Model of galaxy and star cluster formation corrected

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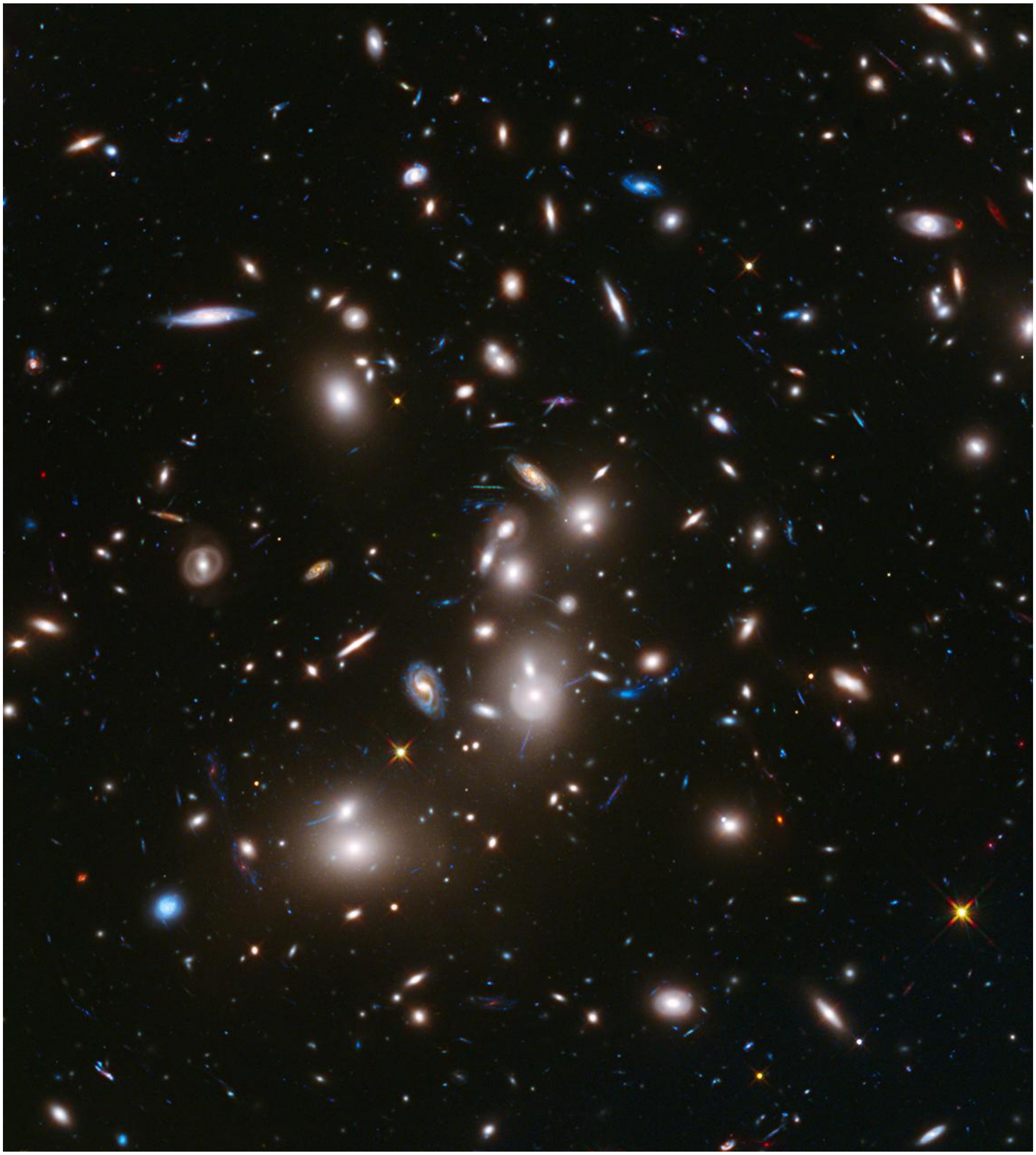

This is a long-exposure image from NASA's Hubble Space Telescope of massive galaxy cluster Abell 2744. It shows some of the faintest and youngest galaxies detected in space. Credit: NASA/ESA/STScI

When galaxy clusters and globular star clusters form, a phenomenon called "violent relaxation" occurs. After interacting intensely, the thousands or even millions of bodies reach a state of relative gravitational equilibrium and a fairly long-lasting spatial distribution.

A new study developed by Brazilian researchers and published in *The Astrophysical Journal* argues that astrophysicists' understanding of violent relaxation is wrong and sets out to correct it.

"The problem is that Vlasov's Equation assumes constant entropy in the system, meaning there's no production of entropy. This is equivalent to saying the situation is symmetrical in time, since the arrow of time is determined by increasing entropy. It evidently isn't in the actual phenomenon," says Laerte Sodré Júnior, one of the authors of the study, full professor, and ex-director of the University of São Paulo's Institute of Astronomy, Geophysics & Atmospheric Sciences (IAG-USP) in Brazil.

According to Sodré, the relaxation process has always been analyzed using the Vlasov Equation, a differential equation proposed in 1931 by Russian physicist Anatoly Alexandrovich Vlasov [1908-75] to describe the kinetic processes that take place in plasma.

If it were true, a process of this kind—reversible in time—would require a revision of the very foundations of physics. For this reason, the specialized literature refers to it as "the fundamental paradox of stellar dynamics."

"It was clear to us that something was wrong, and our suspicion was confirmed by the study," Sodré said. "The solution we found to the purported 'paradox' can be summed up in one short sentence: The Vlasov Equation simply doesn't apply to this case."

Virial equilibrium

The researchers leveraged powerful computational resources, such as employing a computer cluster as a means of proving this intuitive idea. As expected, the simulations showed that entropy increases, but another outcome was hard to understand: While entropy increases in the long run, at the start of the relaxation process, it fluctuates, alternately increasing and decreasing.

"It may seem to contradict what we know about entropy, which is understood to be a quantity that always increases. It certainly does increase inexorably in the long run, but not all the time. Owing to the large scope of gravitational interactions, bodies establish correlations with each other, and these correlations determine the oscillatory nature of entropy in the initial stage of the process," Sodré said.

"We can think about the question like this. Entropy has two aspects. One is purely chaotic, associated with the second law of thermodynamics—this is conventional entropy. The other derives from these correlations, which fade away over time, albeit slowly. This is what determines its oscillatory behavior."

It might be easier to understand the problem by imagining a cluster of 1,000 stars or 1,000 galaxies confined in a certain volume. They initially have zero velocity, but owing to gravitational interaction, each one begins to attract all the others, and the initial distribution changes, alternately contracting and expanding.

This to-and-fro determined by long-range interactions is associated with oscillations of entropy. It lasts until the entire system reaches a state of relative equilibrium, in which it remains somewhat stable in terms of its general properties. In the 19th century, this state was given the name "virial equilibrium," a term that is still in use.

"It's a specific feature of gravitational interactions. Electromagnetic interactions are also long-range, but because matter is in general electrically neutral, their effects are confined to a limited volume. The shielding effect doesn't occur with gravitational force. In principle, it can extend to infinity. This is what creates those correlations," Sodré said.

Although galaxy clusters and globular star clusters interact with the entire universe, they can be thought of here as closed, "non-dissipative" systems, meaning that their total energy is not lost to the external medium, but conserved.

Some bodies acquire large amounts of kinetic energy and accelerate beyond escape velocity, becoming detached from the system, but this is not especially significant, overall. Entropy oscillation generally should be considered an internal process, which does not involve an exchange of energy with the medium.

"No other types of system display entropy oscillations that I know of, bar one: chemical reactions in which the compound produced serves as a catalyst for the inverse reaction. As a result, the reaction switches to and fro, and entropy in the system oscillates," Sodré said.

The new study resolves the "fundamental paradox of stellar dynamics," and describes the formation of cosmic macrostructures more realistically. The other researchers who took part were Leandro José Beraldo e Silva, Walter de Siqueira Pedra, Eder Leonardo Duarte Perico and Marcos Vinicius Borges Teixeira Lima.

Methodology

The gravitational interaction between these celestial bodies—galaxies or stars—is well described by Newton's law of universal gravitation, published 330 years ago. The problem is mathematically easy to solve for a two-body system, but the analytical solution becomes unworkable in systems involving thousands or millions of bodies, each of which interacts gravitationally with the rest. Hence the need to resort to complex numerical simulations.

"We used numerical techniques developed by Norwegian astronomer Sverre Aarseth, the leading expert on this kind of simulation involving many bodies," Sodré said. "These simulations require so much computer power that we had to use clusters of GPUs, which was far more efficient than the more usually deployed CPUs. Even so, each simulation took several days."

During the project, the Brazilian researchers were actually visited by Aarseth, who remains highly active at age 83. In addition to being a leading astronomer, the prizewinning Norwegian scientist is a keen trekker, mountaineer and nature lover, and he is ranked as an International Correspondence Chess Master.

"Aarseth's computer programs enabled us to solve the problem efficiently and reliably," Sodré said. "We then tested the results by comparing them with the solutions obtained using other cosmological programs. They matched."

More information: Leandro Beraldo e Silva et al, The Arrow of Time in the Collapse of Collisionless Self-gravitating Systems: Non-validity of the Vlasov–Poisson Equation during Violent Relaxation, *The Astrophysical Journal* (2017). DOI: 10.3847/1538-4357/aa876e

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