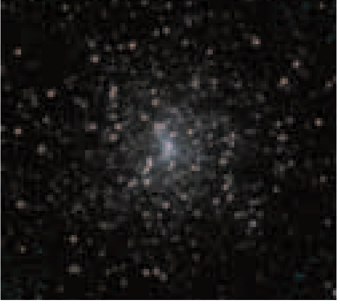
The Dynamic Lives of Globular Clusters

These ancient stellar systems continue to surprise astronomers with a host of fascinating phenomena.

By
S. George Djorgovski



Globular star clusters are the delight of amateur and professional astronomers alike. The oldest star systems known, globulars witnessed the birth of our galaxy. They now serve as laboratories for theories of stellar dynamics and evolution. Extensively studied since the birth of modern astronomy, globulars continue to yield surprising results and challenge our understanding.

The simple beauty of globular clusters is that they combine an elegant spherical symmetry with the glittering richness of thousands of individual stars. This apparent simplicity has enticed astronomers to construct mathematical models of them. Early attempts arrived at a basically correct picture: collections of stars held together by their aggregate gravity, with members that move randomly like molecules of gas, interacting with Newtonian gravity. In simple systems with a limited number of essentially pointlike masses (such as our solar system or a widely separated binary) the dynamics are mostly regular, predictable, and even boring. However, put a million or so stars together in several cubic light-years of space, let them orbit a sizable disk galaxy, and many interesting new phenomena result.

Competing Theories for Collapsing Clusters

The first successful dynamical models of globular clusters were developed in the early 1960s by Richard Michie, Ivan King, and Michel Hénon, each working independently. The starting point for Michie and King was the ongoing random encounters between cluster stars, roughly like those between molecules in a uniform-temperature gas. The stars are not physically colliding in this celestial pinball game, just deflecting each other gravitationally. This energy exchange eventually leads to thermal equilibrium. In a typical cluster this takes about a hundred million years, during which an individual star may cross the cluster a hundred times. Thus there has been plenty of time for globular clusters to reach relaxed equilibrium states, since they formed at least 10 billion years ago.

The King-Michie simulations produced globular clusters with cores of nearly uniform stellar density. The concentration of stars then gradually declines out to an invisible boundary called the cluster's tidal radius. Here the gravitational attraction of the Milky Way is stronger than that of the cluster itself, and stars become unbound and join the galaxy's stellar halo. Globular clusters were thus predicted to evaporate slowly, with galactic tides constantly stripping away their stars.

These models were spectacularly successful. They predicted cluster structures in excellent agreement with the observations available at the time, and they still provide good fits with the greatly superior data we have today.

However, cluster models developed by Hénon at about the same time did something entirely different: his simulated clusters didn't stay in a slowly changing equilibrium. Instead, the models predicted that globulars would fall in upon themselves in a process called the gravothermal catastrophe, or core collapse.

Hénon reasoned like this: at any given moment the random motions of stars in a cluster's core can be considered to balance the gravitational potential of the stars' mutual attractions. When a fast-moving star escapes the gravitational pull of the cluster core, taking with it some kinetic energy, the core must shrink a little. The remaining stars have to move a bit faster to compensate for the increase in the gravitational binding energy of a denser core. More of them can then es-

Facing page: One of the southern sky's showpieces, 47 Tucanae (NGC 104) glimmers from 15,000 light-years away with the combined light of perhaps a million stars. Courtesy the European Southern Observatory. _Above:_ An easily located jewel in Pegasus, M15 is a prime example of a highly evolved cluster that has undergone core collapse. This color-composite image was taken with the Canada-France-Hawaii Telescope. Courtesy Peter B. Stetson, Dominion Astrophysical Observatory. _Below:_ Many amateurs' first acquaintance with globular clusters came courtesy the Messier catalog, named for its 18th-century author, Charles Messier. The Messier globulars depicted here and on the following page were photographed by Evered Kreimer with a 12½-inch reflector. North is up with east to the left in each photo.

M55 M5 M56

cape, and so the process repeats itself and accelerates. This eventually leads to a rapid shrinking of the cluster core. The density profile of such a cluster is much steeper than the uniform cores of the King-Michie models, declining approximately as the inverse of the radius squared.

At first glance, there doesn't seem to be any way to stop the collapse and stabilize the cluster. But since globular clusters abound, and none seem to have little quasars within them, Hénon's models were all but disregarded for more than 20 years. Yet subsequent theoretical investigations in the 1980s by Donald Lynden-Bell, Haldan Cohn, Jeremy Goodman, and many others have essentially confirmed and extended Hénon's ideas.

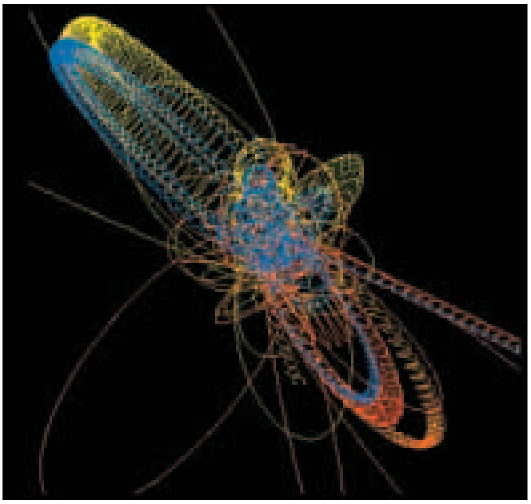
Virtually the same process of core collapse happens in protostars, but with a crucial difference: in protostars the core becomes hot and dense enough for thermonuclear reactions to start. These reactions provide energy that compensates for thermal losses, preventing collapse. But what can substitute for nuclear reactions in the core of a collapsing globular cluster?

Such an energy source does exist, in the form of binary stars. Binaries can exchange energy during close encounters with single stars, thereby becoming either more or less tightly bound. These interactions can be very complex, resulting in the formation of a temporary triple-star system, the disruption of the binary, or the exchange of partners. When all is said and done, however, in most cases the interaction ends with a binary flying off in one direction and a single star flying off in another. And this is where the miracle happens. As it turns out, so-called hard binaries — those with binding energies larger than the average among stars in the cluster — tend to lose energy in such encounters. They become ever more tightly bound and more likely to provide energy to the next star that passes by.

Extensive numerical simulations of binary-star/single-star interactions performed in the 1980s have confirmed this prediction. Binaries provide a huge reservoir of energy; a single hard binary can have a binding energy equal to that of the cluster as a whole! Here was the resolution of Hénon's paradox: binaries can serve as energy sources that stabilize globular-cluster cores against collapse.

And thus both King and Michie on one side and Hénon on the other were right: globular cluster cores do collapse, but the collapse is arrested by the presence of one or more hard binaries. Precollapse clusters can look just like the King-Michie models, and some stabilized postcollapse ones can too. But clusters that have undergone a recent collapse and recovery still retain the characteristic Hénon density profile, with its very small core. In the mid-1980s, in the first systematic surveys of globular-cluster structure, about one-fifth of all galactic globulars showed the characteristic post-core-collapse morphology — a cusplike density distribution near their centers. Examples include M15 and M30. On the other hand, M5 and M13 are King-Michie type clusters. We now believe that most globulars evolve only gradually toward core collapse, unless they evaporate first.

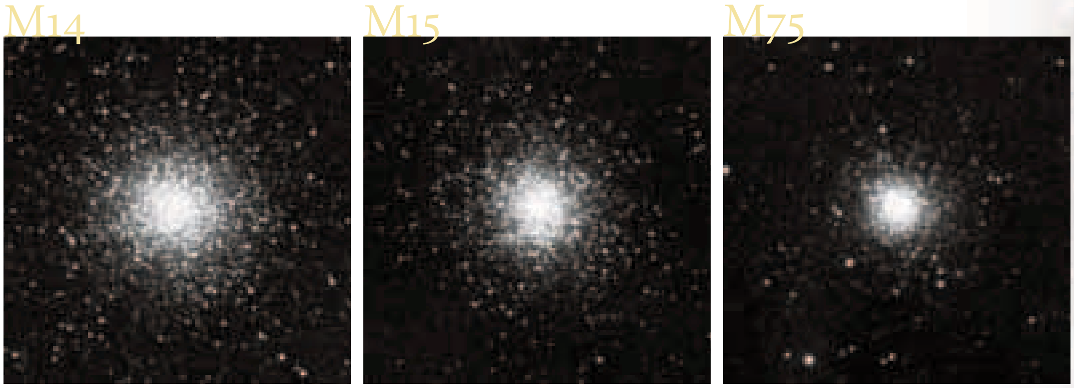
Cluster cores may never settle down

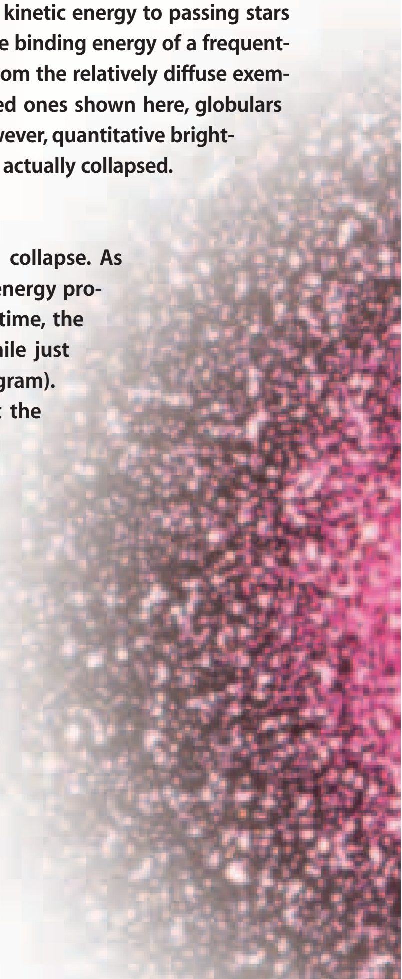


E. STERL PHINNEY, CALTECH / STEIN SIGURDSSON, UNIVERSITY OF CAMBRIDGE

Left: **This simulation shows the interaction of a single star with a "hard" (tightly bound) binary in the core of a globular cluster. Such interactions typically provide kinetic energy to passing stars at the expense of the binary's orbit, which tightens. Eventually, the binding energy of a frequently star-crossed binary can rival that of the entire cluster.** ***Below:*** **From the relatively diffuse exemplars on the bottom of the previous page to the more condensed ones shown here, globulars present a wide range of morphologies to eyepiece observers. However, quantitative brightness measurements are required to tell which clusters' cores have actually collapsed.**

Opposite page, bottom: **The origin of a globular cluster's core collapse. As more stars are lost the process accelerates, until it is halted by energy provided by "hard" binary stars.** ***Opposite page, top:*** **At any given time, the core of a collapsing globular cluster has a uniform density, while just outside the core the density sharply decreases (left side of diagram). As time passes the core shrinks and the density increases, but the overall shape of the density profile remains roughly constant.**





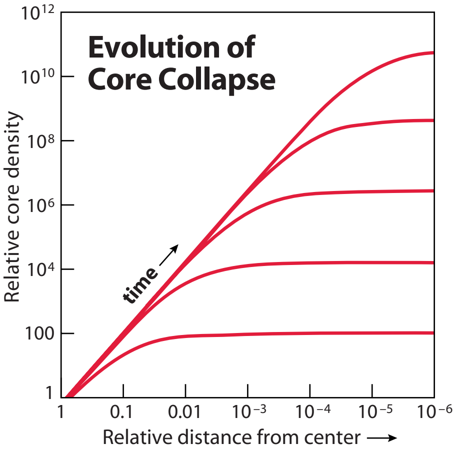
completely: core collapses and bounces can recur in a cycle called gravothermal oscillation. Obviously, a collapse-and-recovery sequence cannot be observed directly, as it may take tens or hundreds of millions of years to complete, but the cycle's existence seems convincingly established in numerical experiments.

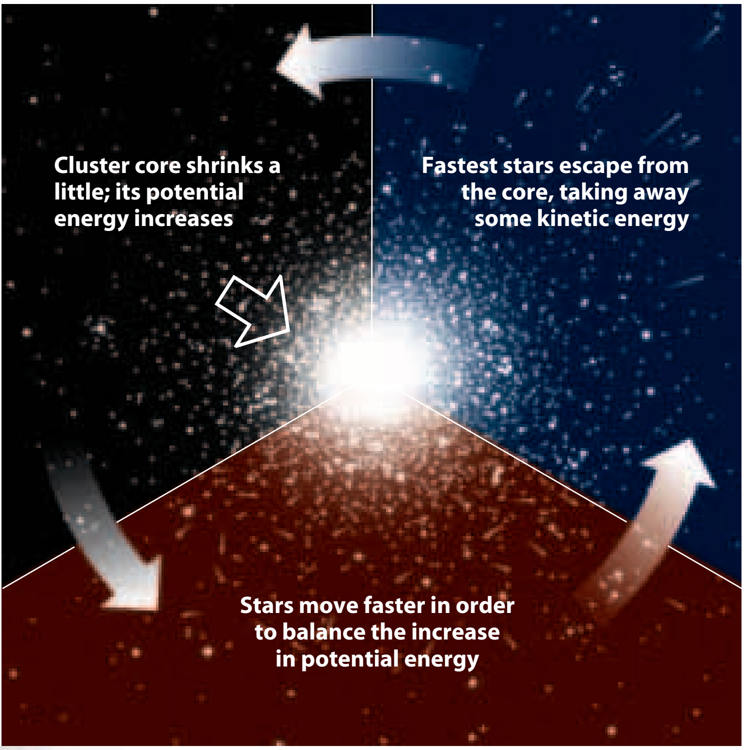
Cluster Environments: External and Internal

So far we have neglected an important aspect of the story. Far from being isolated systems, globular clusters evolve within the tidal field of the Milky Way — that is, within its uneven and ever-changing gravitational influence. As clusters pass through the galactic bulge or the disk, they are subject to so-called tidal shocks, in which tides suddenly increase or decrease in strength. These shocks, originally investigated by Lyman Spitzer, Jeremiah Ostriker, and their collaborators in the 1970s, can be very effective in hastening the dissolution of clusters. (Think about driving fast over speed bumps and you will understand why.) It is now generally believed that our galaxy's entire stellar halo was produced from disintegrated star clusters along with some dwarf satellite galaxies. The 150 or so globulars surviving today are probably just a small fraction of those that once populated the galactic halo.

Tidal shocks can also accelerate the evolution of clusters toward core collapse. Whether a cluster will evaporate before it has a chance to undergo collapse depends on its initial mass and concentration (being high in both makes for sturdier survivors), as well as on the cluster's position in the galaxy. Shocks are stronger for clusters whose orbits pass closer to the galactic center and more often through the plane of the disk. On the basis of such an analysis, David Chernoff (Cornell University) and his collaborators predicted that most clusters near the galactic center should have collapsed cores. Indeed, there is a larger fraction of post-core-collapse clusters found in the inner Milky Way. Their more diffuse siblings have been obliterated. Relatively sparse globulars can be found only in the halo's outer reaches. Models of the Milky Way's entire globular-cluster system suggest that nowadays a few clusters undergo core collapse every billion years. In that same period, several clusters evaporate under the influence of tidal shocks. Eventually there will be none left!

Everything said so far presumes that stars can be treated as point masses interacting gravitationally. But stars are extended objects and they can get very close to one another, especially during a cluster-core collapse. In our neck of the galaxy, there is about one star per 3 cubic light-years, and direct stellar collisions are extremely unlikely. But in some globular-cluster cores, many millions of stars can occupy the same amount of space. Under such conditions physical interactions and collisions of stars can and do occur. In some cases two stars merge, producing





a single, more massive object. In weaker encounters the outer envelopes of red giants are stripped away. Close binaries can also form, allowing mass exchange to take place. In any case, the subsequent evolution of the affected stars is modified, sometimes profoundly.

Such processes have spurred one of the more active topics in globular-cluster research today. The details of these interactions are not yet known, and observed phenomena continue to baffle both dynamicists and stellar-evolution theorists. However, evidence for unusual stellar populations in many clusters is strong and abundant.

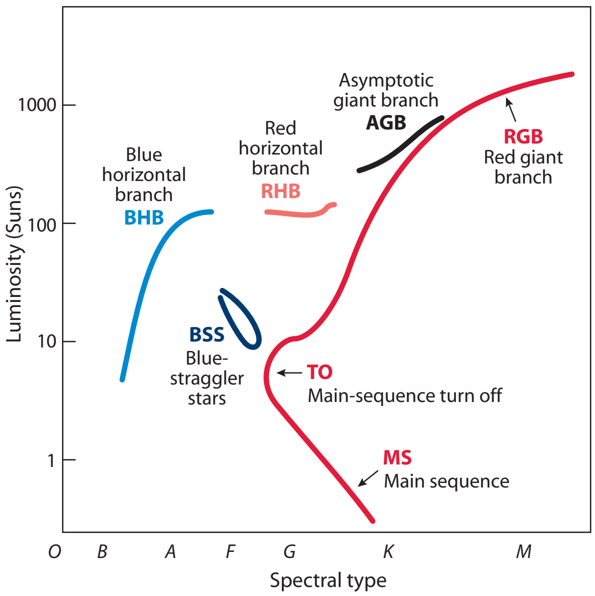
Blue-Straggler Stars

Among the long-standing puzzles in globular-cluster research is one such stellar population, so-called blue stragglers. Discovered first in M3 more than 40 years ago by Allan R. Sandage (as a part of his doctoral thesis at Caltech), these stars seemed to be lagging behind the rest of the cluster's members in their evolution. That is, all stars above a certain mass and luminosity in the globular have evolved off the main sequence, as shown by its Hertzsprung-Russell (H-R) diagram. Yet the blue stragglers, which fall above this cutoff, remain on the main sequence (see below).

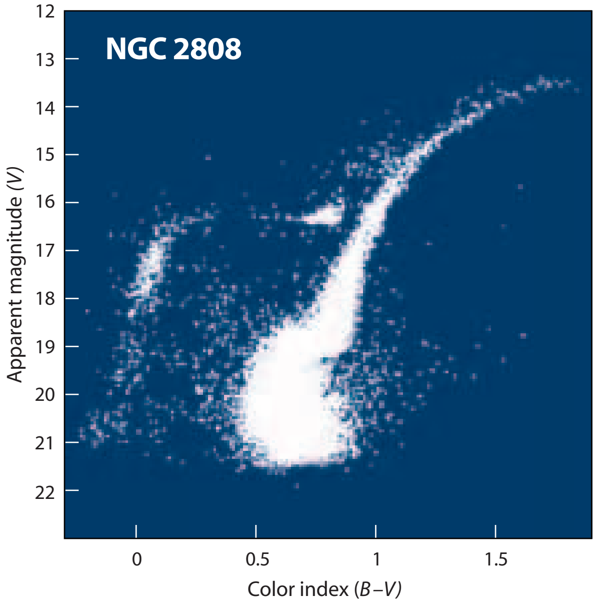
Blue stragglers have now been seen in many globulars, and in all cases they seem more concentrated toward the cluster center than the rest of the visible stars. This suggests that they have higher masses than either red giants or normal main-sequence stars, since heavier stars are expected on average to sink farther toward the cluster center. This is consistent with the plotted positions of blue stragglers on the H-R diagram. Although there are many proposed mechanisms for the origin of blue stragglers, in the context of globular clusters most astronomers now agree that they are the product of direct stellar collisions that result in a single star with a mass higher than that for the main-sequence turnoff. Some blue stragglers have been shown to be in close, eclipsing binaries. They are expected to eventually dissipate enough of their orbital energy to merge.

More subtle evidence for stellar interactions that can affect a star's evolution is seen on the so-called horizontal branch on the H-R diagrams of some globular clusters. In the course of normal evolution, a star like the Sun spends most of its lifetime on the main sequence, burning hydrogen in its core. Once the hydrogen fuel is spent in the center, the star leaves the main sequence and becomes a red giant. Eventually the star's helium core ignites. The giant loses much of its extended envelope as it descends on the horizontal branch. Where exactly a star ends this step in its evolution depends on the amount of mass lost in earlier phases.

As it turns out, the color of horizontal-branch stars depends mainly on the

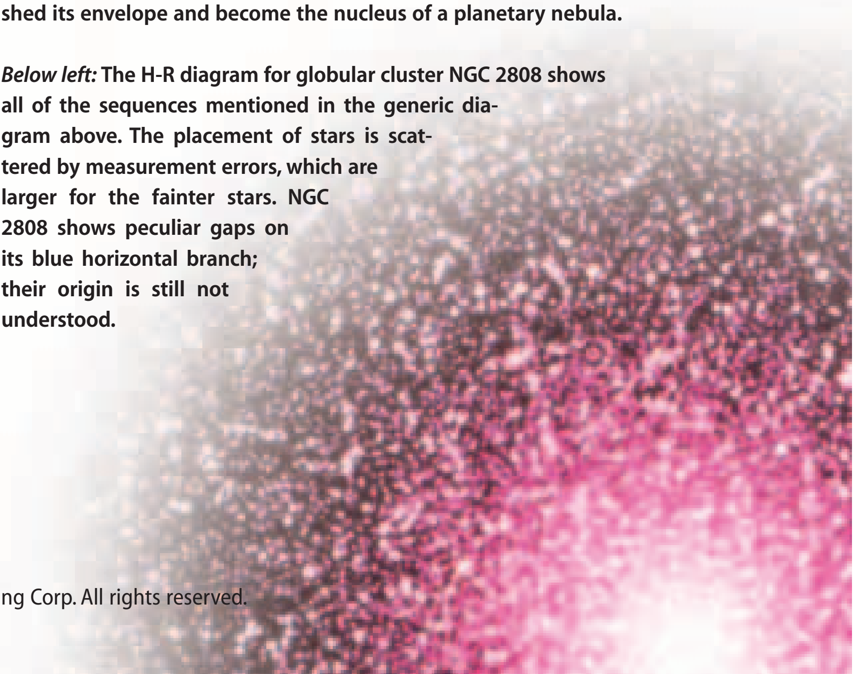


Top left: **A star spends most of its lifetime on the main sequence, burning hydrogen into helium. When the core hydrogen is exhausted the star has reached the main-sequence turnoff, evolving into a red giant while burning hydrogen in a shell around an inert helium core. (Blue-straggler stars form an extension of the main sequence past the cluster's turnoff point.) Soon the helium core ignites, and the star sheds some of its envelope and enters the horizontal branch. Those that have lost only a moderate amount of mass as red giants end up on the red horizontal branch, while those that have lost more enter the blue horizontal branch. The next phase is the asymptotic giant branch, with helium burning in a shell around an inert carbon core, and hydrogen burning in another shell around the first one. Lastly, a star may then shed its envelope and become the nucleus of a planetary nebula.**



DATA: CRAIG SOSIN AND COLLABORATORS

Below left: **The H-R diagram for globular cluster NGC 2808 shows all of the sequences mentioned in the generic diagram above. The placement of stars is scattered by measurement errors, which are larger for the fainter stars. NGC 2808 shows peculiar gaps on its blue horizontal branch; their origin is still not understood.**



amount of material they possess other than hydrogen or helium, also known as their metallicity. Stars in more metal-rich clusters are red, while those in more metal-poor clusters are blue. Since the chemical composition of stars within a single globular cluster is highly uniform, there should be a single, well-defined bunch of horizontal-branch stars in any given cluster. In most clusters this is indeed the case, but there are many exceptions to this metallicity rule; obviously, some other factor must be at work. This is the notorious "second parameter" effect (metallicity being the first parameter determining the morphology of the horizontal branch). There have been many candidates proposed for the mythical second parameter, including small variations in age between globular clusters.

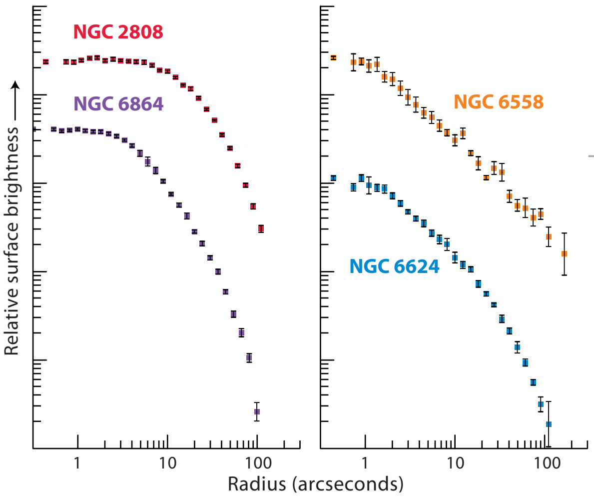
However, as pointed out by Flavio Fusi Pecci (University of Bologna), Roberto Buonanno (Astronomical Observatory of Rome), and their collaborators, many other factors can influence the appearance of a globular's horizontal-branch stars. For example, the more mass a star loses, the bluer it will appear. These astronomers have found that among the clusters of a given intermediate metallicity, the morphology of the horizontal branch depends on the cluster density and concentration, in the sense that denser and more concentrated clusters tend to have more pronounced blue tails of the horizontal branch. Pecci and colleagues proposed that this is a consequence of stellar interactions, such as grazing collisions or an enhanced formation of binaries in denser clusters, which would lead to some additional stripping of red-giant envelopes. Giampaolo Piotto (University of Padua) and his collaborators found that red giants seem to be depleted near the centers of some post-core-collapse globulars. Again, stellar dynamics and interactions in globular clusters can affect the evolution of their stellar populations.

The Effort Continues

The exact mechanisms responsible for these puzzling effects within globular clusters have not yet been found. Explaining the observed phenomena remains a challenge for theorists, just as their measurements are a challenge for the observers. Superb data on globular-cluster cores are essential for this task, and the story is still unfolding.

All this is just a small part of the ongoing saga of trying to understand these fascinating objects and their evolution. Globular clusters are fun to observe from Earth. But consider some lucky creatures living on a planet in the core of a rich globular cluster — now *that* would be a starry sky!

S. George Djorgovski *is a professor of astronomy at Caltech. His scientific interests include observational cosmology, digital sky surveys, globular clusters, and gamma-ray bursts, among other topics. He can recognize maybe three or four constellations and couldn't find a globular cluster using binoculars if his life depended on it.*



Right: **The surface-brightness profiles on the left are for two relatively unevolved clusters with large, flat cores, while those on the right are for two clusters with sharply dropping densities characteristic of core collapse. Courtesy the author. *Below left:* This color-composite Hubble Space Telescope image reveals the central half arcminute of M15. Astronomers are unable to resolve its ultracompact core fully, even with Hubble's resolution. Courtesy STScI. *Below right:* Blue stragglers (circled) deep in the core of 47 Tucanae (NGC 104), also imaged by Hubble. These stars may be products of stellar mergers that occurred during an earlier stage of this massive, highly concentrated cluster's dynamical evolution. Courtesy AURA/STScI.**