, the predictions of the first two can be compared in certain situations despite their different formalism, and the different processes at stake may act in concert. We highlight that solutions to the cusp-core discrepancy invoking fundamental changes in the cosmological model have also been proposed.

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