MOCCA – a new tool for simulating the evolution of star clusters

Clusters Full of Stragglers

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Numerical codes play a very important role in astrophysics. They make it possible to describe physical theories using mathematical equations. If the results of numerical simulations match observational data, it means that the physical theory provides a good description of reality

Star clusters are astronomical objects comprising hundreds or thousands of stars gravitationally bound to one another. The MOCCA (MOnte Carlo Cluster simulAtor) code is used to perform simulations of their evolution.

Star clusters are usually simulated using either the N-body approach or codes based on statistical solutions of the Fokker-Planck equation. The former method, N-body, is more precise and calculates the interactions between all stars within a cluster. The key advantage of such simulations is that no additional assumptions have to be made about the structure of star clusters. However, the extremely long calculation time means that simulating actually existing clusters, numbering at least hundreds of thousands of stars, is beyond the capacity of the fastest computer clusters available currently.

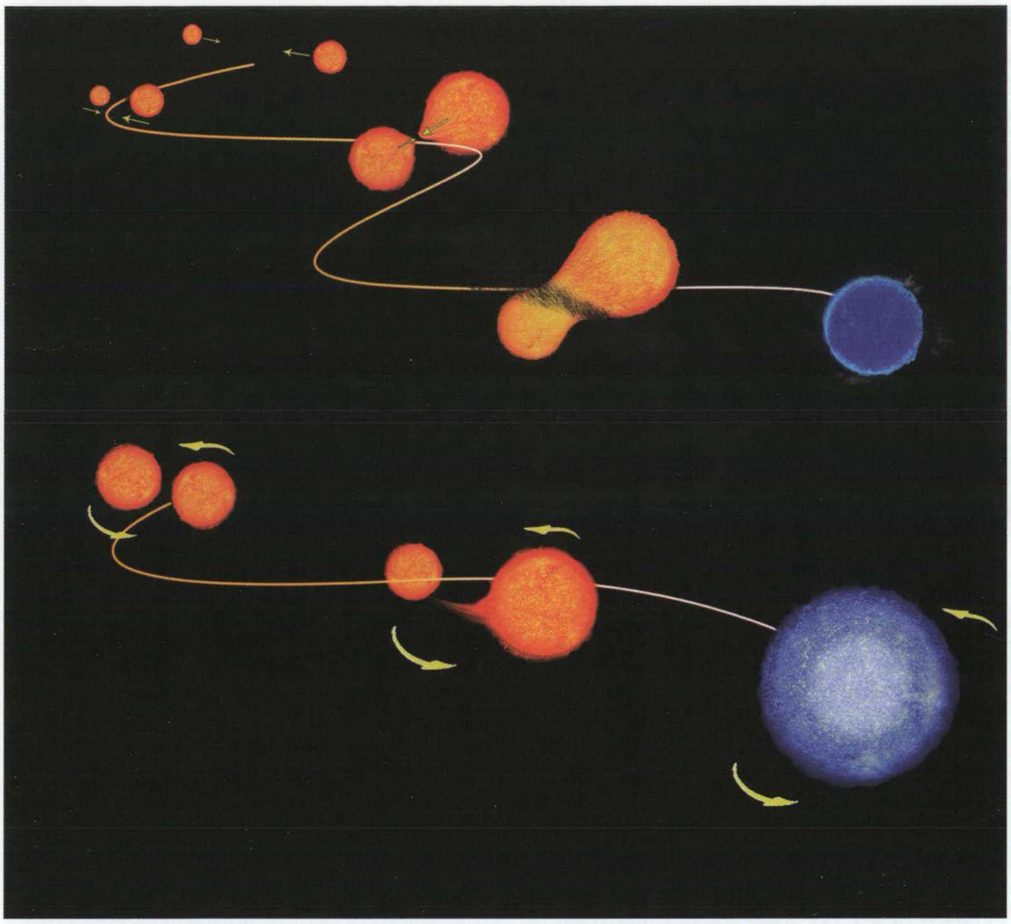
MOCCA, in turn, generally utilizes the latter method. The first main simplification of such statistical codes is the assumption of spherical symmetry: each star is treated as a sphere rather than a point in a three-dimensional space. The second is that the process of relaxation, responsible for the redistribution of energy within the cluster, is approximated by just a single interaction between two neighboring stars.

The MOCCA code is being developed at the Nicolaus Copernicus Astronomical Centre in Warsaw by Mirosław Giersz and the present author. It has recently been expanded by FEWBODY – an N-body code used to simulate close encounters between a single and a binary star, as well as binary-binary interactions. This means MOCCA can be used to study the formation and evolution of individual objects within a cluster, such as blue straggler stars (BSS), black holes, cataclysmic variables, and so on. This addition has turned MOCCA into a hybrid of the Monte Carlo and N-body approaches. Its simulations are now even closer to reality; currently, MOCCA is one of the most advanced numerical codes used in star cluster simulations. It traces the evolution of clusters in a similar manner to N-body simulations while being incomparably faster. In the time required to conduct a single N-body simulation, MOCCA calculates hundreds of simulations for various sets of initial conditions. This makes it possible to conduct statistical research of population changes to objects of interest, depending on the initial conditions in the cluster.

Stars gone astray

Recently, we have used MOCCA to study the formation of BSS. They are extremely interesting objects, potentially offering valuable information on the relationship between the evolution of stars and the dynamics of star clusters. Our research shows that MOCCA is an outstanding tool for full analysis of star cluster evolution and for comparing the results against observational data.

BSS are main sequence stars, although they are more luminous and bluer than stars at the main sequence turn-off point of the star cluster. During their evolution, most stars "travel" along the main sequence, becoming increasingly hot and luminous, until they



Two main channels of formation for blue straggler stars. Top panel depicts a physical collision between two least-massive stars; bottom panel shows mass flow from a more massive star to a less massive one, leading to the formation of a BSS

reach the turn-off point - then they change properties, turn off the main sequence, and become red giants. For example, our own Sun is a main sequence star, and it will spend the next several billion years in a state of relative stability. Once the hydrogen at its core is used up, it will depart from the main sequence and turn into a red giant. Blue stragglers are stars which have gone astray along the main sequence, and have not turned into red giants at the same point as other stars. The fact that BSS tend to have a higher mass than is typical of stars at the turn-off point means that they must have undergone some past event that resulted in them gaining this additional mass.

The literature describes two main mechanisms that may be responsible: one involves mass transfer, the other a collision with another star from the main sequence. By obtaining additional mass, the star becomes "rejuvenated," allowing it to spend additional time along the main sequence before it turns into a red giant.

During our research on different channels of BSS formation, we observed a range of physical processes responsible for the process. For blue stragglers formed by mass transfer in binary systems, we observed two distinct groups: BSS created by the flow of mass through the L1 Lagrangian point, or via stellar wind and ejected matter from a companion star that has started evolving off the main sequence.

Our simulations have shown that BSS formed as a result of stellar collisions within a single binary system were created in close binary systems with orbital periods of around a day, and with circular or near-circular orbits. During the first few billion years of a cluster's existence, the main physical process within it is the flow of mass through the L1 point, leading to stars merging together. For systems formed after a few billion years, stars mainly combined as a result of magnetic braking. Blue stragglers formed as a result of a collision in

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Globular cluster M53 with a numerous group of blue stragglers (visibly bluer than the other stars)

dynamic interactions are mainly created following the collapse of the star cluster's core. We have only observed a single instance of BSS formation as a result of a collision between two single stars; all others involved binary systems. This is especially important for observers, since it highlights the role played by binary systems in the evolution of star clusters.

One of the most interesting relationships we have observed is the appearance of signs of bimodal spatial distribution of BSS accompanying the collapse of the cluster's core in our test simulation. For a cluster 4 billion years old, blue stragglers are the densest in the center, and their numbers get gradually lower outside it. In the test simulation, the collapse of the core is dated at around 6-8 billion years. Weak signs of bimodal spatial distribution become noticeable for a cluster around 10 billion years old. In these cases, we can observe the highest density in the center, we can also observe an increasing number of these objects in regions far more distant from the center. This is notable, since if bimodal spatial distribution were to appear after the core's collapse for all or at least many different clusters, it would provide an excellent means of studying a given cluster's dynamic status.

In many BSS, we noted a significant delay between the event which caused the formation of the object (mass transfer or physical collision) and the time of detection of the blue straggler within the cluster. The difference can be as long as a few billion years, and the effect can be seen in a significant number of BSS. Again, this is important for observers, since it means that many of these fascinating objects may actually lie hidden along the main sequence.

Most BSS formed following physical collisions (dynamic blue stragglers) quickly escape from the cluster, having gained additional kinetic energy during the interactions. Other BSS may escape the cluster as a result of relaxation processes, which are far less energetic. These we have named "slow escapers." We also studied the numbers of fast escapers before and after the core's collapse, in percentage terms: 43% escaped the cluster while they were still blue stragglers, whereas the number rose to 60% following the collapse of the core, making the process significant for observers. The escapers could be detected near star clusters.

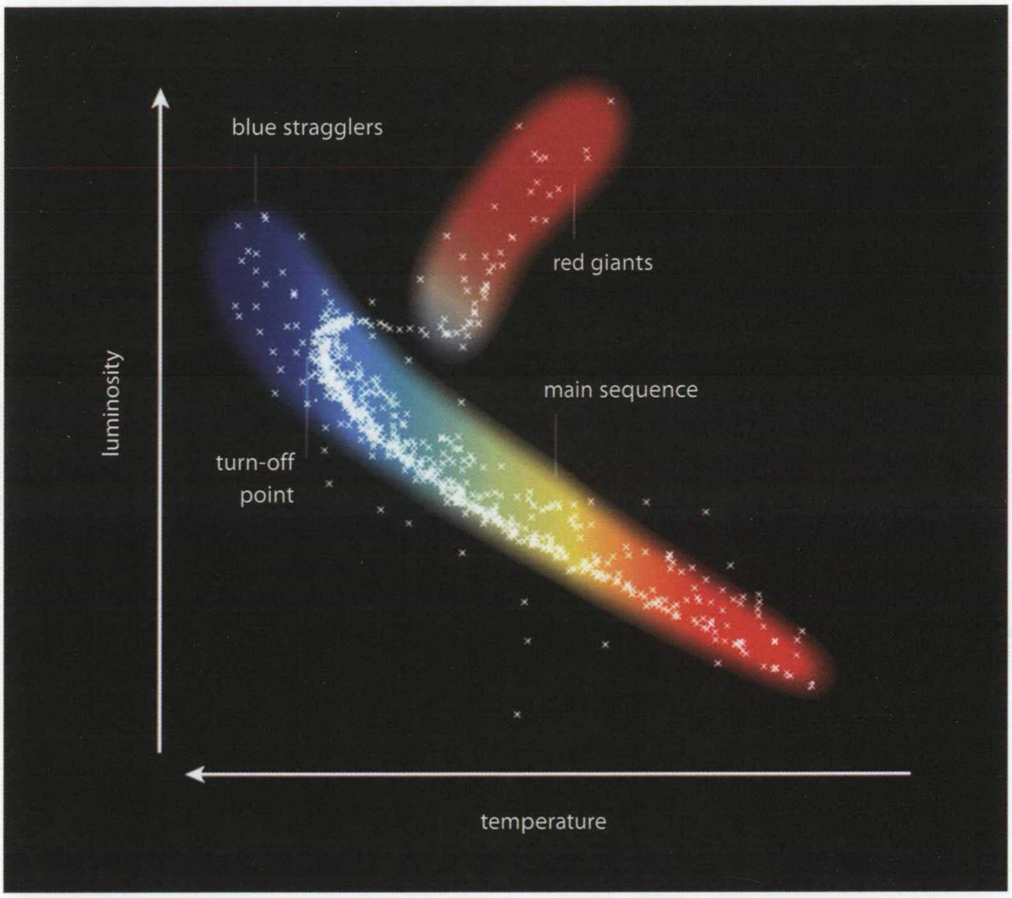
These findings are just selected examples demonstrating the precision, simplicity, and efficiency with which MOCCA can help trace the evolution of stellar properties.

Codes of the future

MOCCA is being expanded with new functionalities aiming to make the program increasingly useful to growing circles of researchers. In the future, we aim to conduct a systematic analysis of BSS populations for different initial conditions, functions of mass, binary system parameters, concentrations, metallicity, and many other factors. Our goal is to confirm existing and discover previously unknown correlations between parameters of BSS populations and parameters describing global structures of star clusters.

We also hope to share databases of models and launch an online application allowing scientists from around the globe to search for initial conditions of star clusters by entering their parameters as currently observed. Such a project can only be implemented using codes based on the Monte Carlo method, and MOCCA is perfect for the task. We hope that such an online database will be well received by the scientific community, and it will help build interest in stellar dynamics among observers.

Currently, MOCCA is programmed with procedures for studying interactions between single and binary stars. However,



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Hertzsprung-Russell diagram showing star evolution and classification. Most stars' temperature and luminosity increase with time, moving along the main sequence until the turn-off point, when they become red giants. Stars which have gone astray, continuing along the main sequence past the turn-off point, are known as blue stragglers

recent research reveals that in star clusters - in particular in objects such as BSS - an important role may actually be played by hierarchical systems (groups of three or four stars, or even greater hierarchies). As such, we will soon expand the code with functionalities making it possible to track their evolution in stellar systems.

The MOCCA code has been presented at several international conferences, including the assembly of the International Astronomical Union in Beijing in 2012. It has been very well received by both observers and theoreticians, and scientists from other research teams have likewise noted the potential of our code. As a result, we have entered into a collaboration with the Cosmic-Lab project led by Francesco Ferraro. Cosmic-Lab is a five-year European project aimed at probing the complex interplay between dynamics and stellar evolution in galactic globular clusters. Our first task will be to attempt to reconstruct two BSS sequences observed in the M30 cluster. Another project, conducted jointly with Luigi R. Bedin, will search for massive companions in binary stars and compare the results against observations obtained by the Hubble Space Telescope. ■

Further reading:

Hypki A., Giersz M. (2012). *MOCCA code for star cluster simulations - I. Blue Stragglers, first results.* arXiv1207.6700H

Giersz M., Heggie D. C., Hurley J., Hypki, A. (2011). *MOCCA Code for Star Cluster Simulations - II. Comparison with N-body Simulations. arXiv*1112.6246G

http://www.cosmic-lab.eu/

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Globular cluster NGC 6397 photographed by the Hubble Space Telescope, showing a group of blue stragglers