Uncovering the size-complexity rule in stars

Details

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Bio

Georgi Georgiev has been interested in evolution and development and self-organization processes at all levels in nature since high school. He graduated with a master's degree in physics and chemistry from Sofia University, Bulgaria, and moved to the United States to obtain a PhD in physics from Tufts University and a postdoc at Northeastern University. Georgiev is now Professor of Physics at Assumption University, and an Affiliate Professor of Physics at the Worcester Polytechnic Institute, Massachusetts.

Further reading

Butler, TH, Georgiev, GY, (2022) Self-organization in stellar evolution: Size-complexity rule, In *Efficiency in Complex Systems* (pp 53–80). Springer, Cham. doi.org/10.1007/978-3-030-69288-9

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- From national economies to living organisms, many systems where self-organization can be found will become more complex as their size increases.
- So far, these relationships have generally been studied separately, with little consideration for their similarities.
- In a new study, Professor Georgi Georgiev at Assumption University, Massachusetts, USA, shows for the first time how the 'size-complexity' law emerges clearly and unambiguously in stars.
- His results shed new light on how complex systems spanning numerous fields of research are all connected.

For thousands of years, philosophers have pondered the question: how can complexity emerge out of simplicity? Researchers have now uncovered deeply complex phenomena in areas as wide-ranging as natural ecosystems, national economies, and physical states of matter which can only be explained with the help of quantum mechanics.

Yet despite the intricacies of each of these systems, the individual elements which compose them are often far simpler: whether they are atoms, animals, or individual human interactions. As Aristotle elegantly put it, 'the whole is something besides the parts.'

All of these systems are linked by a single phenomenon named 'self-organization', which describes how systems consisting of numerous interacting parts and parameters may be composed out of simple, underlying elements. Today, self-organization is actively studied by physicists, chemists, biologists, economists, sociologists, and scientists across virtually every conceivable field of research in between.

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Yet despite the immense diversity of systems where self-organization can be found, their degree of complexity is ultimately governed by the same set of rules. 'These regularities must hold on to these levels of organization, regardless of the nature of the system', Professor Georgi Georgiev at Assumption University, USA, describes. 'An open question in science is how and why complex systems self-organise to produce new structures and properties.'

There are many different aspects of self-organization which could be explored – but in his latest study, Georgiev focuses on just one. Named the 'size-complexity rule', it describes how as systems become larger, they tend to become more complex – a scaling law. Through his research, Georgiev aims to learn more about the universal laws which apply to this relationship.

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The size-complexity rule

In previous research, Georgiev developed mathematical models to show how in certain systems, neither size nor complexity can exist without the other. Rather, they build each other up in a positive feedback loop as the system becomes larger and more intricate. As it grows, each characteristic of a complex system is then proportional to every other characteristic – not just the size and complexity of the overall system.

'The larger the system is, the greater potential it has for self-organization', Georgiev describes. 'More recently, this has been termed the size-complexity rule: which means that to increase their size, systems must increase their complexity, and to increase their complexity, they must grow.'

Self-organization in stars

The size-complexity rule can be found in branches of science ranging from anatomy to economics. In his study, Georgiev focused on one particular example: how self-organization in stars progresses as their size increases.

As more massive stars age, the nuclei in their cores will coalesce into progressively heavier elements through nuclear fusion. Over time, these different types of atoms will settle into different layers – each with their own unique temperatures, densities, and types of nuclear reaction taking place.

> **Just as he expected, the two quantities followed a robust mathematical relationship – distinctly similar to the relationships found in numerous examples of the size-complexity rule.**

Since more complex layered structures can only emerge in larger stars, Georgiev predicted that stars should follow the same size-complexity relation found in other complex systems. 'As a measure of complexity of a star, we use the degree of grouping of particles into atoms', Georgiev explains. 'This increases the variety of elements and changes the structure of the star.'

As higher numbers of particles group together through fusion, they produce a richer variety of elements over time. As a result, stars carrying higher fractions of heavy elements will have generally reached more advanced evolutionary stages – and therefore, a higher degree of complexity.

Studying simulations

To search for evidence of a size-complexity rule in stars, Georgiev turned to simulations of stars with different masses that explode as supernovae. These dramatic explosions occur at the end of a star's life, when the energy it releases via fusion is no longer enough to balance out its gravity – causing it to finally collapse in on itself.

Spectroscopy is the study of the absorption and emission of light and other radiation by matter.

The simulations Georgiev studied had been checked against real observations of exploding stars. In this case, the atomic constituents of the supernovae could be determined by analysing their spectra (the light waves emitted by the stellar remnants) in which every element present in significant quantities had imprinted its own unique signature over a specific range of wavelengths.

By analysing these spectra, the researcher had a reliable gauge on the complexity of the layered structures of the stars which triggered the supernovae just before their death. In addition, the energy released by the simulated supernovae were directly tied to the sizes of the stars at the end of their lives. Using this data, Georgiev could finally map out a relationship between the sizes and complexities of stars.

Uncovering the relationship

Just as he expected, the two quantities followed a robust mathematical relationship – distinctly similar to the relationships found in numerous examples of the size-complexity rule. 'The growth in one characteristic of a star causes growth in the rest of them', Georgiev concludes. 'This is one of the mechanisms of self-organization, expressed in evolution and development in complex systems.'

The discovery presents an important step forward in researchers' understanding of the universal nature of the size-complexity rule. Even so, the phenomenon still represents just one aspect of self-organization. In his upcoming research, Georgiev delves deeper into the emergence of complexity of our universe, with the aim of discovering more about the fascinating ways in which phenomena across numerous branches of science are interconnected.

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Personal response

What has so far prevented scientists studying different instances of the size-complexity rule from sharing their ideas?

Scientists have studied instances of the size-complexity rule in different disciplines and have developed distinct terminology, making the rule largely unrecognizable. The division of science into disciplines also contributes to this divergence; therefore, an interdisciplinary approach is the best to bring all of them together. For example, physicists don't often read papers in ecology and, similarly, ecologists don't frequently read physics papers, but in both disciplines the same scaling laws, such as the size-complexity rule, apply.

Why did you choose to focus on stars instead of other examples of the size-complexity rule?

We have looked at the size-complexity rule previously in Core Processing Units (CPUs) of computers, and currently have data for a variety of systems, among them the chemical processes of metabolism and photosynthesis, cities, supercomputers, the internet, and others. In this paper, we focussed on stars because it is an important example, as stars are the main form of organization in the universe and they produce the chemical elements needed for all other complex systems after that. Any additional knowledge about stellar evolution helps us understand the universe, and on the other hand, the information from stellar evolution helps develop the science of complexity. This research is possible because of the abundant high-quality data from astronomy on stellar composition and size and of simulations exploring stellar evolution.

What other aspects of self-organization do you plan to study in the future?

Other aspects of self-organization that we are planning to study are the properties of flow networks comprising complex systems, for example in organisms, ecosystems and economies. Another question is which basic physics laws guide the processes of self-organization towards future states and can be considered as the driving force of self-organization. For example, the principle of least action, which is used to derive all branches of physics, shows that the paths which are shortest require the least amount of energy and time. They are the most probable in complex systems; therefore, it creates an arrow of time towards paths with less action, ie, more efficient and with higher levels of organization. This can be one answer to the question why the processes of self-organization from the Big Bang to us and our society have not stopped, but have progressed at ever-accelerating rates. Based on this physics principle, we can expect future systems to reach more efficient and organized states even faster than in the past. Other characteristics of complex systems that are possibly in a scaling relation with the size are the density, efficiency, number of events, variety of elements, energy flows, robustness and many others. We hypothesize that they are in scaling relations also between themselves and change simultaneously with the evolution of complex systems. The change in each of them causes change in all others. This growth happens incrementally, in small limits around their proportionality relations. Larger deviations of each of them cause destabilization or even destruction of the complex system. This knowledge may help us manage better ecological, social and economic systems.


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