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Elliptical Galaxies in MOND

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Abstract. Fully self-consistent simulations of the formation of elliptical galaxies in the early Universe are performed assuming no dark matter. We start with a post-Big Bang pre-galactic gas cloud, allow it to collapse under self-gravity thereby following the star formation history and chemical enrichment. Phantom of Ramses (POR) is a customized version of RAMSES and includes all its features but uses Milgromian dynamics. We compare these theoretical results with the empirical downsizing results obtained previously to infer the allowed initial conditions, given the observed properties of elliptical galaxies.

Introduction

Galaxies are gravitationally bound structures and theoretical descriptions that explain their, structure, formation and evolution are still not well defined. This could be partly because of the fact that it is currently not possible to perform a simulation that would resolve the components in the galaxy down to a single star that includes all the dynamical and hydrodynamical effects. But that isn't the major concern when leading to a theory of cosmology that could incorporate structures within the 8Mpc scale. The widely accepted cosmological theory (LCDM) fails to reproduce galaxies in the local cosmological volume that has been observationally well studied. The reported failures include, for example, the fact that there are only about a handful of galaxies around the Milky Way (the Missing Satellite Problem) but LCDM predicts thousands of satellite galaxies. There are other different issues when LCDM is considered such as the satellite planes problem, the Local Group symmetry problem, the downsizing problem and others, which are well documented [*Kroupa*, 2012; *Famaey and McGaugh,*, 2012; *Kroupa*, 2015]. A large number of research groups work on these problems where they try to tweak the theory here and there to fix one of the issues but fail to account for another. It is important to establish a theoretical framework that can accommodate the observational data rather than slightly changing certain aspects of a theory in-order to solve a part of the problem and reverting back to the same to explain something else. LCDM failed to explain the aforementioned issues while MOND (MilgrOmiaN Dynamics) is likely to provide a better solution. As of now, only a few simulations have been done in MOND which includes the simulations of Antennae-like galaxies [*Renaud et al.*, 2016], simulations of the Sagittarius satellite galaxy [*Thomas et al.*, 2017], simulations of the Local Group producing the planes of satellites [*Banik et al.*, 2018; *Bilek el al.*, 2018], simulations of streams from globular clusters [*Thomas et al.*, 2018] and most recently on the formation of exponential disk galaxies [*Wittenburg et al.*, 2020].

This paradigm is yet to produce elliptical galaxies. The simple monolithic collapse of a non-rotating gas cloud does produce a galaxy with the properties of an elliptical galaxy as discussed in the next few sections but they turn out to be rotation dominated which makes it difficult to produce ellipticals (that are highly pressure supported) under this paradigm. Elliptical galaxies have been suspected for a long time to have formed with a top-heavy IMF [*Matteucci*, 1994] and to have formed within less than a Gyr [*Recchi et al.*, 2009; *Thomas et al.*, 2010]. The early and rapid formation time scale has been difficult to understand and simulations of galaxy formation have not been taking into account a possibly evolving galaxy-wide IMF (apart from the first such attempt by *Ploeckinger et al.* [2014] concerning tidal-tail galaxies). In particular, none of the existing hydro-dynamical simulations primordial of galaxy formation ensure consistency of the galaxy-wide IMF with the IMF found in star-forming molecular cloud cores. This project aims to do exactly this for the first time.

Currently, we have been working with minimal feedback mechanism (only heating/cooling) in an isolated environment with a non-varying IMF but we aim to extend this to more complex feedback processes that include a varying galaxy-wide IMF and chemical evolution, such as already documented for closed-box models [*Yan et al.*, 2019].

MOND and POR

Newtonian dynamics when it was formulated in the 18$^{\text{th}}$ and early 20$^{\text{th}}$ centuries was motivated by solar system objects. Extrapolating this empirical formulation to galaxies in the late 1970's lead to tight dynamical deviations on the scale of galaxies. *Milgrom* [1983] suggested a non-Newtonian gravity theory which can be applied to celestial bodies also beyond the solar system. Milgromian gravitation may be a consequence of the quantum vacuum [*Milgrom*, 1999; *Pazy*, 2013; *Verlinde*, 2017; *Smolin*, 2017] and the equations of motion follow from the action, [*Bekenstein and Milgrom*, 1984],

$$L_N = -\int \left\{ d^3 r \rho \phi + (8\pi G)^{-1} a_0^2 \mathcal{F}\left[(\nabla\phi)^2 / a_0^2 \right] \right\}, \tag{1}$$

which upon extremization, leads to the generalised (MOND) Poisson equation,

$$\nabla \cdot [\mu(|\nabla\phi| / a_0)\nabla\phi] = 4\pi G\rho, \tag{2}$$

where, ϕ is the Newtonian potential, ρ the baryonic mass density and $\mathcal{F}$ is an arbitrary function that relates to μ in Eq.2 such that $\mu(x) = d\mathcal{F}(x^2)/dx^2$, which determines the true potential. *Bekenstein and Milgrom* [1984] noted a correspondence with some theories of quark confinement.

Thus, the empirical finding is that the galaxies follow a scale-invariant dynamics (Milgromian) in the lower acceleration limit. Milgrom originally formulated an equation where the actual gravitational acceleration, g is a function of the Newtonian gravitational acceleration, g_N and is given in spherical symmetry by,

$$g = \sqrt{a_0 g_N}, \tag{3}$$

where $a_0 \approx 10^{-10}$ m s^{-2} is Milgrom's constant, and it is only valid in the low acceleration (deep MOND limit). For generalisation it can be written as follows:

$$g = \nu(g_N/a_0) g_N, \tag{4}$$

with ν(y), y $= g_N/a_0$ being the transition function, which is defined by its limits:

$$\nu(y) \to 1 \text{ for y} \gg 1 \text{ and } \nu(\text{y}) \to \text{y}^{-1/2} \text{ for y} \ll 1. \tag{5}$$

This equation predicted the galaxy scaling relations such as the Baryonic Tully Fisher Relation (BTFR) and led to new scaling relations like the Radial Acceleration Relation (RAR) [*Sanders*, 1990; *McGaugh*, 2004, 2005, 2012].

Poisson equation (Eq. 2) can be written,

$$\Delta\Phi(x) = 4\pi G(\rho(x) + \rho_{ph}(x)) \tag{6}$$

where $\rho(x)$ and $\phi(x)$ fulfil the standard Poisson equation, $\Delta\phi(x) = 4\pi \mathrm{G}\rho(\mathrm{x})$, $\rho_{ph}(x)$ is the phantom dark matter (PDM) density which is a mathematical ansatz that allows to compute the additional gravitational potential predicted by the Milgromian framework and Φ(x) is the total gravitational potential. This Eq.(6) is called the quasi linear formulation of MOND (QUMOND) [*Milgrom*, 2010].

The POR code [*Lüghausen et al.*, 2015] is a customized version of the RAMSES code applying the adaptive mesh refinement (AMR) method. It uses a multi-grid and a conjugate gradient solver to solve the Poisson equation. Due to the non-linearity of Milgromian dynamics Eq.(3), the QUMOND Eq.(6) is used.

First, the standard Poisson equation is solved to compute the Newtonian potential, $\phi(x)$. Then the PDM density is calculated,

$$\rho_{ph}(x) = \frac{\nabla \cdot [\nu(|\nabla\phi(x)|/a_0)\nabla\phi(x)]}{4\pi G}. \tag{7}$$

This is done using a diskrete scheme which is explained in *Lüghausen et al.* [2015]. Now, the Poisson equation is solved for a second time using Eq.(6) with the Newtonian density, $\rho(x)$ and PDM density, $\rho_{ph}(x)$ to compute the total gravitational potential.

Method

Models

The simulations presented here are computed to investigate the collapse of pure (idealized post-Big-Bang) gas clouds of certain mass and radius in an isolated box environment. The molecular cloud setup is the same as used in *Wittenburg et al.* [2020] but here the clouds are assumed to have zero initial rotation so as to expectedly, produce elliptical galaxies. The initial rotation velocity of the gas cloud with an initial uniform density ρ_{init} is defined by $v_i = \eta \cdot \mathbf{r} \times I_z$, where η is the angular velocity parameter, $\mathbf{r}$ the radius vector and I_z the unit vector in the direction of z-axis. An intergalactic medium (IGM) of density, $\rho_{IGM} = 10^{-5} \times \rho_{init}$ is set up outside the gas sphere such that after the cloud collapses, further accretion from the IGM onto the formed galaxy is not significant. This is done in-order to mimic an isolated system. Table 1 lists the initial conditions of the models.

Table 1. Models of galaxies in the simulations

Model (Galaxies)	M_i ($10^9 M_\odot$)	r_i (Kpc)	SFR_i ($M_\odot$/yr)	duration (Gyr)	SFR_m ($M_\odot$/yr)	time(SFR_i) (Gyr)	Density ($M_\odot$/Kpc^3)
a	6.4	50	0.046947	0.9	26.096725	0.52	1.2×10^4
b	64	50	0.140842	0.7	724.094036	0.22	1.2×10^5
c	64	100	0.140842	1.0	397.610884	0.49	1.5×10^4
d	6.4	50	0.126757	1.1	22.670552	0.5	1.2×10^4
e	64	50	0.084505	0.95	706.572099	0.21	1.2×10^5
f	6.4	500	0.093894	3.4	3.86304	5.98	1.2×10^1
g	64	500	0.046947	3.1	86.025746	2.61	1.2×10^2
h	0.6	300	0.046947	2	0.2535149	7.92	5.3
i	0.6	200	0.046947	3.1	0.3145462	5.13	1.7×10^1
j	0.6	100	0.046947	2.1	0.4882509	2.47	1.4×10^2
k	0.6	50	0.140842	1.8	0.671345	1.19	1.1×10^3

Note. M_i is the initial cloud mass, r_i the initial cloud radius, SFR_i the initial SFR calculated after cloud collapse, *duration* the time taken calculated from full-width half maximum of the SFH, SFR_m the maximum calculated SFR, $time(SFR_i)$ the time at which the first SFR was calculated, *Density* the initial density of the gas cloud.

Triaxiality

The distribution of the Hubble types can be statistically related to the axes ratios to determine the type of galaxy formed [*Tremblay and Merritt,*, 1995, 1996]. The centre of mass is calculated first so as to shift the coordinates to the centre of mass of the system and then the moment of inertia tensor is calculated. The single value decomposition method is then used to get the rotation matrix and the length of the semi principal axes (a, b, c). The axes ratios (p = b/a and q = c/a) can be used to define the triaxiality parameter, T as:

$$T = (1 - p^2)/(1 - q^2). \tag{8}$$

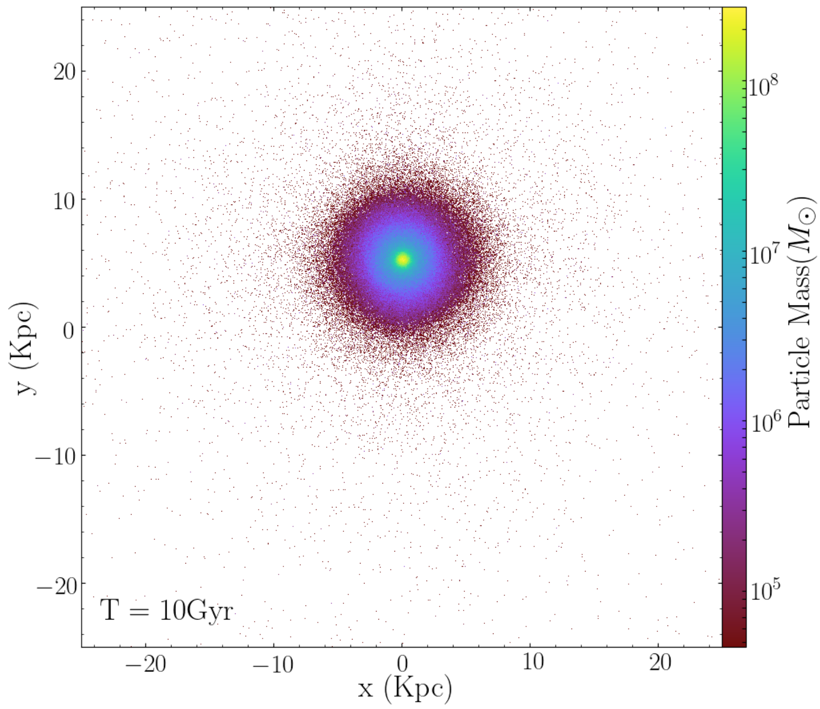

Figure 1. Face-on particle plot of model ‘b’ at the end of the simulation.

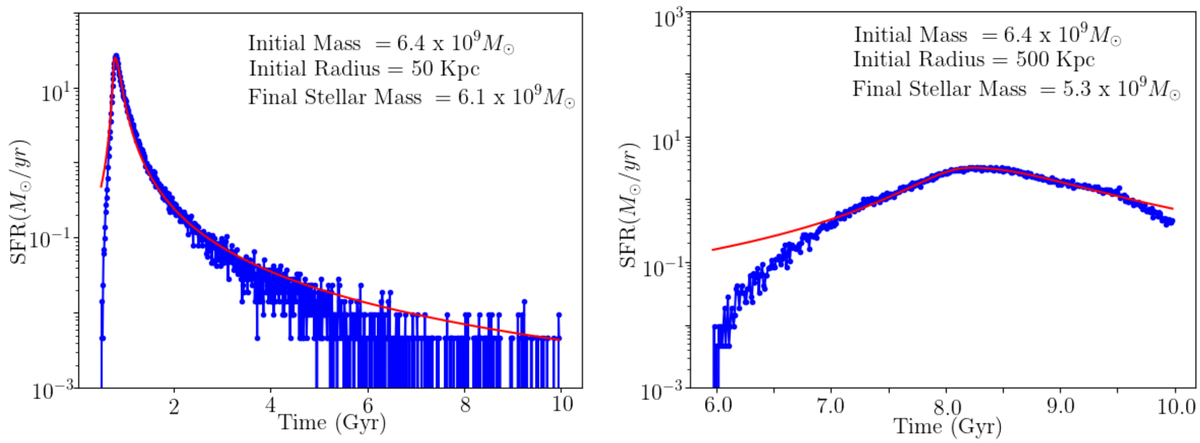

Figure 2. A plot showing SFH of model ‘a’(left) and model ‘f’(right). The red lines are the best-fit for these high initial density models that follows a Cauchy–Lorentz distribution.

A prolate shape corresponds to a > b = c (T = 1, q = p) and an oblate shape corresponds to a = b > c (T = 0, p = 1). The models mentioned here all have a triaxial parameter close to one, hence resembling a prolate structure. These results are obtained by invoking the minimal feedback mechanism, including complex baryonic feedback has to be investigated in the future. We note though that the properties of the formed disk galaxies have not been significantly affected by including the complex baryonic feedback [*Wittenburg et al.*, 2020].

Results

A downsizing SFH

The total mass of the stellar particles formed at each time step is calculated by POR and is outputted in physical units. This mass is then binned in 50 Myr bins. The star formation rate (SFR) is then expressed as the total mass of stars formed per year.

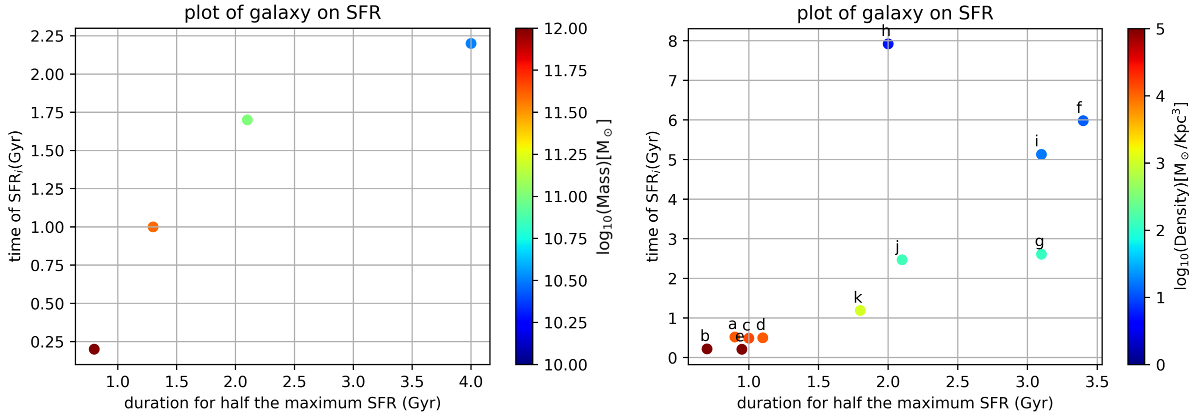

Figure 3. A plot showing the duration of the full-width half maximum of the SFH vs the time when the star formation first began for each model. The colour chart on the right side of the y-axis shows the mass density. The figure on the left is the observational result from *Thomas et al.* [2010] and on the right is the result from this project.

The initial density of the cloud determines the peak of the SFH as can be seen from Table 1. For models with high initial clouds density, the SFR increases sharply till a maximum is reached and then decreases exponentially. A Cauchy–Lorentz distribution gives a good fit to the data for these high density models as seen in Figure 2 (left). But the model with the lower density in Figure 2 (right) does not show this sharp rise after the collapse. Therefore a different fitting model should be assumed. Further investigation has to be done on a generalised fitting parameter that would describe all models.

Figure 3(left) is based on observational results from the absorption spectra of early-type galaxies from *Thomas et al.* [2010] and it is seen that the more massive galaxies formed most of their stars in a shorter duration. This empirical result [*Thomas et al.*, 2010] when compared to the grid of galaxies in this work follows a similar trend. This is an important result and is found to be a natural consequence of monolithic collapse from gas cloud with different post-Big-Bang densities in MOND. By mapping out these initial density vs mass or radius of the post-Big-Bang clouds that lead to the same location of models as in the left panel of Figure 3 we will be able to place cosmological constraints on the formation of elliptical galaxies.

Density profile

An important constraint on the models is for the formed galaxies which fill the *Thomas et al.* [2010] constraints (Figure 3) to also show realistic surface brightness profile. The de Vaucouleurs law is an empirical model that describes how the surface brightness of an elliptical galaxy varies as a function of apparent distance from the centre of the galaxy. The surface brightness profile is analogous to density profile in theoretical terms and the de Vaucouleurs' model shows a good fit for the model (Figure 4).

Discussion and conclusion

A grid of initial radius and mass values is now being computed in order to obtain first the information on how such initially non-rotating clouds collapse in the early Universe and if they might lead to galaxies which are comparable to the observed early type galaxies today (disk galaxies being well reproduced, from collapsing rotating clouds as shown previously by *Wittenburg et al.* [2020]).

All the simulations presented here were done for an isolated monolithic initially constant density cloud collapse but that is not the case in the real Universe. Introducing turbulence would be the step towards more realistic initial conditions. This would be the next step in

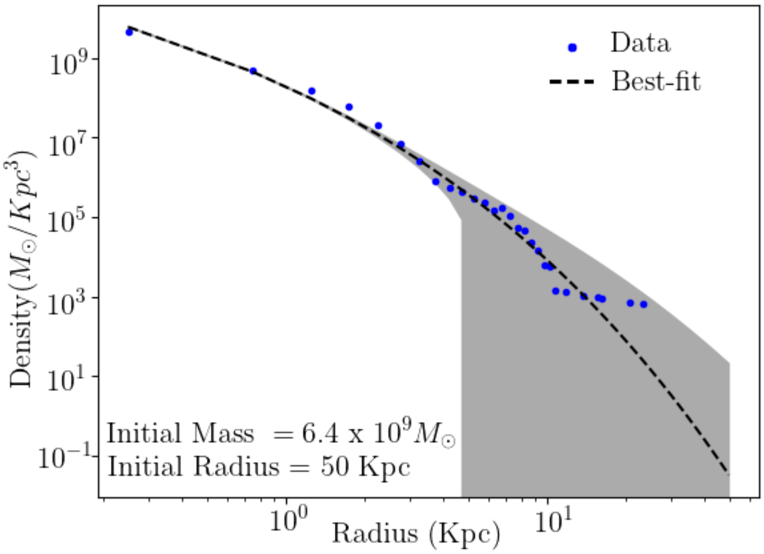

Figure 4. Density profile of model 'a' fitted with the de Vaucouleurs function. The blue data points are the density at each radial bins. The shaded region corresponds to the three standard deviations from the mean region.

the project which could possibly produce some structure before the cloud collapses entirely. Implementing the varying IMF would be the next major step. The incorporation of the locally varying IMF will follow the prescriptions developed by *Ploeckinger et al.* [2014] and will, here for the first time, also take into account the variation of the IMF shape as prescribed by *Marks et al.* [2012]. Various parameter dependencies (time-step for populating the IMF, various baryonic feedback processes such as simple heating up to full radiative transfer and supernova exploding schemes as already incorporated into the RAMSES code) will be investigated. The RAMSES code is well used by the research community on related problems and the IMF variation has also received significant observational support. Different prescriptions for the galaxy-wide IMF variation (such as suggested by *Hopkins* [2018]) will also be considered.

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