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DARK MATTER CORE FORMATION FROM OUTFLOW EPISODES

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Abstract. While cold dark matter numerical simulations predict steep, 'cuspy' density profiles for dark matter halos, observations favor shallower 'cores'. The introduction of baryons alleviates this discrepancy, notably as feedback-driven outflow episodes can expand the dark matter distribution. We present a simple model for the response of a dissipationless spherical system to a sudden gas outflow or inflow from its center. The response is divided into an instantaneous change of potential at constant velocities followed by an energy-conserving relaxation. The model is tested against NIHAO cosmological zoom-in simulations, where it successfully predicts the evolution of the inner dark matter profile between successive snapshots in a large number of cases, failing mainly during mergers. It thus provides a simple understanding of the formation of dark matter halo cores by supernova-driven outflows, which can be extended to other situations such as the formation of ultra-diffuse galaxies.

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

1 Introduction

The cold dark matter (CDM) model of structure formation is extremely successful at describing the large scale structure of the universe, but it faces different challenges at galactic scales. In particular, while CDM-only simulations predict steep, 'cuspy' central density profiles for dark matter haloes, observations favour shallower 'cores' (e.g., Oh et al. 2011). The introduction of baryonic processes such as cooling, star formation and feedback resulting from star formation or active galactic nuclei (AGN) in the simulations enables to alleviate this 'cusp-core discrepancy' by reproducing cored density profiles (e.g., Governato et al. 2012; Teyssier et al. 2013). However, complex hydrodynamical simulations do not necessarily specify nor isolate the physical mechanisms through which baryons affect the dark matter distribution. Our main goal here is to propose a theoretical model describing from first principles how episodes of outflows resulting from the different feedback processes can form cores in dark matter haloes.

Since dark matter interacts gravitationally, baryons can affect it through the gravitational potential. When baryons cool and accumulate at the center of a dark matter halo, they steepen the potential well, leading to an adiabatic contraction of the dark matter distribution (Blumenthal et al. 1986). When a clump of gas or a satellite galaxy moves within the halo, it can transfer part of its orbital energy to the dark matter background through dynamical friction (Chandrasekhar 1943). This latter process dynamically 'heats' the dark matter halo and has been shown to contribute to core formation (El-Zant et al. 2001). When stellar winds and supernova explosions generate outflows, they induce mass and potential fluctuations that can also dynamically heat the dark matter and form cores (Pontzen & Governato 2012). We aim here at modelling how a dissipationless dark matter halo react to sudden mass changes resulting from outflows.

The process at stake during dark matter core formation could also explain the formation of ultra-diffuse galaxies (UDGs). These galaxies are characterized by dwarf stellar masses but sizes comparable to that of the Milky Way. They could be failed galaxies that lost their gas after forming their first stars (van Dokkum et al. 2015), dwarf galaxies with particularly high halo spin (Amorisco & Loeb 2016), tidal debris from mergers or tidally disrupted dwarfs (Beasley & Trujillo 2016), or precisely galaxies whose spatial extend is due to episodes of outflows resulting from stellar feedback, as suggested by Di Cintio et al. (2017). In this latter scenario,

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gravitational potential fluctuations lead to the expansion of both the dark matter and the stellar distributions. Field UDGs in simulations consistently have typical halo spins, cored dark matter haloes and bursty star formation histories (Jiang et al. 2019a,b). Since stars can be considered as collisionless particles, the model we propose can be generalized to describe the puffing-up of the stellar distribution of UDGs from outflows.

2 Description of the model

To model the response of a spherical collisionless halo to a sudden mass change m at its center ($m > 0$ for an inflow and $m < 0$ for an outflow), we follow the evolution of spherical shells enclosing given collisionless masses $M(r_i)$, where r_i denotes the initial shell radii. These shells end up at radii r_f when the halo relaxes to a new equilibrium after the mass change.

If the mass change is slow compared to the orbital time at r_i, angular momentum conservation on circular orbits yields

$$\frac{r_f}{r_i} = \frac{M}{M+m} = \frac{1}{1+f} \tag{2.1}$$

with $f = m/M$ the ratio between the mass change and the enclosed mass at r_i. This equation notably applies to adiabatic contraction.

For a sudden mass change, we assume (i) that the gravitational potential adjusts instantaneously while the velocities and hence the kinetic energy are first frozen to their initial values and (ii) that the system subsequently relaxes to a new equilibrium with no dissipation and no energy exchange between shells. If the initial equilibrium state of the halo is described by a density profile $\rho(r; p_i)$ parametrized in terms of p_i allowing an analytical potential $U(r; p_i)$, the initial energy of a shell at r_i can be written as

$$E_i(r_i) = U(r_i; p_i) + K(r_i; p_i), \tag{2.2}$$

where the kinetic energy K is set by the Jeans equation (Binney & Tremaine 2008, Chapter 4). Given our first assumption (i), this energy becomes

$$E_t(r_i) = U(r_i; p_i) - \frac{Gm}{r_i} + K(r_i; p_i) \tag{2.3}$$

right after the mass change. The system is then assumed to relax to a new equilibrium, where the shell that was initially at r_i has moved to r_f. If the mass distribution of this new equilibrium state can be parametrized by the same functional form $\rho(r; p_f)$ with different parameters p_f, the final energy of the shell is

$$E_f(r_f) = U(r_f; p_f) - \frac{Gm}{r_f} + K(r_f; p_f, m), \tag{2.4}$$

where the kinetic energy is again set by the Jeans equation but also depends on the mass m that has been added or removed. The radius r_f can be retrieved from the parameters p_f since the enclosed collisionless mass within each shell is conserved. Our second assumption (ii) means that $E_f(r_f) = E_t(r_i)$ for each shell. Given functional forms $U(r; p)$ and $K(r; p, m)$ for the potential and kinetic energies, this energy conservation equation can be solved numerically to obtain the final parameters p_f. We can thus predict the evolution of the halo density profile when mass is suddenly added or removed at its center. Fig. 1 illustrates the different steps assumed by the model, with the addition of a stellar component.

To describe the transition from cusps to cores, we use a Dekel et al. (2017) parametrisation of the halo density profile where

$$\rho(r) \propto \frac{1}{x^a (1 + x^{1/2})^{2(3.5-a)}} \tag{2.5}$$

depending on parameters a and c with $x = cr/R_{\rm vir}$ ($R_{\rm vir}$ being the virial radius), which has the advantage to have an analytical potential and a free inner slope. This parametrisation was shown to yield excellent fits for haloes in simulations with and without baryons, ranging from steep cusps to flat cores. The associated $U(r; a, c)$ and $K(r; a, c, m)$ can be found in Freundlich et al. (2019) and agree well with simulated potential and kinetic energy profiles.

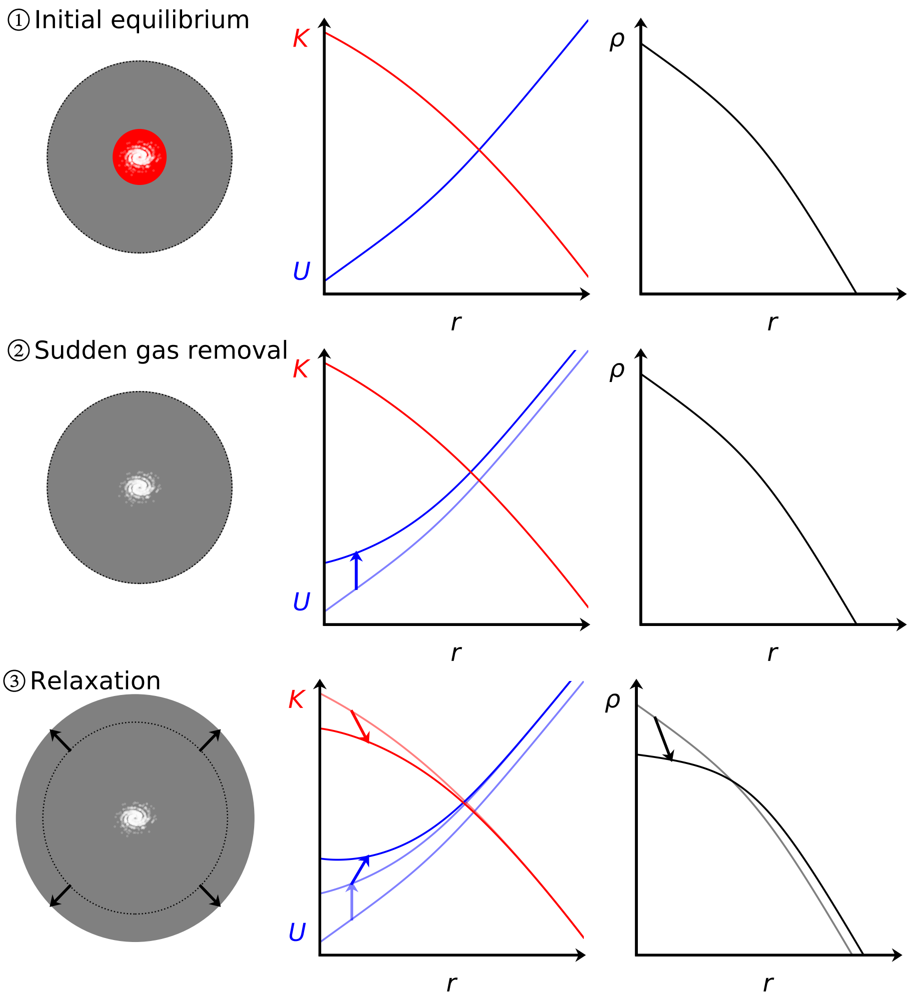

Fig. 1. Schematic representation of the different steps assumed by the model for a gas outflow episode affecting the dark matter distribution: (1) an initial dark matter halo at equilibrium (in gray in the upper left panel), where the dark matter density profile ρ and the associated gravitational potential energy U follow the Dekel et al. (2017) parametrisation while the kinetic energy K stems from the Jeans equation (Eq. 2.2), with gas (in red) and stars (in white) at its center; (2) a sudden gas mass loss with the potential adjusting instantly while the velocities and the kinetic energy remain frozen to their initial values (Eq. 2.3); and (3) a relaxation to a new equilibrium at constant energy $U + K$ (Eq. 2.4) leading to the expansion of the dark matter distribution.

3 Test against the NIHAO simulations

We test the model predictions for the evolution of the dark matter density profile on successive outputs of NIHAO cosmological zoom-in simulations, which are characterized by a relatively strong feedback implementation and a spatial resolution of 1% of the virial radius (Wang et al. 2015). We focus on the 33 galaxies whose stellar mass at $z = 0$ lies in the range $10^7 - 10^9$ $M_\odot$ where core formation happens according to Di Cintio et al. (2014), Tollet et al. (2016), and Dutton et al. (2016). For each output, the model prediction is determined from the Dekel et al. (2017) fit to the initial average density profile $\overline{\rho}$ and the mass change m (which is allowed to depend on the shell radii r_i) according to the energy conservation equation. Fig. 2 shows an example of a successful prediction. We find that the model is able to predict the evolution of the inner part of the dark matter density profile and its inner logarithmic slope in about 70% of the cases, although with some scatter. Mergers are found to be the main cause of failure of the model, which we explain by the fact that mergers and fly-bys break the assumed spherical symmetry and lead to processes that are not accounted for in the model such as dynamical friction and tidal interactions. We also test the model predictions over successive outputs, finding that it is able to recover (again with some scatter) the evolution of the inner part of the dark matter density profile up to a few Gyr in the absence of mergers.

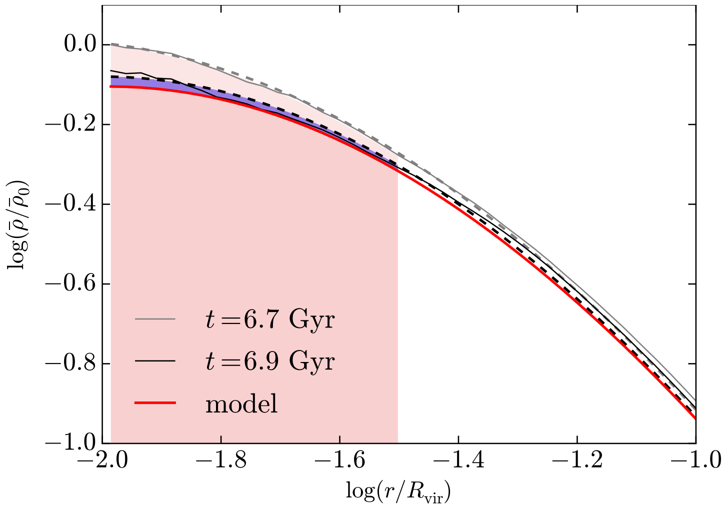

Fig. 2. Evolution of the inner part of the average dark matter density profile between two successive outputs of a NIHAO zoom-in simulation compared to the model prediction. The Dekel et al. (2017) fits are shown as dashed lines.

4 Conclusion

We present a theoretical model providing a simple understanding of the formation of dark matter halo cores from bulk outflows resulting from feedback. This model, which is presented in more detail in Freundlich et al. (2019), can be extended to describe the formation of UDGs. It was successfully tested against NIHAO cosmological zoom-in simulations, where it reproduces well the evolution of the dark matter density profile in the absence of mergers. We nevertheless note that the effect of feedback on dark matter haloes or UDGs can also be modeled as a diffusion process where stochastic density fluctuations induce small 'kicks' to the collisionless particles and progressively deviate them from their initial orbits, as proposed in El-Zant et al. (2016, 2019) and summarized in Freundlich et al. (2016). Both models may be relevent in different situations.

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