COSMOLOGY, GRAVITATION, ASTROPARTICLE PHYSICS, HIGH ENERGY PHYSICS

https://doi.org/10.18524/1810-4215.2023.36.289962

GALAXY CLUSTER MERGERS: THE USE OF THE COMPUTER MODELING

M. Berkovskyi[1], E. Panko[2], N. Miroshnik[3]

[1] National Centre "Junior Academy of Sciences", under the auspices of UNESCO, Kamianske, Dnipropetrovsk region, Ukraine
[2] Department of Theoretical Physics and Astronomy, I.I. Mechnikov Odessa National University, Odesa, Ukraine
panko.elena@gmail.com
[3] Communal institution "Anatoliy Lyhun Scientific Lyceum" of the Kamianske City Council, Dnipropetrovsk region, Ukraine

ABSTRACT. We show the possibilities of the methods of computer modeling of the galaxy cluster merger process with different initial parameters for the investigation of the features of the clusters after colliding.

We considered the galaxy clusters as evolving objects including through collisions. Computer modeling of galaxy cluster mergers and comparing its results with observational data makes it possible to determine the evolutionary status of real clusters with complex internal structures. Within the study, we analyzed in detail a series of models of the galaxy clusters' merger consequences by ZuHone under different initial conditions like mass ratio, initial collision parameter, or plasma coefficient β. The considered time intervals were from 0 to 4.8 billion years, from 0 to 6 billion years, and from 0 to 10 billion years, depending on the initial conditions.

Based on the images of the simulated galaxy clusters, maps of the distribution of the total mass density and X-ray radiation were created and compared with observations. We showed a good perspective to use this catalog for studying galaxy clusters having compound inner structure.

Keywords: Galaxy clusters: morphology, inner structure; data analysis: modeling.

АНОТАЦІЯ. У дослідженні на основі каталогу змодельованих зіткнень скупчень галактик ("The Galaxy Cluster Merger Catalog: An Online Repository of Mock Observations from Simulated Galaxy Cluster Merg ers", on-line data: http://gcmc.hub.yt/) вивчено можливості методів комп'ютерного моделювання процесу зіткнення скупчень галактик із різними початковими параметрами для дослідження особливостей скупчень після процесу злиття. Ми розглядаємо скупчення галактик як об'єкти, що еволюціонують, зокрема через зіткнення. Комп'ютерне моделювання злиття скупчень галактик і порівняння його результатів зі спостережними даними дає змогу визначити еволюційний статус реальних скупчень зі складною внутрішньою будовою. У рамках дослідження ми детально проаналізували серію моделей наслідків злиття скупчень галактик за різних початкових умов, таких як відношення мас, початковий параметр зіткнення або коефіцієнт плазми β. Було розглянуто часові інтервали від 0 до 4.8 млрд років, від 0 до 6 млрд років і від 0 до 10 млрд років, залежно від початкових умов. Також проаналізовано та порівняно між собою змодельовані результати зіткнень скупчень галактик. На основі зображень змодельованих скупчень галактик побудовано карти розподілу загальної густини маси та рентгенівського випромінювання, які порівняно зі спостереженнями. Наведено приклади аналізу двох реальних збурених скупчень галактик за допомогою мап розподілу загальної густини маси та рентгенівського випромінювання. Зроблено висновок, що порівняння оброблених зображень із реальними дає змогу оцінити параметри скупчень, що злилися, та визначити час цього зіткнення. Показано перспективність використання цього каталогу для вивчення скупчень галактик зі складною внутрішньою структурою. Каталог також буде корисним при викладанні курсу "Позагалактична астрономія".

Ключові слова: скупчення галактик: морфологія, внутрішня структура; аналіз даних: моделювання

1. Introduction

A common modern paradigm about galaxy clusters forming is arising the large-scale structures according to the primordial distribution of the adiabatic fluctuation in the early Universe, as it was studied in a lot of works, beginning from theoretical papers (Zeldovich, 1970 and Peebles, 1969) and observed data analysis (Wen et al., 2009, Dietrich et al., 2012, Parekh et al., 2020). The special place in this study occupies the numerical simulations which are based on the DM distribution (Springel et al., 2005, Vogelsberger et al., 2014, Artale et al., 2017, Cui et al., 2018, Tomoaki et al., 2021). Overdence regions evolved to the galaxies, galaxy groups or clusters in dependence on their own scale. The simulations improve the accuracy of simulations of the dynamics of gas, dark matter, and stars in the expanding cosmological background, starting from an initial state of high-redshift matter fluctuations. Clusters of galaxies form in these simulations at the junction between filaments of gas and dark matter. Depending on the physics used, stars form from cold, dense gas and explode as supernovae, providing a source of energy for the environment and enriching it with metals. Some simulations include the formation of black holes and the resulting feedback from active galactic nuclei. The next growing of these structures occurs, among other things, due to peculiar mowing inside the Hubble flow, and the interaction and collisions of the galaxy groups and clusters appear in their inner structure/substructures.

In the optic, we can see the complex inner structure of galaxy clusters as the peculiarities or regular substructures in the distribution of galaxies. Their main features are reflected in the morphological classification schemes of galaxy clusters. The idea by Struble & Rood (1987) about the connection between the morphological type and evolutional status of galaxy clusters was improved in the Panko (2013) classification where the influence of the close neighbors is reflected as regular cluster substructures. However, the galaxies are the smallest mass part of galaxy clusters, and hot intracluster gas has also different features in the distribution. In the X-ray range, the distribution of the density and temperature is described in corresponding classification schemes. Buote & Tsai (1995, 1996) developed a method to quantify cluster morphology and substructure by "power ratios" that measure the square of the ratio of high-order multipole moments of the two-dimensional potential to the monopole moment. Weißmann et al. (2013), using the Buote & Tsai (1996) approach discussed regular, intermediate, complex, double as well as relaxed, mildly disturbed, and disturbed X-ray clusters. More, the multeity in X-ray images of galaxy clusters (tails, cold fronts, sloshing, etc.) requires to use of the modern method of comparing the observed data with the models, calculated on powerful computers or supercomputers. The DM distribution inside the galaxy cluster is the most difficult task, but the comparison of the distributions of all three components of the cluster is the key to galaxy cluster evolution.

The aim of the present paper is to use the grids of models to reproduce the effects of collisions of galaxy clusters, to study the distribution of dark matter and hot gas at different initial parameters of the collision on a time scale of up to 4.8 and 10 billion years as well as to compare the grids of models with the observed data.

2. Simulation of Galaxy Cluster Collisions

For the study of the results of galaxy cluster collisions, we used "The Galaxy Cluster Merger Catalog: An Online Repository of Mock Observations from Simulated Galaxy Cluster Mergers" (ZuHone et al., 2018, on-line data: http://gcmc.hub.yt/). The original set of simulations was performed using the computational resources of Argonne National Laboratory and Lawrence Livermore National Laboratory, with this updated and improved set performed using the Pleiades supercomputer at NASA's Ames Research Center. The simulation of collisions of galaxy clusters is represented by three types of simulations, which are divided into one or more subtypes. They are: N-body collisions/hydrodynamic binary collisions, hydrodynamic binary collisions with hard gravitational potentials, and clusters in cosmological simulations, which improve the accuracy of simulations of the dynamics of gas, dark matter, and stars in the expanding cosmological background, starting from an initial state of high-redshift matter fluctuations. All of them differ in initial conditions and approximations. In each type of simulation, certain theories are adopted and there are parameters that make it possible to understand the content of the simulation, namely, DM, DE in the ΛCDM paradigm, H_0, metallicity Z (at usual, $Z \sim 4\,\%$ near the center of galaxy clusters, and $Z \sim 0.5\,\%$ on the object's outskirts, in these models it was assumed $Z = 0.3 Z_{\odot}$), velocity dispersion (it allows calculation the mass of such a group by applying the virial theorem), the critical density of the Universe ρ_c, the radius enclosing a volume with a mass density 200 times the critical density ρ_c, at cluster redshift r_{200}, cosmological parameter corresponding to the mass density, which includes baryonic mass and dark matter Ω_m, cosmological constant that corresponds to the fraction of the effective mass of the Universe that is accounted for by dark energy Ω_Λ, the mass ratio between two clusters R, the distance between the centers of clusters d - the initial collision parameter in kpc or Mpc b, and the cosmological epoch of the simulation in Gigayears t, and also magnetic induction and Spitzer viscosity. The typical box size for N-body/Hydrodynamic Binary Mergers was $L = 14.26\,$Mpc, the finest cell size was $\Delta x_{min} = 6.96\,$kpc, and primary cluster mass was $M_{200} = 6 \cdot 10^{14} M_{\odot}$. For sloshing of Cold Gas in Galaxy Cluster Cores the corresponded values were:

$L = 10$Mpc, $\Delta x_{min} = 4.88$ kpc and $M_{200} = 10^{15} M_{\odot}/$. The output figure is FITS image.

3. The Grids of Models and the Comparison with the Real Data

The catalog, which we used in the present study, contains interactive static images that show the state of the cluster at a particular moment of its evolution. Depending on the needs of the study, one can use images of various physical quantities (temperature, X-ray radiation, total density or dark matter density, etc.) in 3-axis projections. Since modern researchers mostly use maps of the distribution of physical quantities to compare images of distant space objects, it is worth doing the same with the catalog materials to use them in research. For a basic comparison of several simulations with each other, the creation of distribution maps is not necessary. Thus, after processing the graphical elements and their distribution, we get model grids, which are a good way to conveniently compare the effects of collisions with each other. We can compare the distributions of X-ray emission, temperature, magnetic induction, and dark matter density of the clusters at the beginning and end of the simulation in the same axis projection.

3.1. Comparison with Typical Perturbed Galaxy Clusters

To create clear isolines on the distribution maps, we used the free online graphic editor *Photopea* and the built-in Hue/Saturation, Trace Contour, and Black and White filters with the same parameters. These filters made the image more saturated, highlighted the transition lines between the most contrasting colors of the images, which made it possible to highlight the gradual transition between the values of the physical quantities under consideration with isolines, and converted the images to black and white for easy comparison, respectively. The example of isolines is shown in Fig. 1. The processed image (right panel), one can see isolines separating the transitions between colors within specific values of the considered parameter for the image which is shown in the left panel. Isolines form clear intervals of value, which makes it easy to compare images with critical values that differ by several orders of magnitude.

By comparing the distribution maps of simulated and real clusters (Fig. 2), it is possible to determine, for example, the approximate time of a past or future collision between two objects in a short time. When comparing and extracting the data, attention is first paid to determining the mass ratios of the interacted clusters, which is done using the density distribution

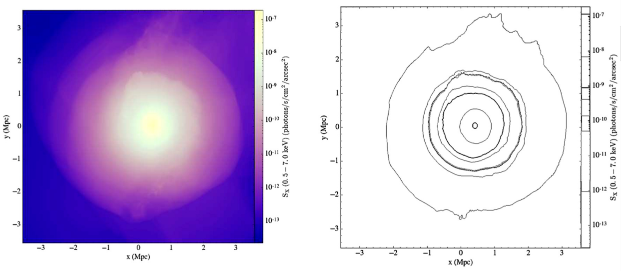

Figure 1: An unprocessed image of the distribution of the X-ray photon flux density of the hot gas of the clusters with the values of the parameters $R = 1 : 3$ and $b = 1000$ kpc at the end of the simulation $t = 10.00$ Gyr in the z-axis projection, left panel; a map of the distribution of the X-ray photon flux density after applying filters and converting the image to black and white, right panel

maps of the total mass or the dark matter mass. Then, the distance between the centers of the two colliding objects is extracted and the moment in the simulation where this distance is equal to the distance between the real subclumps is found. To update the results, we take into account the distribution of X-rays, so we can determine the degree of perturbation of the object.

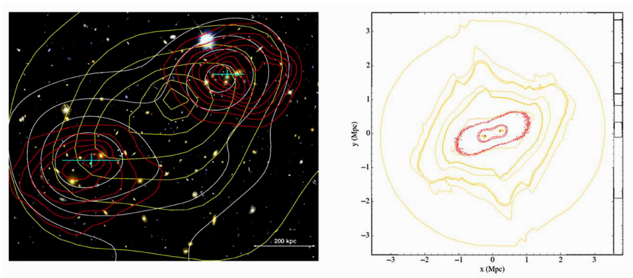

Figure 2: An image of the contours of the surface mass concentration of the MACS J0025.4-1222 cluster (red) and the contours of the X-ray brightness (yellow), left panel; a colored map of the distribution of the total mass density (red) and the X-ray photon flux density (yellow) of the simulated clusters with the values of the parameters $R = 1 : 1$ and $b = 500$ kpc at the moment of simulation $t = 2.60$ Gyr in the z-axis projection, right panel

3.2. Comparison of the Subtype "A Parameter Space Exploration of Galaxy Cluster Mergers"

We compare the changes in the position of the total mass density concentration and gas distribution with the time of the simulated and real collisions. The distribution of the hot gas of the galaxy cluster in the simulation with mass ratio $R = 1 : 3$ and $b = 500$ kpc is similar to that of the real colliding clusters 1E2215 and 1E2216. Comparing the changes in the gas distribution with time, we can conclude that the time after which the collision of clusters 1E2215 and 1E2216 will begin approximately is 1.30 billion years. The same comparison for the collision of the MACS J0025.4-1222 cluster found the collision of the MACS J0025.4-1222 cluster (Fig. 2) took place 1.2-1.28 billion years ago.

We can conclude about the simulations of the cluster collisions the next:

- Comparing the results of simulations at fixed values of the parameter R and values of $b = 0$, 500, 1000 kpc within the subtype "A Parameter Space Exploration of Galaxy Cluster Mergers" it follows that at $R = 1 : 1$ the effects of collisions are the simplest – clusters of almost regular shape are formed. At $R = 1 : 3$, the newly formed clusters are disturbed and quite heterogeneous, and at $R = 1 : 10$, the clusters are generally of the correct shape, except for small regions of inhomogeneity in the distribution of baryonic matter.
- Due to the fixed values of the parameters R and b in the subtype "Sloshing of Cold Gas in Galaxy Cluster Cores", the distribution of the photon flux density and temperature values look almost identical. However, in the simulation without taking into account the viscosity, the distribution of hot gas is more heterogeneous compared to the simulation with the Spitzer viscosity.
- In the subtype "Sloshing of the Magnetized Cool Gas in the Cores of Galaxy Clusters", the simulation results look almost identical at values of the plasma coefficient $\beta = 100$, $\beta = 200$, $\beta = 500$, $\beta = 1000$, differing only in that at higher values of plasma – β the central region of the cluster has increasingly higher values of the photon flux density, temperature and magnetic induction.

.

4. Conclusion

The "The Galaxy Cluster Merger Catalog: An Online Repository of Mock Observations from Simulated Galaxy Cluster Mergers" (ZuHone et al., 2018) defines a wide range of calculated parameters of the collided galaxy clusters. Comparing the simulation results and the created distribution maps with typical disturbed galaxy clusters, it follows that 1.2-1.28 billion years have passed since the collision of the MACS J0025.4-1222 cluster, and the time after which the collision of the 1E2215 and 1E2216 clusters will begin is approximately 1.3 billion years. So, the comparison of the calculated images with the real ones makes it possible to assess the parameters of the collided clusters and determine when events occurred. It is possible to use the model grid and catalog in the academic teaching for the "Extra-Galactic Astronomy" course.

Acknowledgements. This research has made use of NASA's Astrophysics Data System.

References

Artale M. C., Pedrosa S. E., Trayford J., et al.: 2017, *MNRAS*, **470**, 1771.
Buote, D., & Tsai, J.: 1995, *ApJ*, **452**, 522.
Buote, D., & Tsai, J.: 1996, *ApJ*, **458**, 27.
Cui W., Knebe A., Yepes G., et al.: 2018, *MNRAS*, **473**, 68.
Dietrich J. P., Werner N., Clowe D., et al.: 2012, *Nature*, **487**, 202.
Parekh V., Lagana T. F., Tho K., et al.: 2020, *MNRAS*, **491**, 2605.
Peebles P.: 1969, *AJ*, **155**, 393.
Springel V., White S.D., Jenkins A., et al.: 2005, *Nature*, **435**, 629.
Struble M.F. & Rood H.J.: 1982, *AJ*, **87**, 7.
Tomoaki A.A., Francisco P., Klypin A.A., et al.: 2021, *MNRAS*, **506**, 4210.
Vogelsberger M., Genel S., Springel V., et al.: 2014, *MNRAS*, **444**, 1518.
Wen Z.L., Han J.L. & Liu A.C.: 2009, *ApJSS*, **183**, 197.
Weißmann A., Böhringer H., Suhada R. & Ameglio S.: 2013, *A&A*, **549**, A19.
Zeldovich Y.B.: 1970, *A&A*, **5**, 84.
ZuHone, J.A., Kowalik, K., et al.: 2018, *ApJSS*, **234**, 4.