Merger is Intermittent Accretion

Morgan Le Delliou

Astronomy & Astrophysics manuscript no. ODpaper4aaHAL.hyper20738
May 8, 2007

LETTER TO THE EDITOR

Merger is Intermittent Accretion

Morgan Le Delliou[1]

Centro de Física Teórica e Computacional, Universidade de Lisboa
Av. Gama Pinto 2, 1649-003 Lisboa, Portugal
e-mail: delliou@cii.fc.ul.pt

Received ...; Accepted ...

ABSTRACT

Aims. The Self-Similar Secondary Infall Model (SSIM) is modified to simulate a merger event.
Methods. The model encompass spherical versions of tidal stripping and dynamical friction that agrees with the Syer & White merger paradigm's behaviour.
Results. The SSIM shows robustness in absorbing even comparable mass perturbations and returning to its original state.
Conclusions. It suggests the approach to be invertible and allows to consider accretion as smooth mass inflow merging and mergers as intermittent mass inflow accretion.

Key words. Cosmology:theory – Dark Matter – Galaxies:formation – Galaxies:halos – Gravitation.

1. Introduction

Structure formation in the Cold Dark Matter (CDM, or more simply DM) paradigm is dominated by the hierarchical picture of repeated mergers. This picture was emphasised by Syer & White (1998), explaining the dynamical formation of halo density profile with a feedback mechanism provided by repeated mergers. Whereas it is now believed that isotropisation of the velocity dispersion (angular momentum; see Le Delliou & Henriksen, 2003; MacMillan et al., 2006; Barnes et al., 2005) via the radial-orbit instability is responsible for the density profile formation, their picture remains a good description of the merger digestion mechanism. Despite its simple spherical symmetry and apparent lack of compliance with the merger paradigm, some studies have shown that the Secondary Infall Model (SIM) is a viable model to predict the structure and density profile evolutions of DM haloes as compared to N-body simulations (Ascasibar et al., 2007). This letter proposes to understand this paradox by examining the merger paradigm within the SIM and studying how merger events impact on the relaxation and structure of a CDM halo.

The SIM stems from the seminal work of Gunn & Gott (1972), and the SSIM started when Fillmore & Goldreich (1984) and Bertschinger (1984) independently found self-similar solutions to the SIM. It was later shown that those solutions can be reached from non-self-similar initial conditions (e.g. in White & Zaritsky, 1992; Ryden, 1993; Henriksen & Widrow, 1995, 1997; Avila-Reese et al., 1999; Henriksen & Widrow, 1999; del Popolo et al., 2000; Henriksen & Le Delliou, 2002; Le Delliou & Henriksen, 2003) and a systematic approach to the SSIM was used in Henriksen & Widrow (1995, 1997, 1999); Henriksen & Le Delliou (2002); Le Delliou & Henriksen (2003), derived from the Carter-Henriksen formalism (Carter & Henriksen, 1991, hereafter CH). Some extensions to the SIM were proposed that included the effects of angular momentum to explain flat halo cusps (Hioletis, 2002; Le Delliou & Henriksen, 2003; Ascasibar et al., 2004; Williams et al., 2004; Lu et al., 2006), but no fundamental attempt was made before Le Delliou (2002) to confront the SIM to the merger paradigm.

The following section (Sec. 2) will describe how the SSIM can be extended to model a merger event. Then Sec. 3 will discuss how the symmetry of the SSIM still allows for a form of tidal stripping and dynamical friction, before to present the consequences of such a merger in the SSIM in Sec. 4, and to make some concluding remarks in Sec. 5.

2. Merger in an Infall

Modeling a merger event in a spherical geometry may appear contradictory but it is possible to a certain extent. The SSIM has been implemented with fully dynamical Lagrangian treatment of infall using the CH (Carter & Henriksen, 1991) self-similar variables that reveals when the system reaches naturally a self-similar regime. A halo is modeled from a radial power law perturbation $\delta\rho/\rho \propto r^{-\epsilon}$ on an Einstein-de Sitter homogeneous background, that is evolved to reach its quasi-stationary self-similar regime in its core (Henriksen & Widrow, 1999). The SIM is known to establish a self-similar infall phase (Henriksen & Widrow, 1997), which then leads to a semi-universal power law density profile (Fillmore & Goldreich, 1984; Bertschinger, 1984): for initial power index $\epsilon \leq 2$, the isothermal sphere ($\rho \propto r^{-\mu}$ with $\mu = 2$) is the semi-universal attractor, whereas in the converse initial conditions, there is a continuum of attractors with $\mu = 3\epsilon/(1+\epsilon)$. Positive overdensity and the requirement of a finite initial core mass in the centre limit the range to $0 \leq \epsilon < 3$. The cores explored here were chosen, according to their SSIM behaviour defined by their power index, as typical shallow ($\epsilon = 3/2$) and steep ($\epsilon = 5/2$) profiles, with the addition of an extreme steep case ($\epsilon = 2.9$) to test the behaviour of a highly concentrated parent halo (the steep and shallow denominations refer to the comparison with the isothermal sphere).

In this geometry, an overdensity (hereafter OD, or satellite), considered to represent a satellite halo, is modeled by a region of overdense shells at the edge of the core, considered as the parent

Table 1. Density, mass and mass perturbation ratios for the mergers in the SSIM.

ϵ, panel	M_{ratio}	D_{ratio}	M_{OD}/M_{BG}
$\frac{3}{2}$, upper panel	0.751	0.282	1.173
$\frac{3}{2}$, middle panel	4.25×10^{-2}	7.10×10^{-2}	9.38×10^{-2}
$\frac{3}{2}$, lower panel	6.92×10^{-2}	0.168	1.453
$\frac{5}{2}$, upper panel	0.889	5.51×10^{-2}	0.319
$\frac{5}{2}$, middle panel	0.439	5.54×10^{-2}	0.290
$\frac{5}{2}$, lower panel	0.178	0.454	1.133
2.9, upper panel	0.753	9.19×10^{-2}	0.416
2.9, middle panel	0.407	0.641	1.118
2.9, lower panel	0.301	9.71×10^{-2}	0.344

halo. The OD is evolved dynamically from an initial gaußian density profile added on top of the background density profile over a finite region. That evolution runs long enough to observe the signature of the OD's own stationary regime in phase space. This is manifested in the mixing of its Liouville sheet during the dynamical mass accretion of halo shells from its environment. The OD's definition as a set of satellite particles is frozen when the core swallows it.

At that point are recorded the ratio of the OD over core masses M_{ratio}, of their densities D_{ratio} and the measure of the perturbation in mass provided by the OD M_{OD}/M_{BG}. For each case, three different satellites were chosen trying to obtain various types of mass and density ratios between satellites and parents.

Since the satellites were allowed to accrete mass dynamically from their environment, ODs were laid close the the edge of the core to maintain some control over the final frozen mass and density ratios. Some configurations of those ratios were too difficult to obtain: in the shallow case, with high M_{ratio}, lower values for D_{ratio} were prevented by the massive background to accrete from, while for the steep cases, also with high M_{ratio}, higher D_{ratio} couldn't be maintained because of their very concentrated cores' depleted backgrounds which tended to spread the ODs.

The ratios indicated are measured at the time of core entry. The explored values are presented in Table 1.

It is crucial to point out that the numerical implementation of the SSIM entails a shell code where finite size shells model the continuous system. That will play a role in the discussion of the results.

3. Merger paradigm and SSIM

Syer & White (1998) have attempted to define the singularity of mergers in an effort, at the time, to explain the universality of the density profile found in N-body simulation by Navarro et al. (1996, hereafter NFW): their key feature is the feedback mechanism between dynamical friction from the parent halo and tidal stripping of the satellite. Even though this is not anymore considered to hold the formation of the density profile, their merger digestion mechanisms still describes the behaviour of satellites. I argue that both mechanisms can be modeled within the SSIM despite its one-dimensional nature.

Tidal acceleration on an infinitesimal shell of mass $m = 4\pi\rho r^2 dr$ – located at radius r, containing the system mass M and with thickness dr – can be defined as the differential gravity between its boundaries. Defining the cumulative average density

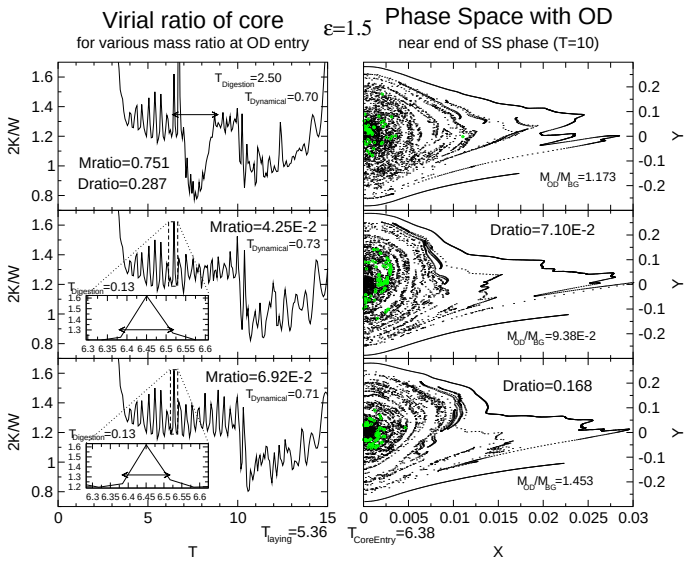

Fig. 1. Shallow case: Virial ratio and phase space diagrams at the end of the self-similar phase for three sets of OD parameters in the semi-universal attractor SSIM case ($\epsilon = \frac{3}{2} = 1.5$). The digested overdensity shells are emphasized in phase space. The middle and lower left panels also contain each a zoomed encapsulation of the small spike from the absorption of the OD. T, X and Y are respectively the self-similar time, radius and radial velocity, which units are set by $G = M(\infty) = 1$.

profile

$$\langle\rho\rangle_r = \frac{M(r)}{\frac{4\pi r^3}{3}}, \tag{1}$$

the inward oriented elementary tidal acceleration reads, at leading order

$$dT = 4\pi G dr\left(\rho - \frac{2}{3}\langle\rho\rangle_r\right). \tag{2}$$

It is thus clear that regions of peak density above the cumulative average ($\rho > \frac{2}{3}\langle\rho\rangle_r$) will experience a net disruptive tidal acceleration spreading apart shells in those regions, modeling tidal stripping.

Dynamical friction classically is defined as the creation of a wake by a moving mass in a gravitating medium which back reaction entails a net drag force upon the moving mass. In the SSIM, a massive shell is crossing the core's shell in its travelling inwards or outwards. This crossing results in outer shells feeling more or less mass pulling inwards, depending on the inwards or outwards motion of the massive shell, leading to a differential tightening or spreading of the core's shell behind the moving one, in the fashion of a wake following it. In a similar fashion, the crossing of core's shells by the massive shell lead to a decrease or increase, depending on the direction of motion, of the resulting inner mass of, and thus inner pull on, the moving shell, which can be interpreted a dragging force that adds to the total force that should be experienced in the opposite direction of the motion.

Therefore, the SSIM with an outer overdensity can be interpreted to model the main features of the merger paradigm.

4. Digestions

Indeed, it is possible to keep track in the Lagrangian shell model of the defined satellite's, or OD's, components once they have

Table 2. Digestion and dynamical times and strength parameter of the OD for the mergers in the SSIM.

ϵ, panel	$T_{digestion}$	$T_{dynamical}$	$\frac{T_{digestion}}{T_{dynamical}}$	$M_{ratio}.D_{ratio}$
$\frac{3}{2}$, upper p.	2.50	0.70	3.57	0.212
$\frac{3}{2}$, middle p.	0.13	0.73	0.178	3.017×10^{-3}
$\frac{3}{2}$, lower p.	0.13	0.71	0.183	1.163×10^{-2}
$\frac{5}{2}$, upper p.	4.21	1.21	3.48	4.989×10^{-2}
$\frac{5}{2}$, middle p.	3.07	1.12	2.74	2.432×10^{-2}
$\frac{5}{2}$, lower p.	2.11	0.98	2.15	8.081×10^{-2}
2.9, upper p.	4.83	1.17	4.13	6.920×10^{-2}
2.9, middle p.	4.94	1.10	4.49	2.609×10^{-1}
2.9, lower p.	3.07	1.11	2.77	2.923×10^{-2}

been absorbed by the parent, or core, and it can be considered isolated (end of the accretion phase, Henriksen & Widrow, 1997). Their phase space configurations are displayed on the right panels of Figs. 1, 2, and 3, distinguished from the core and halo's accreted shells. This reveals how the different ODs, in their various (shallow or steep) environments, either retain some degree of coherence after being ingested by the core or have been digested and scattered over the core's phase space by this process.

The left panels of Figs. 1, 2, and 3 examine the Virial ratios of the corresponding cores, and show a remarkable robustness in the SSIM: the quasi-stable self-similar phase is shown to be either marginally or strongly disturbed by the OD absorption and to return to the **original** undisturbed level of the parent after a digestion time $T_{digestion}$, provided there is still a mass flow to fuel the self-similar equilibrium. The digestion is manifested by the presence of a more or less pronounced initial decrease, followed by a spike and then, for the stronger effects, a trough, which deepness depends primarily on the M_{ratio}. The measurements of the digestion time are shown on the left panels of Figs. 1, 2, and 3 (double horizontal arrows), and are summarised in Table 2, where they are compared with the free fall dynamical time $T_{dynamical}$ of the OD through the core, also indicated on the figures. This dynamical time is defined as the free fall time to the centre of a test shell across a constant density distribution equivalent to the core in self-similar variables. From Table 2 without the two lowest panels of Fig. 1, where the definition of the digestion time is problematic, the average $T_{digestion} = 3.33 * T_{dynamical}$ with a standard deviation of 0.77 can be computed, showing that the core digests the OD in 2 to 4 passages in the relaxation central region of phase space which is comparable to the number of distinguishable Lagrange-Liouville streams present in the core's outer phase space regions, from the right panels of Figs. 1, 2, and 3.

From the OD point of view, the mergers display their effects in the phase spaces represented on the right panels of Figs. 1, 2, and 3 on which two features are crucial: the spread (or compactness) of the OD over the core at the end of the infall phase and the presence of some, or all, of its shells in the centre of the core's phase space. This reflects the digestion mechanisms adopted by Syer & White, 1998. Their proposal aimed at a dynamical explanation of the NFW profile. Although this explanation is not anymore considered (see Sec. 1), it is interesting to note that the presently discussed single merger model in the SSIM shows signs of inflections (central flattening and edge steepening) from its semi-universal, almost isothermal, density profile. However this is not the focus of this paper.

The compactness of the OD resists to tidal stripping while its presence in the centre is driven by dynamical friction. The

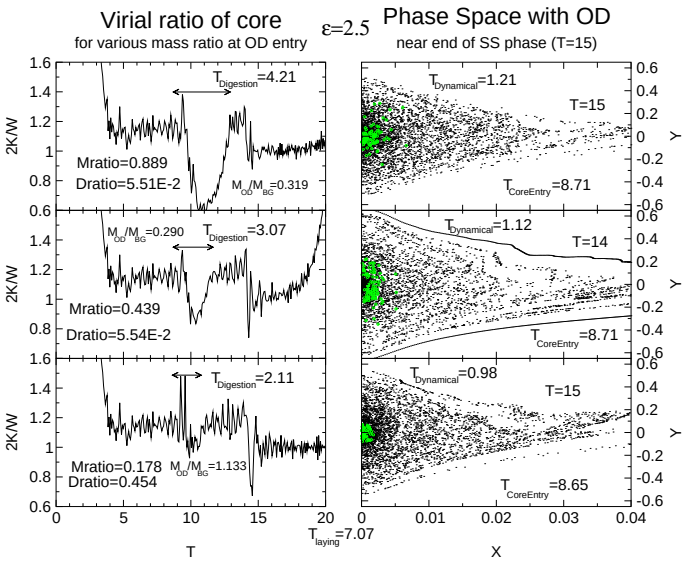

Fig. 2. Steep case: Virial ratio and phase space diagrams at the end of the self-similar phase, for three sets of OD parameters in the SSIM continuum of attractors case ($\epsilon = \frac{5}{2} = 2.5$), including an emphasis on digested overdensity shells in phases space. Same units as in fig. 1.

fate of a model satellite in the SSIM displays behaviour well in agreement with the repeated merger digestion mechanisms proposed by Syer & White: in the SSIM a combination of density and mass ratios leads to emphasise each effect. High D_{ratio}s seem to be the dominant factor for compactness of the OD, while high M_{ratio}s promote the sinking of the OD to the centre of the core.

All the possible qualitative types of behaviour are present: if both ratios, M_{ratio} and D_{ratio}, are strong enough, then the OD survives almost intact to the centre (Figs. 2's lower and 3's middle right panels). If only M_{ratio} is high while D_{ratio} is low, the OD is scattered at the centre (Figs. 1, 2 and 3's upper right panels). Conversely, a high D_{ratio} and low M_{ratio} lead to a compact OD around but not reaching the centre (Fig. 1's lower right panel). However it can be argued on the latter observation that the SSIM is not clearly showing a void in the centre and that Fig. 1's lower right panel should be considered to have in fact a high enough M_{ratio} to count in the first category set above. Finally if both ratios are too low, the OD is scattered without reaching the centre (Figs. 1 and 2's middle and 3's lower right panels).

A step further in this phenomenology would be to note that a combination of both ratios should be taken ($M_{ratio}.D_{ratio}$, see Table 2), for which a threshold can be defined for reaching the centre and another for compactness of the OD. However this classification seems to require an additional dependency with the steepness of the initial profile. Indeed the available data offer different ranges for each initial profile case. The shallow case calls for higher values for the $M_{ratio}.D_{ratio}$ thresholds than the steep cases. This manifests the shallow case's wider spread of material, compared with the steep cases, that have to be crossed by the OD in its journey towards the centre.

5. Discussion and conclusions

The SSIM has proven its capacity to model a merger event. Its simplicity allows one to probe the dynamics of the merger and the most remarkable result of this work shows that the self-similar quasi-stable regime of quasi Virial equilibrium is extremely **robust** to perturbations that can be of comparable size

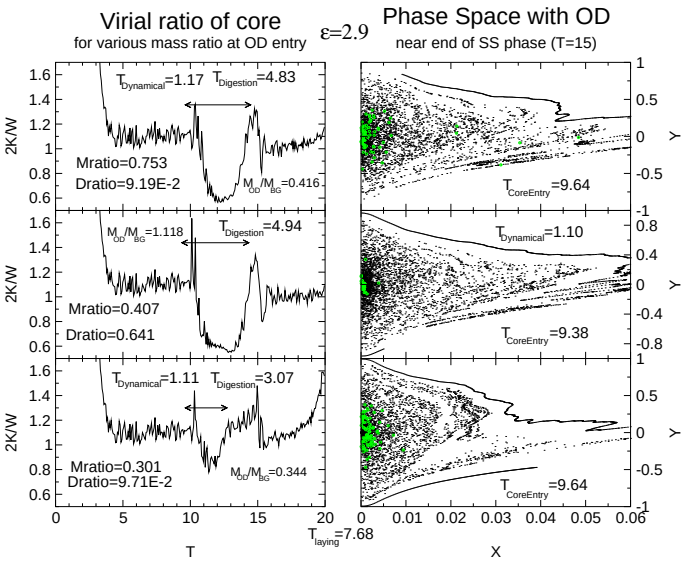

Fig. 3. Extreme steep case: Virial ratio and phase space diagrams at the end of the self-similar phase, for three sets of OD parameters in the SSIM continuum of attractors case ($\epsilon = 2.9$), including an emphasis on digested overdensity shells in phase space. Same units as in fig. 1.

to the core (equal mass mergers): the Virial ratio, after a more or less long period of digestion returns to its stabilised **original** undisturbed level and continues its usual evolution. The spreading and sinking of the satellite's particles across the parents and towards its centre agree with the tidal stripping and dynamical friction picture from Syer & White, 1998, provided some adaptation to the language of the SSIM's symmetry. Finally, and this is the claim of this paper, the numerical implementation of the model requiring discretisation, the rapid oscillations of the Virial ratio in the accretion phase offer a novel interpretation in the light of the SSIM merger model: instead of a continuous stream of mass, the model presents a repeated bombardment of finite mass shells that can be understood as small overdensities; Fig. 1's zoomed two lowest right panels show a spike to manifest the weakest mergers digestion; thus the wiggles in the Virial ratio can be interpreted as manifestation of repeated mergers that are at this level indistinguishable from accretion. Therefore there is no fundamental difference between mergers and accretion, the latter being a series of repeated merger with vanishing mass, while the latter is just intermittent accretion.

Acknowledgements. The work of MLeD is supported by FCT (Portugal) under the grant SFRH/BD/16630/2004 and hosted by J.P.Mimoso and CFTC, Lisbon University, Portugal. Evidently, thanks should go the R.N.Henriksen for discussions and comments and for directing MLeD's thesis work from which these results are extracted.

References

Ascasibar, Y., Hoffman, Y., & Gottlber, S. 2007, MNRAS, 376, 393
Ascasibar, Y., Yepes, G., Gottlber, S., & Mller, V. 2004, MNRAS, 352, 1109
Avila-Reese, V., Firmani, C., & Klypin, A.and Kravtsov, A. 1999, MNRAS, 310, 527
Barnes, E., Williams, L., Babul, A., & Dalcanton, J. 2005, ApJ, 643, 797
Bertschinger, E. 1984, ApJS, 58, 39
Carter, B. & Henriksen, R. 1991, JMPS
del Popolo, A., Gambera, M., Recami, E., & Spedicato, E. 2000, A&A, 353, 427
Fillmore, J. & Goldreich, P. 1984, ApJ, 281, 1
Gunn, J. & Gott, J. 1972, ApJ, 176, 1
Henriksen, R. & Le Delliou, M. 2002, MNRAS, 331, 423
Henriksen, R. & Widrow, L. 1995, MNRAS, 276, 679
Henriksen, R. & Widrow, L. 1997, Phys.Rev.Lett., 78, 3426
Henriksen, R. & Widrow, L. 1999, MNRAS, 302, 321
Hioletis, N. 2002, A&A, 382, 84
Le Delliou, M. 2002, PhD thesis, Queen's University, Canada
Le Delliou, M. & Henriksen, R. 2003, A&A, 408, 27
Lu, Y., Mo, H., Katz, N., & Weinberg, M. 2006, MNRAS, 368, 1931
MacMillan, J., Widrow, L., & Henriksen, R. 2006, ApJ, 653, 43
Navarro, J., Frenck, C., & White, S. 1996, ApJ, 462, 563, (NFW)
Ryden, B. 1993, ApJ, 418, 4
Syer, D. & White, S. 1998, MNRAS, 293, 337
White, S. & Zaritsky, D. 1992, ApJ
Williams, L., Babul, A., & Dalcanton, J. 2004, ApJ, 604, 18