NEWS

The Milky Way's Restless Swarms of Stars

Violence is routine in globular clusters, where suns crash, binaries burn, and the whole cluster teeters on the brink of collapse

The night sky would look spectacular from a planet near the core of a globular cluster, one of the Milky Way's compact swarms of stars. Instead of the paltry few stars we see within several light-years of our sun, cluster aliens would face a vista of 100,000 stars or more. Astronomers would have crisp views of binary partners that whip around each other in hours or minutes, pulsars that spin nearly 1000 times every second, and perhaps a nest of neutron stars or the event horizon of a sizable black hole at the center of it all.

There's just one problem: Such a planet almost certainly doesn't exist. Stars in the hearts of globular clusters interact so closely and so frequently, in astronomical terms, that planetary systems can't survive the chaos. Indeed, stars themselves are not immune. Many get banished to the cluster's outskirts or ejected into deep space after intense gravitational encounters. Some stars even collide, making bizarre new objects that are at least a billion times more likely to arise in globular clusters than elsewhere in the galaxy.

It's no wonder that scores of observers and theorists peer beyond our sedate galactic neighborhood to study these angry swarms of stellar bees. "Globular clusters are the breeding grounds for stellar exotica," says astronomer Jonathan Grindlay of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts. "They really are weird and wonderful places," adds astronomer Michael Shara of the American Museum of Natural History in New York City. "And it's all because stars get very close and do very unpleasant things to each other."

Stellar ecology

The Milky Way's 150 known globular clusters live within the galaxy's halo, a sparsely populated sphere of old stars that cocoons the disk and central bulge. They dart on vast swooping orbits; a time-lapse simulation of clusters in motion creates the impression of moths fluttering around a street lamp. Many of these tight knots form attractive targets in small telescopes, and they spread gloriously into separate stars when the Hubble Space Telescope (HST) stares at them.

Detailed surveys by both HST and the Chandra X-ray Observatory have given globular clusters a new cachet. Cluster cores, the wellsprings of the exotica Grindlay talks about, are no longer impenetrable walls of light. "They've become transparent to both HST and Chandra," says astronomer Adrienne Cool of San Francisco State University in California. "We see galaxies behind the clusters. Even an incredibly dense core is spread out on the sky."

Such surveys have revealed profound differences among clusters. For example, the nearby object 47 Tucanae teems with millisecond pulsars—old neutron stars revived and spun up to hundreds of revolutions each second, presumably by pulling gas from a newly captured companion star. Indeed, 47 Tucanae might contain about 100 millisecond pulsars, according to an analysis by Grindlay and his colleagues in the 10 December 2002 *Astrophysical Journal*. By contrast, the galaxy's largest cluster, Omega Centauri, has none. An explanation might come from new Chandra and HST images, now under scrutiny by teams that Cool is leading. It's a tall task: HST's Advanced Camera for Surveys required a span of nine exposures to capture 1.7 million stars in Omega Centauri, just half its population, because the cluster sprawls across such a large chunk of the sky.

Other answers about the distinctions among clusters are coming from new computer simulations of how they evolve. The simulations rely on GRAPE boards, ultrafast processors built by astrophysicists at the University of Tokyo to compute gravitational interactions (*Science*, 13 July 2001, p. 201). "I think we are very close to doing a globular cluster from birth to death," says astrophysicist Simon Portegies Zwart of theUniversity of Amsterdam, the Netherlands. Already, GRAPEs simulate the internal motions of a small cluster of 100,000 stars over a breathtaking sweep of time scales: from binary stars that orbit in mere hours to the lifetime of the cluster itself, spanning 10 billion years.

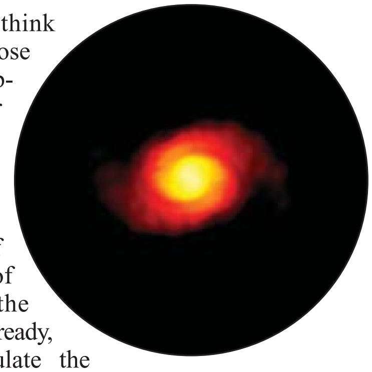
The work reveals that the dynamics of the cluster and the evolution of its stars are inextricably linked. Stars are so close that any changes in their mass or size influence how they interact with neighbors. Portegies Zwart and his colleagues use the phrase "stellar ecology" to convey this point. "We borrowed the term from biology," he says. "Everything goes together into one big pot of interactions, and then something beautiful comes out."

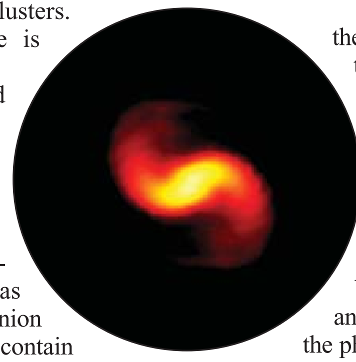
Binary molecules

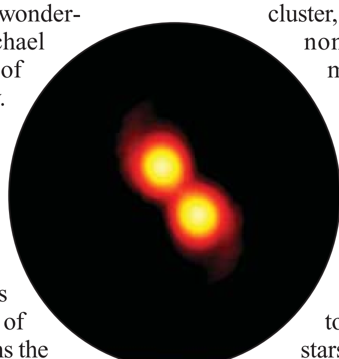
The pot's most critical ingredients are binary stars. "A globular cluster's energy is locked up in these stellar molecules," says astrophysicist Piet Hut of the Institute for Advanced Study in Princeton, New Jersey. "It can be liberated if they interact with other single or double stars, and that can heat the whole cluster."

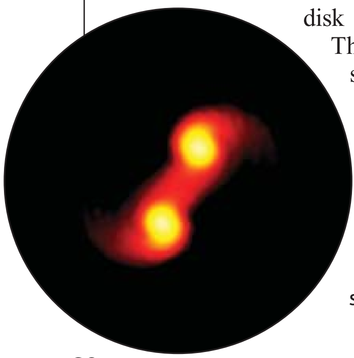
If Hut's words sound like thermodynamics, that's intentional. Scientists draw a parallel between heating a gas and exciting the stars in a cluster with the motions of its binaries. "The particles in the gas are stars instead of molecules, but it's the same physics," says astrophysicist Frederic Rasio of Northwestern University in Evanston, Illinois.

A globular cluster's binary stars respond to the density of the overall cluster. If the cluster is puffed up and stars aren't jammed too close together, there are fewer encounters



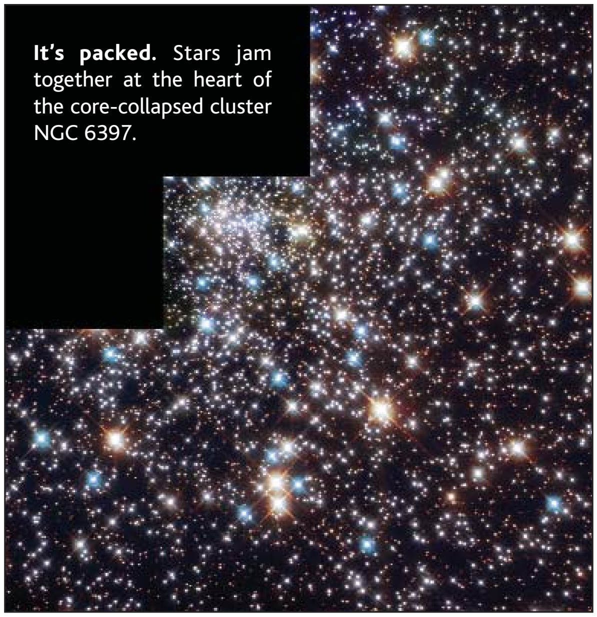






Two, then one. Simulated stars collide near the core of a globular cluster, forming a strange "blue straggler."

CREDIT: A. SILLS/MCMASTER UNIVERSITY, ONTARIO



It's packed. Stars jam together at the heart of the core-collapsed cluster NGC 6397.

between binary systems and other stars. But when gravity pulls the cluster together more tightly—as it inexorably does—the close flybys skyrocket. A third star can swing past a binary and, via a complex gravitational dance, gain kinetic energy. That forces the binary stars into a tighter orbit around each other, a process called binary "burning." In some cases, the third star can replace one of the two binary members and fling it to the cluster's outskirts. Such exchanges puff up the globular again. "It's like having a bunch of tightly coiled springs right at the center," says Shara.

This give-and-take carries a cost. Many of the gravitational boomerangs are so extreme that stars flee the cluster entirely, kicked out by their kin into the galaxy. Such "evaporation," as astronomers call it, is the main threat to a cluster's long-term survival. Moreover, the binary fuel supply runs low as the orbits in each pair grow tighter after repeated interactions. A cluster might last a billion years, 10 billion years, or more, depending on its initial mass and how many binaries it contains. But ultimately, it's condemned to dwindle from a grand swarm of stars into a nubbin of old survivors.

No one knows how easy it is for binary stars to arise when globular clusters are born. However, calculations show that it doesn't take many of them to affect the cluster's evolution. If just 5% to 10% of a cluster's stars are in binaries, they impart enough "heat" to the rest of the stars to prevent the cluster from imploding on itself. Indeed, just a handful of binary stars can yield more energy than the gravitational energy that binds a whole cluster together.

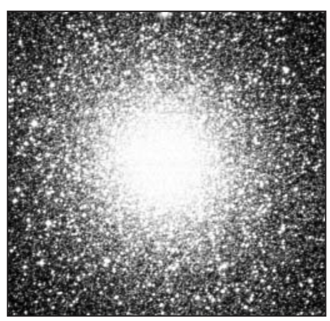
Still, catastrophic collapses do occur. A surprising portion of the Milky Way's globular clusters—as much as 20%, by some reckonings—have undergone "core collapse." In that extreme state, the density of stars keeps rising all the way to the center. The core becomes as crowded as the finite number of stars will allow, perhaps 10,000 times more densely packed than a normal cluster.

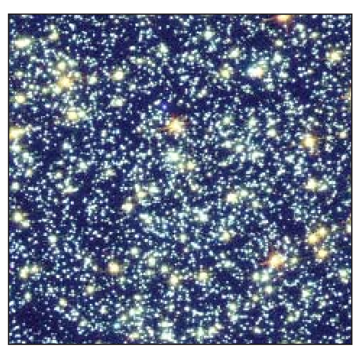
At this point, says Northwestern's Rasio, observations and theory conflict radically. Models predict that a core-collapsed cluster should immediately rebound as the innermost binaries—forced into overdrive by frequent encounters—expel stars to the outskirts once again. According to that scenario, core collapse is such a fleeting state that astronomers should see no such systems today. "After core collapse, we really don't understand what happens," Rasio says. "Anyone who claims to have a viable model is hiding something."

Somewhat better understood are the weird objects that arise when stars near a cluster's core smash together. Once again, binary stars are the catalysts. Two stars orbiting each other create a huge volume of space that a third star can enter and—if the gravitational duel turns deadly—spiral into a collision. "It's a colossal magnification effect," says Shara. "It makes stars millions or even billions of times more likely to interact or collide in globular clusters than anywhere near the sun."

Astronomers have found signs of crashes in virtually every cluster they've studied. Called "blue stragglers," the objects appear younger, hotter, and more massive than the cluster's other stars, all of which were born at about the same time in the galaxy's infancy.

Simulations by theorist Alison Sills of McMaster University in Hamilton, Ontario, and others predict that, by definition, a new blue straggler doesn't become a star for thousands of years after its violent rebirth, because nuclear fusion takes time to resume in its riled-up core. Further, the merged object rotates so fast after the collision that it nearly flies apart. "It may throw off some mass, but we really don't know how to make the spin subside," Sills says. Insights might come from detailed HST observations of nearly 100 blue stragglers, in the final stage of analysis by a team including Shara and astronomer Rex Saffer at Villanova University in Pennsylvania.





Spin factory. Globular cluster 47 Tucanae, seen from the ground (*top*) and space (*bottom*), has spawned dozens of millisecond pulsars.

Getting at the core

Another cluster mystery lies at the center of a swirling debate: What lurks at the innermost core? NASA alluded to this in a press conference in September touting a major discovery by HST: "intermediate-mass black holes" at the centers of two clusters, M15 in our Milky Way and G1 in the neighboring Andromeda galaxy. Weighing in at thousands of times the mass of our sun, these black holes were a putative steppingstone between smaller black holes formed by supernovas and titanic ones at the cores of galaxies. Today, astronomers are standing by their claim for a black hole in G1, but the M15 result has eroded into statistical insignificance.

To identify the suspected midsize black holes, astronomers used HST to measure the orbital speeds of stars at the clusters' cores. Rapid orbits suggested that the gravity of some dark, hidden mass was pulling stars into unexpectedly fast whirls around the centers. But there's a catch: Other compact objects at the center could produce the same dynamics—for example, thousands of neutron stars within a small volume of space. Such nests are improbable in most places. However, they could arise in globular clusters, where massive objects quickly settle to the center like heavier molecules at the base of Earth's atmosphere.

For M15, the HST astronomers relied on an earlier estimate of the number of neutron stars in the cluster. The relatively low figure allowed them to state with confidence that neutron stars alone could not explain the star motions they saw. Only later did the researchers determine that the figure they had adopted was three to five times too low. "We could no longer rule out the no-black-hole case" with the extra neutron

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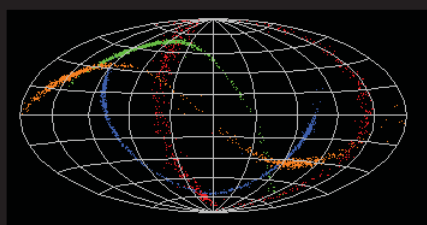
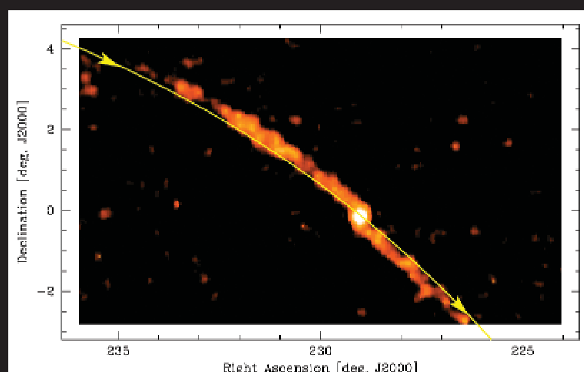
Breaking Up Is Easy To Do

Life as a globular cluster is no picnic. In an ongoing threat to a cluster's survival, gravitational mayhem deep in the core ejects its own stars (see main text) and whittles away its mass. Clusters are threatened from outside, too; our Milky Way snacks on them like finger foods. Over time, the galaxy can shred a compact cluster into ghostly streams of stars. "Once a globular cluster forms, it immediately starts dying," says astronomer Stephen Zepf of Michigan State University in East Lansing. "It's just a matter of how long it takes."

The galaxy's appetite stems from its fierce tides. Just as the moon's gravity raises swells of water on opposite sides of Earth, the Milky Way puffs up stars on both sides of a globular cluster by tugging harder on the cluster's nearer side than its farther side. This process sets a "tidal radius," the boundary where a star feels equally drawn to the cluster and to the galaxy. Beyond this radius, stars drift into space—spreading along the cluster's orbit in both directions to form faint but persistent "tidal streams."





Fossil traits. Dissolved clusters leave streams of stars in the galaxy (*left*), a fate that awaits the disrupted cluster Pal 5 (*below*).

When a globular cluster loops near the galaxy, the gravitational field grows, and the tidal radius shrinks. Each encounter shocks the cluster and forces it to cough up more stars. The most dramatic case is Pal 5, a small cluster caught in the act of dissolving by the Sloan Digital Sky Survey (*Science*, 14 June 2002, p. 1951). "Pal 5 is the paradigm of a tidally disrupted cluster," says astronomer Steven Majewski of the University of Virginia, Charlottesville. His team has observed nodules of stars within Pal 5's tidal streams, marking each time the doomed cluster dove through the Milky Way's disk, compressing the tidal radius and freeing a burst of stars.

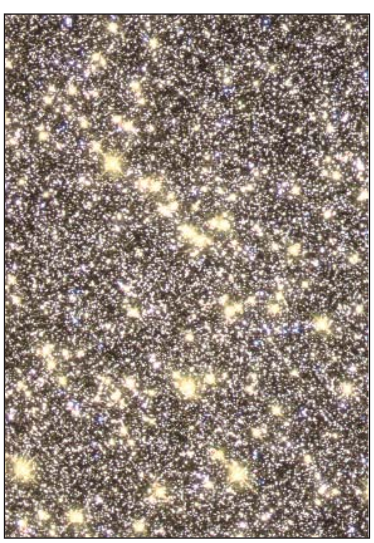
Astronomers think they see tidal streams emerging from as many as 20 other globular clusters, but the dim trails are hard to identify and trace. Still, it's clear that the Milky Way's outskirts are laced with the stretched-out remnants of vanished star systems. "The outer halo is almost completely networked with these streams," Majewski says.

Consequently, today's assembly of about 150 clusters is a shadow of some grander swarm in the past. However, no one knows how many clusters dotted the skies in the Milky Way's youth. Some models by Zepf's colleague at Michigan State, astrophysicist Enrico Vesperini, suggest that the Milky Way originally had about 350 clusters; others peg the initial population at 1000 or more. Moreover, the survivors aren't typical; certain qualities helped them endure, most notably their higher masses and more-distant orbits. "There may have been a collection of fragile, fluffy things that we have no representatives of now, because they've been completely wiped out," Zepf says. Studies of the types of clusters around young galaxies elsewhere offer clues about the Milky Way's globular heritage (see p. 63).

Our galaxy's gluttony actually adds a few clusters here and there. When dwarf galaxies spiral into our own, gravitational tides shred them as well. This is happening now to a loose agglomeration of stars called the Sagittarius dwarf (*Science*, 7 January 2000, p. 62); indeed, Majewski's group sees tidal streams from Sagittarius wrapping clear around the Milky Way. However, several of the dwarf's globular clusters will outlast this dissolution for billions of years. The Milky Way's largest globular cluster, Omega Centauri, might be the core of a dwarf galaxy whose outer parts were stripped off long ago, because it consists of an odd mix of stars with different ages and compositions. Our galaxy, it seems, can't quite finish every morsel it tries to consume. **–R.I.**

stars, says astronomer Karl Gebhardt of the University of Texas, Austin.

That backtracking didn't surprise Hut, Portegies Zwart, and their colleagues, who conducted GRAPE simulations of an M15-like cluster with 128,000 particles. In the 1 January issue of *Astrophysical Journal Letters*, the team reports that M15 probably contains a dense warren of small black holes and neutron stars, all orbiting near the center. For an intermediate-mass black hole to arise, they claim, a cluster's giant stars must merge quickly in their youths, when they are bloated and more likely to crash. Once the stars blow up after about 10 million years to forge black holes and neutron stars, assembling a bunch of them becomes much more difficult. "Compact objects are so tiny that they almost never collide once they form," Portegies Zwart says. "They kick each other out of the cluster rather than merge into something bigger."



City of stars. Vast Omega Centauri is the galaxy's biggest globular cluster.

The debate is far from over. Gebhardt has data in hand from a ground-based survey of star motions in about 15 other Milky Way clusters, most of them easier to study than the crowded heart of M15. His analysis, forthcoming within a few months, suggests that intermediate-mass black holes may yet prove to be the best explanation. "I'm getting much more convinced now that this is a reality," he says. "But I realize it will be an uphill battle for me to convince others."

Whether or not they harbor black holes, globular clusters are unendingly strange to those who study them. "If the universe didn't make globular clusters, nobody would insist that they should be there," says Stephen Zepf of Michigan State University in East Lansing. Fortunately, they do exist—giving astronomers their best clues about what happens to stars when the going gets dense.

–ROBERT IRION

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