Complex Systems in Cosmology: "The Antennae" Case Study

Jean-Claude Torrel[1], Claude Lattaud[2], and Jean-Claude Heudin[1]

[1] IIM lab.
Pôle Léonard de Vinci
92916 Paris La Défense

[2] Lab. d'Intelligence Artificielle de Paris 5
UFR Math-Info - Université Réné Descartes
45 rue des Saints-Pères. 75006 Paris

Abstract. Due to its particular shape, "The Antennae" is a well-known complex cosmological dynamical structure. Classical simulations of this phenomenon are based on "top-down" models that required thousands of point-mass particles. We describe an approach for cosmological simulation, based on a hierarchical multi-agent system, and evidence is shown that this approach significantly reduces the number of elements needed to simulate "The Antennae" structure.

Keywords: complexity, hierarchical multi-agent system, cosmology, patterns formation, Antennae, galaxy.

1 Introduction

A complex system is composed of interacting elements that, as a whole, exhibit properties which cannot be obviously deduced from the ones of the individual elements. Simulating such systems requires the computation of non-linear interactions and, thus, a high computing power bounds to the number of elements.
Cosmology is a perfect example of this computing concern : from globular clusters to spiral galaxies, deep space shows a wide variety of complex patterns and behaviors. For years, numerical simulation in cosmology has tried to reproduce and explain these behaviors by using models based on point-mass particles (such as [1] [2]). Even if this approach has carried out to successes, some problems remain unsolved :

- Observed dynamics highly depend on the number of point-mass particles used in simulation [4] [3]. Using this approach, some complex patterns do not appear in simulations till a high number of particles - typically over 1024^3 (most cosmological models use a grid distribution and, thus, the number of elements is presented this way).
- In addition, a realistic number of point-mass particles should be around 10^{41} [5] for a typical spiral galaxy which is a calculative impossibility.

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To solve this computing power problem two approaches are currently investigated. The classical "top-down" approach is to define increasingly precise models taking in account a very large number of elements and parameters [6]: each physical phenomenon is calculated by a dedicated algorithm and results are combined according to the goal of the experiment. The aim of this approach is to decrease the cost of each interaction by optimizing the algorithms but no algorithm currently allows simulations with a realistic number of particles.

The study of complex systems has obtained a certain success, in particular by the use of qualitative models like cellular automata [7] [11] [8]. This approach modifies the type of interactions, based on the idea that complex behaviors can emerge from interactions between simple elements [10]. However, if these models seem adequate to study general laws and tendencies, they seem inadequate to simulate and predict the behavior of a "real" system [12].

In this paper we present a study of the cosmological phenomenon called "The Antennae". We use a multi-agent model, first introduced in [13], that intends to preserve the global behavior while decreasing the number of elements and, thus, the number of interactions. This model takes advantages of a hierarchical multi-agent modeling while keeping a strong bond with physics : physical laws and interactions governing "The Antennae" are included in the multi-agent system.

The aim of this paper is that, despite a significant reduction in the number of elements and interactions, our model shows an emergent dynamical structure which is close to the observed phenomenon. In the first part, we introduce the phenomenon and our multi-agent hierarchical model. In the second part, results get by simulating "the Antennae" with our hierarchical system are compared with simulations made using a reference cosmological model. We show that there is qualitative evidence of similarity between observational data, reference model and our results.

2 "The Antennae"

The phenomenon called "The Antennae" is a collisional structure (Hubble picture of the structure on Fig. 1) composed of two galaxies, NGC[1] 4038 and NGC 4039. It is a stellar object at a distance of about 63 million light-years that, due to its shape, has been modelized and simulated by many cosmological studies.

The observational data indicate that the collision took place 600 Myr ago[2]. To get the image of simulation corresponding to the current state of these galaxies, it is, then, necessary to let evolve the simulation during 600 Myr (see section 4 for the simulation conversion scale). The distribution of the elements is as follows [24] : 50% of gas, viscous and subjected to gravitation forces and 50% of dark matter only affected by gravity.

[1] New General Catalog: a census of astrophysical structures.
[2] 1 Myr = 1 million years = $3.1536.10^{13}$s

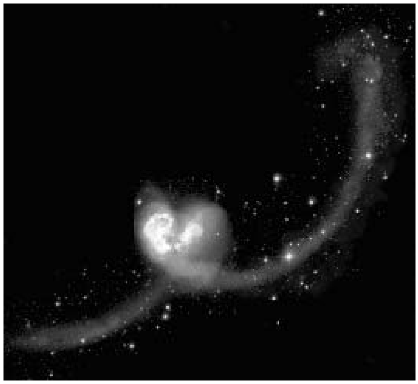

Fig. 1. NGC 4038/9 ("The Antennae") image from the spatial telescop Hubble (http://hubblesite.org/)

3 Hierarchical Multi-agent Model

Our model is a multi-agent system composed by four kinds of agents and complexity levels. Each level is dedicated to a scale of time and space. These levels correspond to : (1) internal interactions, (2) local interactions and interactions applying on a short distance, (3) long range interactions and (4) environmental actions. General model has already been presented in [14] and we focus here on the model used for "The Antennae" simulation.

Level 1
Level one agent are point-mass particles of matter subjected to gravity :

$$\overrightarrow{F}_{ij} = -G \cdot \frac{m_i m_j}{r_{ij}^2} \tag{1}$$

where G is the gravitational constant, m_k the mass of the agent k and with r_{ij} the distance between agent i and agent j.

It exists few algorithms to calculate the impact of the gravitation force (1) on the various elements of a system. Presented by Barnes & Hut [9] the TreeCode is one of these algorithms designed to calculate the effect of gravity. It was proposed to obtain a significant number of particles and a correct resolution. This algorithm allows to specify a parameter θ which determines from which distance the action of n close particles is not dissociable from the action of a particle having the added mass of these n particles. Its use in a wide number of cosmological algorithm ([17], [15], [16] ...) and its adaptability justifies its use in our model. To limit the computing time of transition rules of this level we use a θ near to 0.

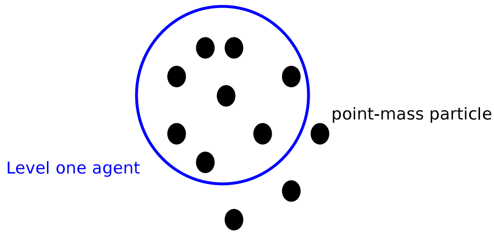

Fig. 2. Schematic illustration of level one agents

Level 2

We have conducted several experiments to study the behavior of level 1 agent under the effect of gravity, in various conditions of mass, distribution, initial velocity, etc. Fig. 3 shows a typical result of these experiments.

These experiments have shown that level 1 agents are driven in disordered rotation whose radius and spin vary according to time. Structures formed at the end of all these experiments are spherical and correspond to what we defined as the level 2 agents.

By correlating the experiments we can realize that it exists in all simulations a transitory series of state (limited in the time or not) during which the particles collapse on themselves. The duration and the speed of collapse (from stabilization to total collapsing) are function of the relationship between the overall mass of the system and the number of agents on which it is distributed (Fig. 3). These results correspond to the evolution function of the radius applied on peripheral elements : agents are approximated as a sphere whose radius and spin varies according to the inner mass. They can represent a mass of gas,

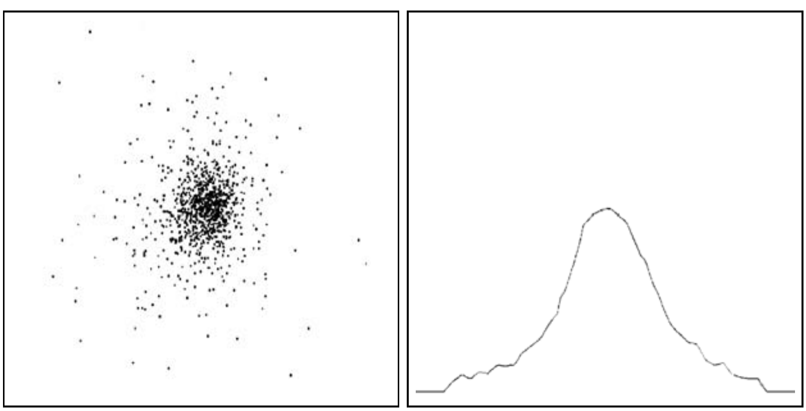

Fig. 3. Left: a typical stable structure formed (1.000 particles) by gravity (G fixed at its physical value) application on a random distribution. Right: evolution of the collapse time according to the mass/number of particles ratio.

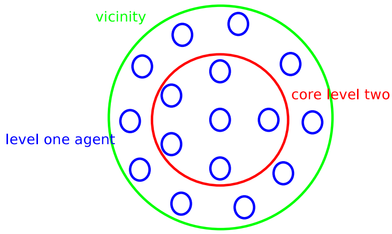

Fig. 4. Schematic illustration of level two agents

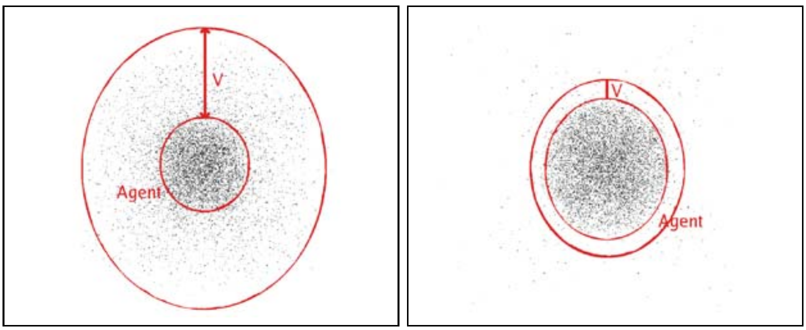

Fig. 5. Illustration of the concept of core and vicinity (v) in the model, from an experiment carried out on a TreeCode.

purely gravitational matter (called dark matter) or a star. Level two gather all the interactions applying on a short distance such as accretion [18]. Therefore the function U applied by this level of complexity will be:

$$Ux_i = \sum_{j=1}^{M} \mu_j^t \cdot \left[V_j^t(x) + s_j^t(x)\right] \tag{2}$$

Where s_i^t is the spin of the agent j at time t, $V_j^t(x)$ the velocity of the agent j at time t and μ_j^t the accretion of the agent j at time t.

Fig. 5 shows examples of this concept of vicinity and level two agents and its physical mapping : structures, self-formed by the effect of gravity, are surrounded of a less dense matter halo on which local forces, such as accretion, apply.

Level 3

Level 3 agents are the abstraction of level 2 agents subjected to long range interactions. Regarded as the principal force responsible for cosmological structures formation, gravity applies to all the elements present in the universe. Transition rule between level 3 agent is still calculated by a TreeCode but with a θ parameter making it more precise than level 1 agent ($\theta >> 1$).

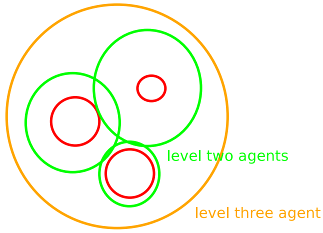

Fig. 6. Schematic illustration of level three agents

Level 4
The universe, as we know it, is expanding. This can be simulated as a force applied to all the agents and aiming at moving away all elements of the system. Level 4 agents will be subjected to a radial force applied by the environment. The aim is to simulate the physical law:

$$v = H \cdot r \tag{3}$$

Where H is the Hubble's constant, r the curvature of space and v the velocity of an unspecified point of the universe.

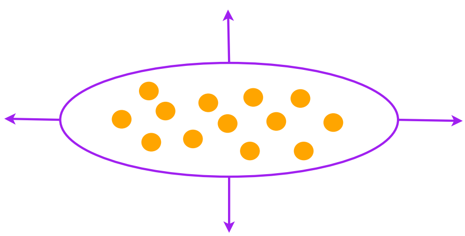

Fig. 7. Schematic illustration of level four agent

4 Results

All experiments describe in this section have been done using a C implementation of the model introduced above and running on dual-core 2GHz PC with 2 Gb of memory. For gravity computing we used Barnes' treecode [19].

To check if our model is less dependent to the number of elements used than a classical model, a series of experiments aiming at repeating the same simulation with a decreasing number of agents/particles has been carried out. We used decreasing numbers of agents/particles : from 10.000 to 500. For each experimental case, we compared our result with the one obtained using a reference simulation model of the phenomenon. We choose J. Dubinski's model [21] - a classical model that uses a treecode and SPH [20]. The same experimental conditions were used

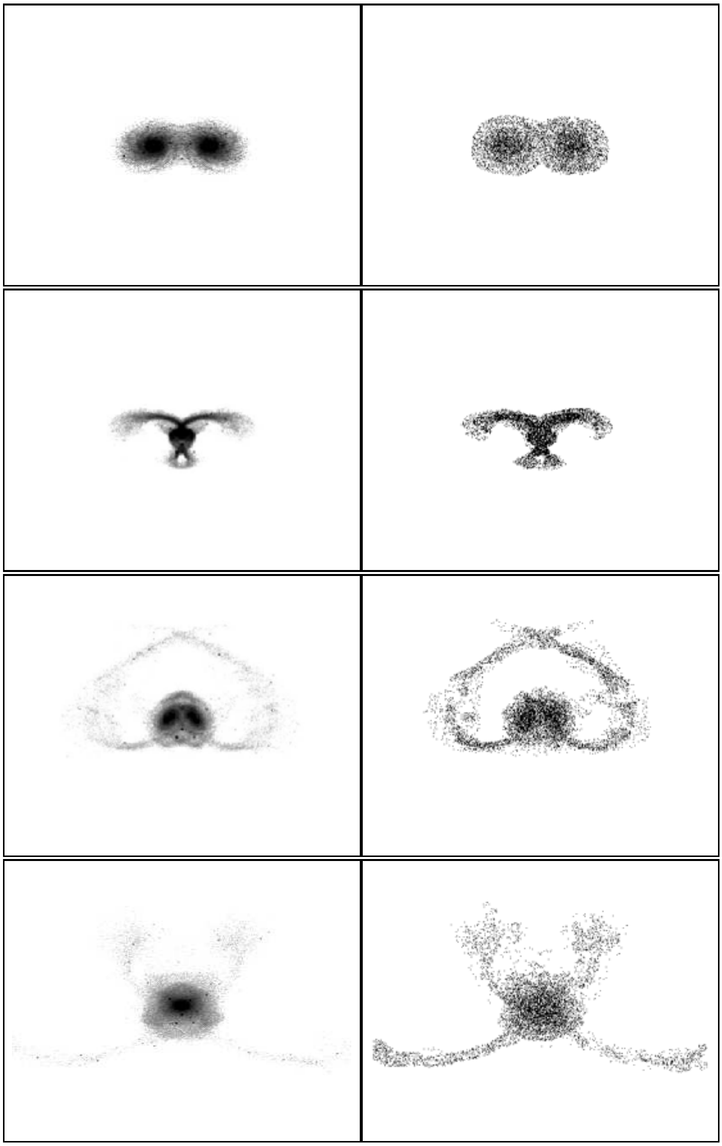

Fig. 8. Left, the result of a simulation using Dubinski's model with 10.000 particles. Right, the same simulation time with our model. Times are t=6.5s, t=10.9s, t=12.1s and t=13.8s.

in each simulation : NGC 4038 and NGC 4039 were simulated with a weight of 1.99e+42 Kg. The time scale was : 1s simulation time = 1.05e+15s cosmological time.

Fig. 8 presents the results of the experiments describe above on our model (right) and the reference simulation model (left). With 10.000 agents, a structure

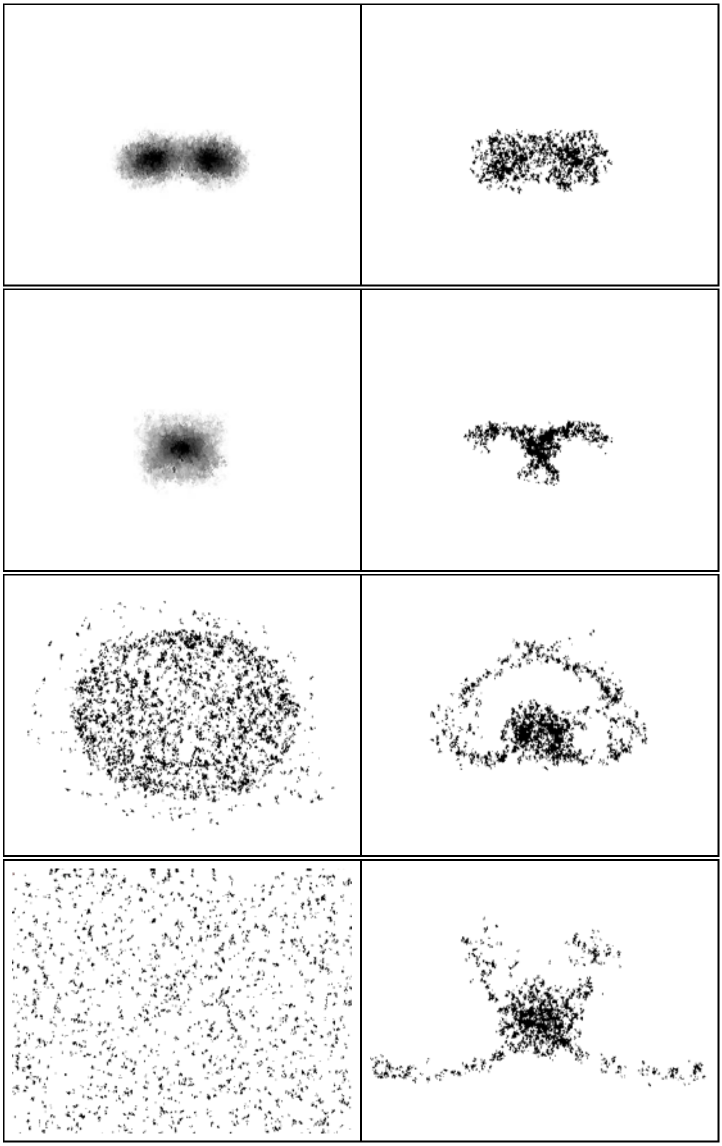

Fig. 9. Left, the result of a simulation using Dubinski's model with 500 particles. Right, the same simulation time with our model. Times are t=6.5s, t=10.9s, t=12.1s and t=13.8s.

similar to "The antennae", emerges from both models : after the collision of NGC 4038 and NGC 4039 both structures remain compact. It appears "tails" of agents because of their inertia, but still subjected to the gravitation of the central mass.

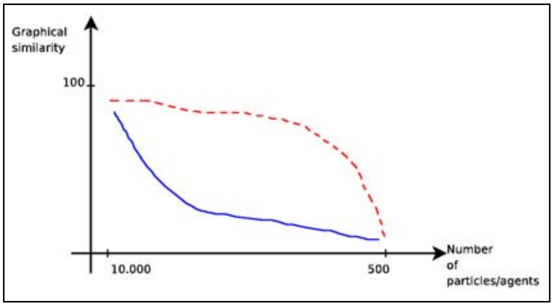

Fig. 10. Percentage of similarity between "The Antennae" shape and the results of our model (indents) and the results of the reference cosmological model

Experiments done using 9.000 agents/particles down to 500 agents/particles led to the same qualitative results presented above in Fig. 9.

With such few agents (compare to the reference cosmological simulation), a structure, qualitatively similar to "The Antennae" continues to emerge from our model. Same experiment with a cosmological model does not lead to any stable structure and all the agents are scattered in the universe : dynamics is linear and the agents scatter progressively.

5 Discussion

The emergence of "The Antennae" shape in our experiments qualitatively show that, in contrast with the reference model, beyond a threshold as shown on Fig. 10, the number of elements does not influence dynamics any more. Such a threshold seems to be due to multi-levels organization but further studies need to be done to specify the conditions and the reasons of appearance of this threshold value.

In contrast to the reference simulation model where a reduction of the number of particles leads to a less homogeneous application of forces, the evolution of the agents at each level on our model compensate this drift : in both models point-mass particles (level 1 agent in our model) are subjected to less important gravity forces. In a classical model, that leads to an expansion dynamics of all the elements. In the hierarchical model, this leads to an increase of the size of the level 2 agents and the size of the vicinity of these agents. Such an increase modifies the importance and the range of the transition functions applied by this level (accretion). These transition functions increase the total cohesion between agents, compensating grativity and improving formation and survival of complex structures.

6 Conclusion

In this paper a new hierarchical multi-agent model aiming to solve the inherent problems of the point-mass particle approach has been described. By simulating a well-known complex cosmological structure, "The Antennae", qualitative evidences have been presented that a hierarchical multi-agent model is less sensitive to the number of elements used in simulation than classical models : beyond a threshold, emergent dynamics remain the same. Such experiments have also already be done in [14] on another structure called "The Mice" [22] [23] [24].

Future works include a deeper quantitative analysis of these results. A second direction is the study of the complexity classes described by a wide parametrization of this model : by replacing the universe *as-we-know-it* in a larger picture of universe *as-it-could-be*, we will try to understand patterns formation and dynamical evolution. Finally, as it exists a difference between observation and numerical simulation on spheroidal galactic formation (radial velocity of peripheral elements does not match with the observable one [25]) we can check if our model can bring some answers.

References

1. Alimi, J.M., Serna, A., Pastor, C., Bernabeu, G.: Smooth particle hydrodynamics: importance of correction terms in adaptive resolution algorithms. Journal of Computational Physics (2003)
2. Gelato, S., Chernoff, D.F., Wasserman, I.: An Adaptative Hierachical Particle-Mesh code with Isolated Boundary Conditions. The Astronomical Journal (1997)
3. Snytnikov, V.N., Dudnikova, G.I., Gleaves, J.T., Nikitin, S.A., Parmon, V.N., Stoyanovsky, V.O., Vshivkov, V.A., Yablonsky, G.S.: Space chemical reactor of protoplanetary disk. Adv. Space Res. 30(6), 1461–1467 (2002)
4. Kuksheva, E.A., Malyshkin, V.E., Nikitin, S.A., Snytnikov, A.V., Snytnikov, V.N., Vshivkov, V.A.: Numerical simulation of self-organisation in gravitationally unstable media on supercomputers. In: Malyshkin, V.E. (ed.) PaCT 2003. LNCS, vol. 2763, pp. 354–368. Springer, Heidelberg (2003)
5. Dawson, J.M.: Gravitational N-Body Problem. Lecar, M. (ed.), p. 315. Reidel, Dordrecht (1972)
6. Alimi, J.M., Chièze, J.P., Teyssier, R., Serma, A., Audit, E.: Simulations numériques en cosmologie. Calculateurs parallèles 11, 255–273 (1999)
7. Wolfram, S.: Statistical Mechanics of Cellular Automata. Reviews of Modern Physics 55, 601–644 (1983)
8. Frisch, U., Hasslacher, B., Pomeau, Y.: Lattice-gas automata for the Navier-Stokes equation. Physical Review Letters 56, 1505–1508 (1986)
9. Barnes, J., Hut, P.: A hierarchical O(N log N) force-calculation algorithm. Nature 324, 446–449 (1986)
10. Wolfram, S.: A New Kind Of Science. Wolfram Media (2002)
11. Schulman, L.S., Seiden, P.E.: Percolation and Galaxies. Science 233, 425–430 (1986)
12. Heudin, J.C.: Modeling Complexity using Hierarchical Multi-Agent Systems. In: Modelling and Simulation in Science. The Science and Culture Series - Astrophysics (2007)
13. Heudin, J.C.: Complexity Classes in Three-dimensional Gravitational Agents. Artificial Life VIII, 9–13 (2003)
14. Torrel J.C., Lattaud C., Heudin J.C.: Studying Complex Stellar Dynamics using a Hierarchical Multi-Agent Model. Modelling and Simulation in Science, The Science and Culture Series - Astrophysics (2007)
15. Cheol-O, A., Sang Hwan, L.: A new treecode for long-range force calculation. Computer Physics Communications 178(2), 121–127 (2008)

16. Kasthuri, S., Vivek, S.: A treecode for accurate force calculations. In: Alexandrov, V.N., van Albada, G.D., Sloot, P.M.A., Dongarra, J. (eds.) ICCS 2006. LNCS, vol. 3991, pp. 92–99. Springer, Heidelberg (2006)
17. Bode, P., Ostriker, J.P., Xu, G.: The Tree-Particle-Mesh N-body Gravity Solver. Astrophysical Journal Supplement Series, 561 (2000)
18. Frank, J., King, A., Raine, D.: Accretion power in astrophysics, 3rd edn. Cambridge University Press, Cambridge (2002)
19. Barnes, J.E.: Treecode implementation (2008), `http://www.ifa.hawaii.edu/~barnes/treecode/treeguide.html`
20. Lucy, L.B.: A numerical approach to the testing of fission hypothesis. The Astronomical Journal 82, 1013–1024 (1977)
21. Dubinski, J., Mihos, J.C., Hernquist, L.: Using Tidal Tails to Probe Dark Matter Halos. The Astrophysical Journal 462, 576–593 (1996)
22. Barnes, J.E., Hibbard, J.E.: Model of Interacting Galaxies, `http://www.ifa.hawaii.edu/~barnes/research/`
23. Hibbard, J.E., Barnes, J.E.: Observations and Simulation of N4676, `http://www.cv.nrao.edu/~jhibbard/n4676/`
24. Mihos, J.C., Bothun, G.D., Richstone, D.O.: Modeling the Spatial Distribution of Star Formation in Interacting Disk Galaxies. Astophysical Journal 418, 82–99 (1993)
25. Burkert, A., Naab, T.: The Formation of Spheroidal Stellar Systems. Carnegie Observatories Astrophysics Series, Coevolution of Black Holes and Galaxies, vol. 1, pp. 1–16 (2004)