

Dynamics of Globular Star Clusters

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Over 150 globular star clusters are known in our Galaxy, although the total must exceed 200 as some are certainly hidden in the obscurity around the Galactic Centre. It is estimated that about 0.1% of the stars in the Universe belong to such clusters.

Globular star clusters are among the most beautiful objects in the sky (Fig. 1). But what attracts astronomers is that they are also among the oldest. The ages of their constituent stars give a tight estimate for the age of the Universe itself, and hence of its expansion rate. The composition of the stars in these clusters also gives us a snapshot of the Galaxy at a time before most of the heavier elements in the Universe were produced. Globular clusters are also surprisingly rich in exotic objects such as rapidly rotating neutron stars (pulsars) and sources of X-rays are a thousand times more abundant in globular star clusters than in the rest of the Galaxy.

Whereas in the company of all these exciting topics, the dynamics of the clusters might seem a stagnant backwater, we shall see that the two aspects of globular clusters — the dynamic and the exotic — are closely linked.

The dynamics of a star cluster has, as Spitzer once said, "an appealing, if somewhat deceptive, simplicity". We shall come to the deceptions later, but the simple picture is of a number, N , of point masses attracting each other by Newtonian gravity: the classical gravitational N -body problem. This seems like an obvious target for computer simulation, but even the fastest computers are much too slow. For example, the simulation of a small cluster of less than 100 000 stars over the age of the Universe would require some 10^{17} arithmetic operations.

A Star Gas

Globular clusters contain up to a million stars, but while this makes them too big to simulate on a computer, they are just about big enough for statistical methods to work. The stars in a cluster can be compared to the atoms in a gas. Like the air in a room, a cluster behaves like a gas in dynamic equilibrium: at each point as many stars are falling into the middle of the cluster as are coming out. Though the stars take only a million years to move in and out, the appear-

ance of the cluster scarcely changes over many millions of years.

Although modelling the cluster gas as an ordinary gas has turned out to be a very successful way of thinking about the dynamics of globular star clusters, in many ways, a cluster gas is quite unlike a typical gas. In ordinary gases, collisions keep the distribution of speeds close to the Maxwellian distribution, but not in a cluster. A star in a cluster can move through the cluster a great many times without physically colliding with another star, and even gravitational deflections from other stars are quite rare. Thus the cluster gas is like one with a very long mean free path between one collision and the next.

Just as the inner planets orbit the Sun more quickly than the outer planets, the stars in the middle of a cluster move faster than those further out, and in terms of a star gas this means that the middle of the cluster is warmer than the outer parts. Gravitational encounters between stars are rare; they nevertheless act like collisions in an ordinary gas, conducting heat from the warmer parts of the cluster to the cooler parts, *i.e.* from the inside to the outside. But the effect of transporting this heat in a star gas is paradoxical. The outer stars, on

being heated up, are boosted into larger orbits, where, as we have already noticed, stars move more slowly. Their speed drops more than was gained in the first place. Similarly stars near the middle, which were cooled, fall closer to the middle, and speed up, their final speed exceeding the original. In other words, taking heat away from the middle of a cluster heats the middle up! The flow of heat, which in normal gases irons out temperature variations, has the opposite effect in a star gas.

This paradoxical behaviour which is sometimes loosely expressed by saying that the gas has negative specific heat, resembles the more familiar behaviour of Earth satellites. These are acted on by a drag force from the atmosphere which causes them to drop to a lower orbit. The drag speeds the satellite up!

Returning to the star cluster: the inner parts are still warmer than before and the outer parts still cooler. Therefore the flow of heat will increase, further enhancing the temperature gradient. The positive feedback is a classic recipe for an instability or runaway, in this case called the gravothermal catastrophe. As the stars in the middle crush closer together, according to the gas picture, their density will increase with-

Fig. 1 — The southern globular star cluster NGC 362, at a distance of about 25 000 light years. Its mass is about 500 000 times that of the Sun. It is possibly an example of a cluster with a collapsed core. (Photograph copyright © 1986 Royal Observatory, Edinburgh.)



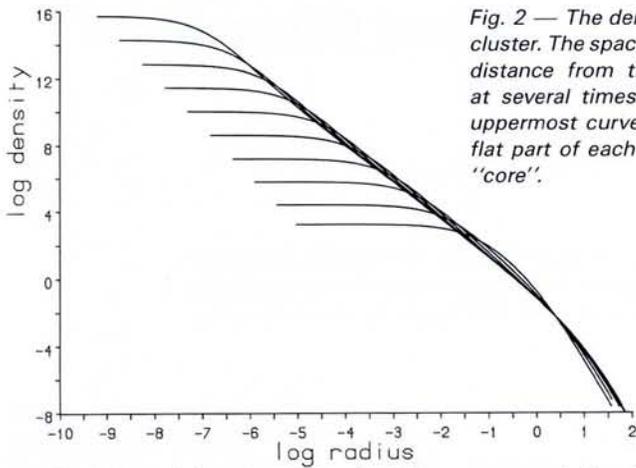


Fig. 2 — The density profile in a collapsing cluster. The space density is plotted against distance from the centre of the cluster, at several times during the collapse (the uppermost curve is the latest). The nearly flat part of each curve corresponds to the "core".

out limit in a finite time (Fig. 2). This dramatic phenomenon is called "core collapse" as the central part of a cluster is often called the core. As Princeton theorist Jeremy Goodman put it, core collapse is the cruel fate of a star cluster forever striving to be what it can never be — in thermal equilibrium.

Of course this picture is highly simplified. But the collapse is real enough, and not just an artifact of the simple gas model. Better statistical models, which take proper account of the long mean free path in a star cluster, show almost exactly the same evolution. Core collapse shows up, too, in computer simulations of clusters with only a few thousand stars. These refined models also show that much the same thing happens even if stars of different mass inhabit the cluster. Only the mechanism is more elaborate, and it is the heavier stars that undergo the collapse, sinking to the middle like a dense fluid.

The theory of core collapse was a long time in the building. First indications came in about 1960, and ten years later the first quantitative picture

emerged. By this time theorists were persuaded that it could happen within the lifetime of many globular clusters and so they turned to the observers, and asked them whether real globular star clusters did indeed have tiny dense cores. But alas the observers just shook their heads. No matter which cluster they looked at, there was no sign of high central densities, no sign either of tiny cores (Fig. 3).

Then in the late 70s the observers took a closer look at M15, a fine cluster in the constellation of Pegasus. In M15 the density of stars kept on increasing as one looked closer and closer to the centre, instead of levelling off within the core, as in all other clusters. This was at a time when the notion of black holes in globular clusters was in vogue, for non-dynamical reasons, and the new observations were first interpreted in this sense. A sufficiently large black hole in the middle of M15 would pull in the bright stars around it, forming the density peak that was observed. But then it was realised that a dense knot of neutron stars would do just as well. Being

heavier than the bright stars that we can see, they would have sunk to the middle, forming a dark mass which would have much the same effect on the bright stars as a black hole.

These studies of M15 were a watershed in matching the theory and observations of globular clusters. Continuing advances in observing technology showed that the cluster was by no means unique and it now turns out that about 1/5 of all clusters show signs of collapsed cores. M15 still had some surprises in store: in the last year or so it has been found that the speeds of the stars right in the middle are much higher than they are just outside. This was a surprise for some theorists who thought that M15 was pretty well understood. What exactly this discovery implies is still unknown.

After Core Collapse

Any physical theory which leads to infinities has to be repaired and the infinite densities that should occur at the conclusion of core collapse are no exception. Clusters which show signs of core collapse are unlikely to be in the middle of the process and are almost certain to have passed it. What should such a cluster look like?

The high densities are a clue. Our simple gas model takes account of interactions between pairs of stars, but at high densities there is an increased probability that a third star may play an essential role in some encounters. What is qualitatively new is that, at the end of the encounter, two may emerge bound together as a binary star (Fig. 4). Three-body interactions are, to use the gas analogy again, exothermic as the extra binding energy of the binary star must

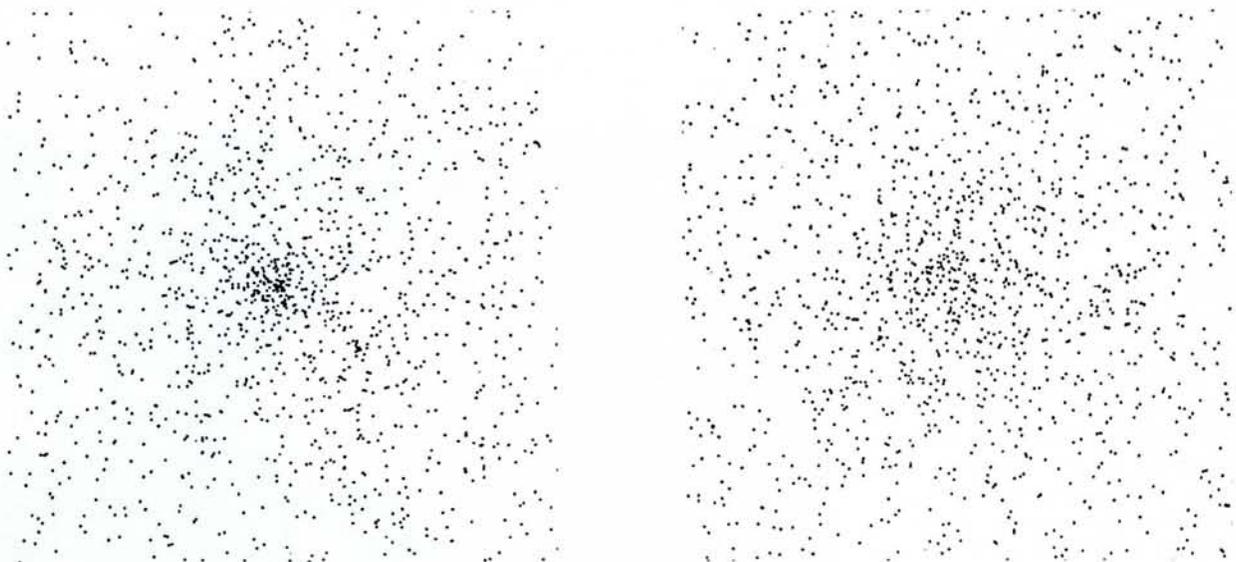


Fig. 3 — Simulated distribution of stars in a cluster with a collapsed core (left) and in one with a normal core (right). Here the core radius is about 1/20 the size of the frame. For a long time it was thought that no cluster resembled the left-hand frame.

be compensated by a release of energy. The products of the encounter (the binary and one single star) move away with much higher speeds (on average) than the three interacting single stars. Having formed, of course, the binary can interact with other single stars and with other binaries, and it turns out that these encounters are also exothermic. In this way energy is constantly fed into the motions of the single stars and the binaries.

Up to a point these reactions have much the same effect as nuclear energy generation in stars. The difference is that the energy emitted in nuclear reactions is eventually radiated away from the surface, and the star can find a stable equilibrium in which the energy radiated just balances the energy generated. By contrast, energy generated inside a star cluster cannot escape. No equilibrium is possible, and instead the cluster expands (Fig. 5).

Beyond the Point-Mass Model

Something else can happen when stellar densities are as high as they are at the close of core collapse. Stars can approach each other to distances of only one or two stellar radii. When this happens they raise strong tides on each other, and when the energy of these tides dissipates, enough energy may have been lost to bind the two stars into a binary, without the intervention of a third body. In this way, thousands of binary stars may form as the core collapses. Just as with binaries formed by triple interactions, the energy they generate may eventually halt core collapse and then cause re-expansion of the core. Which process wins (three-body binaries or tidal binaries) depends partly on whether the collapsing core consists of neutron stars (which are far too small for tidal interactions) or normal stars.

If two stars come close enough together to raise strong tides there is also a high chance that they will actually collide. Even when a tidal binary subsequently meets a third star there is a high chance that two of the three stars will physically collide. The study of stellar collisions is still in its infancy, but one thing seems clear: at the relatively slow speeds at which stars move in star clusters they do not have enough energy to destroy each other. Instead they combine, forming a single more massive star, called a "merger". Compared with a single star, a merger shines brighter, evolves faster, and is itself much more likely to have further collisions. Now it is a race. If the merger can swallow other

stars faster than it can evolve then it will turn into a brilliant massive star which will explode as a supernova, throwing most of its mass out of the cluster. As a result, the cluster expands slightly, just as if it had been heated by binary interactions.

If there are clusters which have passed their first core collapse, what is the main process that is driving their evolution? Is it binaries formed in three-body interactions? Or binaries formed tidally? Or runaway evolution of repeated mergers? Or could it be "primordial" binaries which were formed along with single stars when the cluster itself was

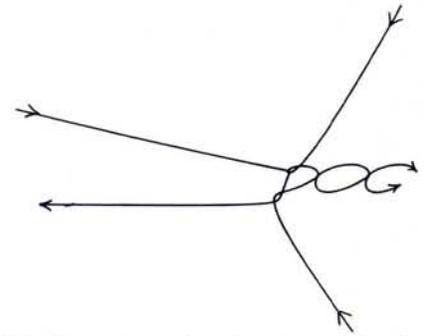


Fig. 4 — Formation of a binary star in a three-body interaction. The initial conditions here look very contrived, but at the high densities which occur late in core collapse, suitable encounters occur frequently.



UNIVERSITY OF LEIDEN

The Department of Astronomy and Physics of the Rijksuniversiteit Leiden invites applicants for the position of

Professor in the Theory of Condensed Matter (v/m)

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The appointee should have a broad experience and should be deeply involved in modern developments in this area. Experience in collaboration with experimental groups will be highly appreciated.

He/she is expected to have a stimulating influence on experimental groups in condensed matter physics in Leiden, where the present research programme includes the following subjects:

- superconductivity and quantum liquids;
- small metal clusters and synthetic metals;
- semiconductors and molecular spectroscopy;
- magnetic phenomena at low temperatures;
- random systems and spin glasses.

The new professor will supervise graduate students in theoretical physics and give theoretical support to the above-mentioned experimental research. His/her teaching duty in the Department will include in particular a course in condensed matter theory. The appointee will be a member of the Institute for Theoretical Physics (Instituut-Lorentz) and is expected to take part in the organisational and administrative duties of this Institute.

Salary according to government rules

Applicants without knowledge of the Dutch language will be obliged to acquire this knowledge at short notice.

Applications including an extensive curriculum vitae, a list of publications and three references should be sent, within four weeks after appearance of this issue, to the chairman of the selection committee, Prof. dr. J.M.J. van Leeuwen, Instituut-Lorentz, Nieuwsteeg 18, 2311 SB Leiden, The Netherlands.

Requests for further information and suggestions for suitable candidates can be sent to the same address.

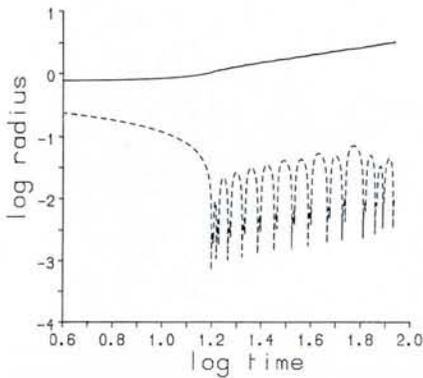


Fig. 5 — Evolution of a star cluster during and after core collapse. The upper curve shows the half-mass radius (the radius of a sphere containing the innermost half of the cluster) plotted against time. In this model the expansion of the cluster is driven by energy emitted by binaries. The lower curve plots the radius of the core (cf. Fig. 2). The collapse is followed by a re-expansion which in this case is unstable to rather regular oscillations. Other models exhibit steady expansion or chaotic oscillations, depending on the size of the cluster, the mechanism of energy generation and other important factors.

born? All these possibilities have their advocates, but they also have their difficulties. Take, for instance, the idea of repeated mergers blowing up as supernovae. It has been shown recently that the presence of all these bright massive stars in a cluster could not have gone unnoticed. On average the core would have to be shining roughly as brightly as all the rest of the cluster put together! No cluster looks like this.

If we think that binary stars are responsible why do we not just look? In recent years there has been a steady growth in evidence, both direct and indirect, for the presence of binary stars in globular star clusters. A few have been discovered directly by careful measurement of variations in the Doppler shifts of their spectra. The indirect evidence includes the discovery, already mentioned, of sources of X-rays in globular star clusters, because these are almost certainly binaries. One star in the binary is a neutron star, and gas from the other star emits X-rays as it falls into the potential well around the neutron star.

Many neutron stars are pulsars, and in the last couple of years a remarkable number of very fast pulsars (so-called millisecond pulsars) have been found in globular star clusters. Just as with the low-mass X-ray sources, their abundance in clusters is much higher than elsewhere in the Galaxy. While some astronomers think that their origin is linked with the X-ray sources, and therefore with binaries, this view is somewhat controversial.

Environmental Issues

So far we have treated clusters as though they were isolated from the rest of the Universe. But they live inside galaxies, and the stars in them are also attracted by the gravitation of the rest of the galaxy. Up to a point this is just a question of asking how far a star can wander before it escapes from the cluster and becomes an ordinary galactic star. The gravitational effect of the rest of the galaxy, however, varies with time, which complicates the simple picture of an escape distance. When a cluster crosses the plane of the galaxy it is subject to a short-lived, intense gravitational field, the shock of which sets the stars moving more quickly and tends to dissipate the outer parts of the cluster. Much the same thing happens if the cluster comes too close to the nucleus of the galaxy.

It might seem that these processes cause the whole cluster to dissipate, and can combat the tendency of the core to collapse. Certainly they have a big effect on the internal dynamics, but not in the obvious way. If you keep stripping off the outer part of a cluster, the temperature difference between inside and outside is accentuated, and core collapse is actually enhanced. Once again the behaviour of self-gravitating systems is counter-intuitive.

There is one other important process that we have not taken into account. As stars evolve, they lose mass. This is expelled from the cluster, and causes it to expand. In old globular star clusters, this process has ceased to be very important, but when they were young, with lots of massive stars evolving quickly, the effects must have been dramatic. We can still see the evidence in nearby galaxies, especially the Magellanic Clouds, where there are young star clusters as rich as most of the old globular clusters in the galaxy. We can see that their outer parts are being stripped off and will be lost to the rest of the galaxy, leaving a much smaller cluster behind, or perhaps leading to complete disruption.

Indeed the interplay of all these dissipative effects — core evolution, mass loss, external effects — would have led to the complete disruption of clusters if they had not had broadly the properties we see in the globular clusters at the present day. We see clusters of a fairly narrow range of size (masses and radii), not only perhaps because they were born that way, but also because these are the ones that have lasted longest. It is the survival of the fittest on a scale that Darwin could not have imagined.

And so the apparent simplicity of the gravitational N -body problem is very superficial. The evolution of N point masses leads to paradoxical thermodynamic behaviour and even chaotic oscillations. It has revived interest in the three-body problem, because of the importance of binary stars. The dynamics of star clusters is closely linked, through the dynamics of binary stars, with the most exotic stellar-sized objects in the Universe. But for the mathematically minded the dynamics of star clusters has become less tidy. Collisions between the stars play an essential role, and it is becoming clear that the point-mass approximation has had its day.

FURTHER READING

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Physical Society of the Soviet Union

The Physical Society of the Soviet Union, first founded in 1872 and then disbanded in 1930 was to be reinaugurated on 17 November in the Grand Hall of the University of Moscow.

The Society aims to unite scientists and teachers active in fundamental and applied research and in teaching. It will cover education at schools and the universities as well as physics research and development. The intention is to provide qualified and independent expertise on professional issues, expanding and strengthening connexions with other organisations active in the field of science education and technology. Particular support will be given to interdisciplinary research in the field of energy, ecology, economics and global problems.

Reports were circulating a few months ago of the formation of a Moscow Physical Society and even a Leningrad Physical Society that seemed to have been set up as the result of an individualistic initiative, principally to challenge the all-dominant Academy of Sciences. Whether these will continue to function once the USSR Physical Society has been re-instated remains to be seen.