ASTROPHYSICS

THE INNER LIFE OF STAR CLUSTERS

All stars are born in groups but then slowly disperse into space. A new theory seeks to explain how these groups form and fall apart or, in rare cases, persist for hundreds of millions of years

By Steven W. Stahler

STAR STUCK: The Pleiades, known as an "open" cluster, is one of the most stable stellar groups in the Milky Way.

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THE NIGHT SKY IS A FIELD OF STARS.

In every direction, stars bright and dim fill the horizon to brimming. Some seem to form distinct patterns, which we recognize as constellations. Yet as beguiling as those patterns may be, most of them are no more than projections of the human mind. The vast majority of stars, in our own galaxy and in others, have no true physical connection to one another.

At least, not anymore. Every star actually begins its life in a group, surrounded by siblings of nearly the same age that only later drift apart. Astronomers know this because some of these stellar nurseries, called star clusters, still exist. The Orion nebula cluster is perhaps the most famous one: in images from the Hubble Space Telescope, its stars wink from within churning clouds of dust and gas. You can see the Pleiades cluster from your backyard: it is the fuzzy patch in the constellation Taurus.

Star clusters vary enormously, ranging from fragile associations with just a few dozen members to dense aggregates of up to a million stars. Some groups are very young—only a few million years old—and others date from the dawn of the universe. Within them, we find stars in every stage of the stellar life cycle. Indeed, observations of star clusters provided the main evidence for today's accepted theory of how individual stars evolve over time. The theory of stellar evolution is one of the triumphs of 20th-century astrophysics.

Yet relatively little is known about the inner workings and evolution of the clusters themselves. What accounts for the variety of forms that astronomers observe? We understand far more about individual stars than we do about the cradles of their formation!

The irony of this situation first struck me 20 years ago, when I began writing a graduate textbook on star formation with Francesco Palla of Arcetri Astrophysical Observatory in Florence, Italy. At the time, the two of us were regularly trading visits between Berkeley, Calif., and Florence. As we followed the many strands of research in this rich field, the unanswered questions about star clusters always lurked in the back of our minds.

One afternoon, as we took a break at Caffe Strada (located in Berkeley, naturally), the germ of an answer came to me. Perhaps the same physical forces had shaped all clusters, regardless of their present ages and sizes. And perhaps one simple variable could account for the way those forces act on an individual cluster: the mass of the parent cloud from which each cluster is born. It would take me the better part of the ensuing decades to gather evidence for this hunch.

CLOUDY WITH A CHANCE OF STARLIGHT

WHEN I BEGAN this work, astronomers knew a lot about how stars form and a good bit about the kinds of clusters they form in. Stars do not materialize from empty space; rather they coalesce within vast clouds composed chiefly of hydrogen molecules, along with other elements and a small admixture of dust. These so-called molecular clouds are distributed throughout all galaxies, and each exerts a gravitational pull—not only on stars and other objects outside the cloud but also on regions in the cloud itself. Because of the cloud's own gravity, regions where gas and dust are especially dense collapse into protostars. In this way, clusters of anywhere from a few dozen to thousands of stars can arise from a single molecular cloud.

Clusters generally occur in five types, distinguished in part by their age and in part by the number and density of the stars they contain. The very youngest stellar groups, called embedded clusters, lie in clouds so thick that light in the visible wavelengths radiating from their member stars is completely obscured.

IN BRIEF

Stars form in clusters, within clouds composed of gas mixed with dust.

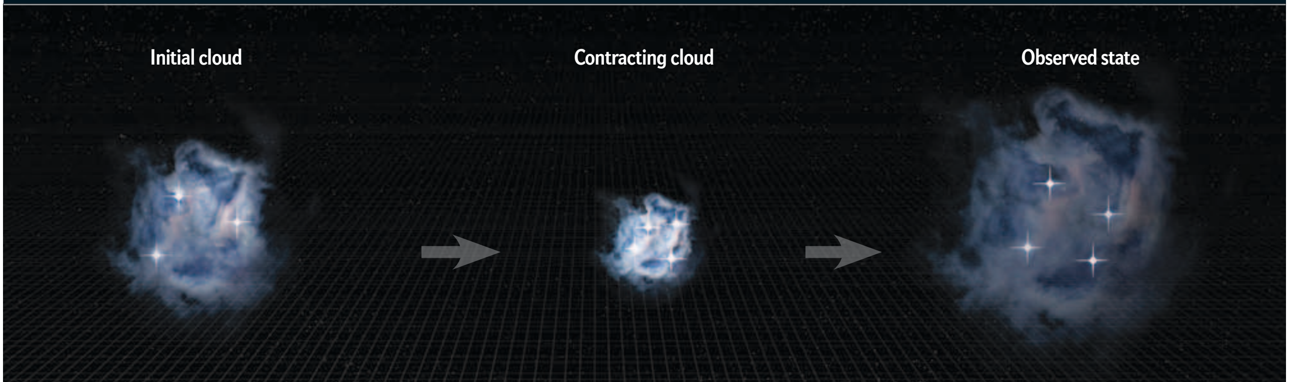
Three types of clusters can be seen in the Milky Way, with differing structures and evolutionary histories.

The mass of the cloud that spawns a stellar group may account for these differences, by affecting the balance of contraction and expansion in the cluster.

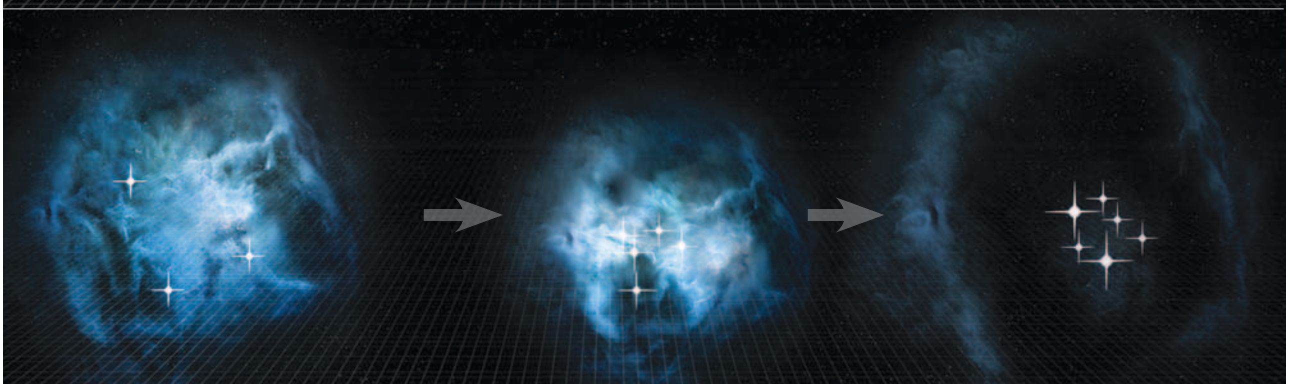
Only open clusters remain intact after the parent cloud has dispersed.

One Driver, Three Outcomes

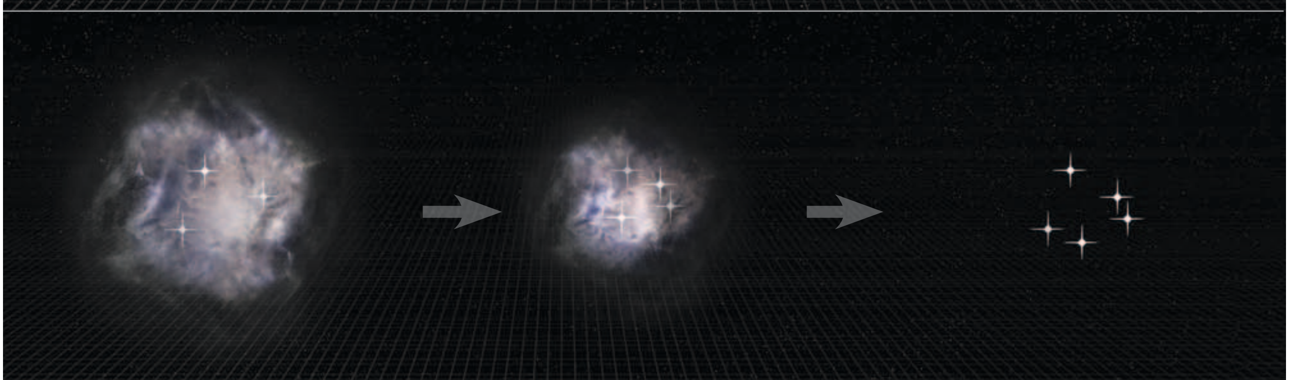
The three most readily observed star clusters in our Milky Way Galaxy all began as a diffuse cloud of dust and gas, within which small regions condensed to form stars. The author proposes that a single factor—the mass of the parent cloud—accounts for the differences in the clusters' subsequent evolution and structure (*below*). First, the clouds contracted, accelerating star production at rates determined by the starting mass; higher-mass clouds contracted most and generated stars most quickly. Later, the clusters expanded, and the clouds dispersed partly or fully, depending on the number and kinds of stars present.



T Association Such clusters typically last just a few million years and possess up to several hundred young stars, called T Tauri, surrounded by remnants of the parent cloud. They probably arise when a low-mass cloud contracts slowly under the influence of its own relatively weak gravitational pull. The mild contraction would produce a smattering of stars. Stellar winds from these stars would later diminish the cloud, causing both gas and stars to spread apart.



OB Association These clusters stay bound together for as long as 10 million years and comprise thousands of densely packed stars, including a few very massive ones called O and B stars. To produce such a dense cluster, the parent cloud would have to be extremely massive and contract very quickly. Harsh ultraviolet radiation from the most massive stars would then shred the parent cloud, and the cluster would expand and eventually disperse.



Open Cluster The longest lasting of the three, open clusters can persist for hundreds of millions of years, but they have far fewer stars than OB associations do. These groups probably arise when a cloud of intermediate mass contracts. Although stellar winds drive the cloud away, the cluster does not disperse for a very long time.

Illustrations by Malcolm Godwin

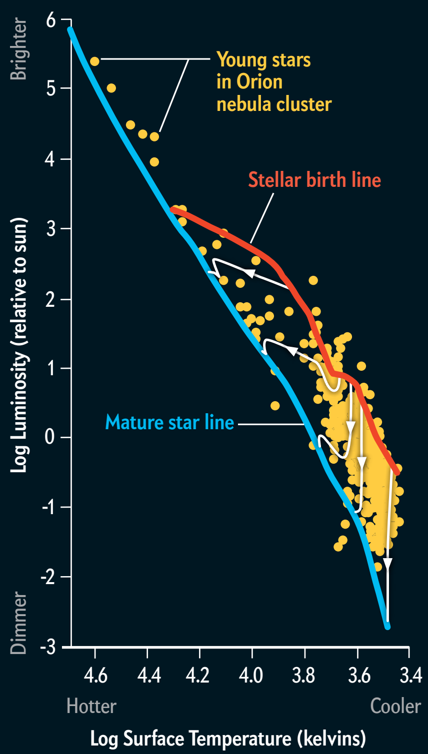
EVIDENCE

Cluster's History Supports Theory

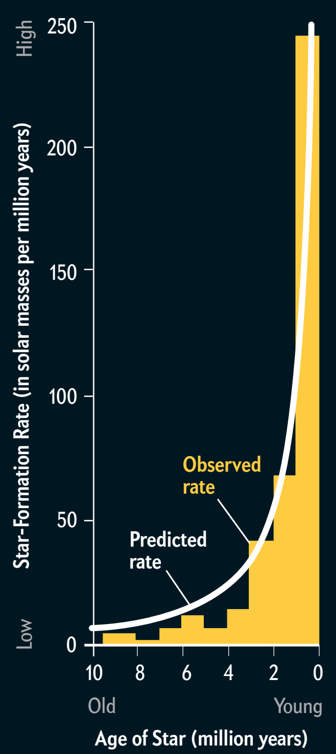
Data from the Orion nebula cluster, an OB association in the Orion nebula (*photograph*), support the author's theory that cloud contraction occurs early in cluster evolution, causing star formation to accelerate as the density of the parent cloud rises. Star formation in the cluster stopped about 100,000 years ago, but until then the parent cloud probably contracted for millions of years. To show that contraction happened, the author first determined the ages of the cluster's young stars (*yellow dots in left graph*), which can be gleaned from their temperature and brightness. In general, the red line represents very young stars that are newly visible in optical wavelengths; these stars get hotter and dimmer in predictable ways as they age (*white arrows in left graph*), until ultimately they are plotted on the blue line. Thus, a star's position between the red and blue lines indicates its age.

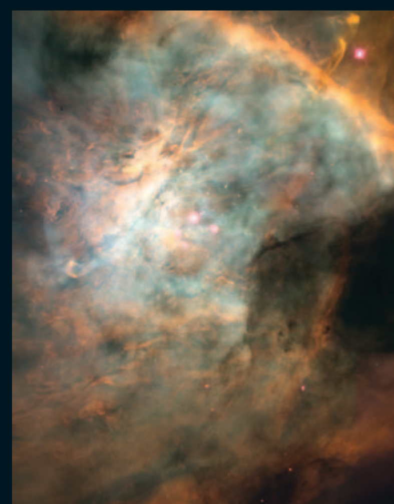
The author then calculated the collective mass of the stars (relative to the mass of the sun) in each million-year age group, revealing the star-formation rate in the cluster during that period (*right graph*). The results indicate that star production increased dramatically over time, just as theoretical modeling (*white line*) predicted.

Young Stars Show Their Age



Star Formation Has Accelerated





Instead we see only the infrared glow of dust heated by the embedded stars and cannot discern the detailed structure of these primitive clusters. They remain an abiding mystery.

Globular clusters, in contrast, are the oldest and most populous stellar group. They date to the dawn of the universe and can contain as many as one million stars packed very closely together. The parent clouds of these mature clusters have disappeared, and the stars within are entirely visible. Yet the closest globular clusters lie at some remove from the disk of the Milky Way galaxy, and so they, too, are difficult for astronomers to study in detail.

For practical reasons, then, I have restricted my theorizing to the three types of clusters that occur in the plane of our galaxy and thus can be seen best of all. The sparsest of these is called a T association because it consists largely of the most common kind of young star, called a T Tauri. (Our sun was a T Tauri star in its youth.) Each T association contains up to several hundred of these stars surrounded, but not totally obscured, by the parent cloud. T associations do not stay together for long: the most aged ones observed are some five million years old—the blink of an eye from a cosmic perspective.

Scientists have known for some time that the mass of the parent cloud in a T association is far greater than that of its collective stellar progeny. I believe this feature accounts for the short life span of these clusters. Mass determines the strength of gravitational force: the greater the mass is, the stronger the gravitational pull is. So if the mass of the parent cloud in a T association is much greater than that of its member stars, the gravity of the cloud—not the gravity exerted by the stars on one another—must be what holds the cluster together. And if the cloud disperses, the stars will drift apart. Astronomers think that stellar winds—jets of gas propelled forcefully outward from the stars—eventually strip away the parent cloud of a T association, freeing the previously bound stars to head into space.

SOURCES: "STAR FORMATION IN THE ORION NEBULA CLUSTER," BY FRANCESCO PALLA AND STEVEN W. STAHLER, IN *ASTROPHYSICAL JOURNAL*, VOL. 525; 1999 (*left*); COURTESY OF NASA, HST, C. R. O'DELL AND S. K. WONG (*right*)

The second type of stellar group readily observed in the Milky Way is named after two extraordinary kinds of stars, designated O and B, that are the most luminous and the most massive stars in the universe. These clusters, called OB associations, typically have about 10 times more stars than T associations do, including a few O and B types. The Orion nebula cluster is a familiar example; located some 1,500 light-years away, it comprises four truly massive stars and about 2,000 lesser ones, including many T Tauri stars. It has the highest stellar density of any region in our part of the galaxy.

All young OB associations have similarly high densities and arise from especially massive parent clouds. Yet despite the tremendous gravity within these systems, the stars in older OB associations are not just gradually dispersing but are actively flinging themselves out into space. Astronomers know this because images of mature OB associations taken just a few decades apart show that the member stars have moved farther away from one another.

One reason for this rapid dispersal is that the stars are moving very quickly to begin with. The terrific gravity of the parent cloud in an OB association spurs its stellar members to orbit at high velocities. Young OB associations are chock-full of these speeding stars, poised to escape the cluster should the parent cloud diminish. And in OB associations, the parent cloud is under siege from the harsh ultraviolet radiation that O and B stars emit during their brief lifetimes. These stars are powered by nuclear fusion, as our sun is, but they burn far more fiercely. A typical O star has 30 times the mass of the sun, for example, yet it exhausts its fuel in just a few million years.

In the course of this self-immolation, ultraviolet radiation streams from the star and ionizes surrounding gas—in effect, burning up the parent cloud. The dust and gas in the Orion nebula cluster are glowing from this ionization. As the parent cloud burns away, its gravity dwindles. When the massive stars have finally expired and the parent cloud is gone, the gravity of the system can no longer contain those smaller, speeding stars, and they are flung far afield.

Thus, both T and OB associations undo themselves, whether through gentle attrition or violent agitation. The third, much less common, kind of stellar group in the Milky Way is remarkably stable, however. Called open clusters, these groups have up to 1,000 ordinary stars and persist for hundreds of millions, and even billions, of years. Yet their molecular clouds and any attendant gravity have long since vanished.

The Pleiades is one such cluster. It is 125 million years old, and its parent cloud has probably been gone for 120 million years or more. The equally famous Hyades cluster, not far from the Pleiades in the sky, is 630 million years old. In the outskirts of our galaxy dwell dozens of open clusters that are even older. The cluster M67, a system of 1,000 stars, arose four billion years ago.

Even open clusters are not immortal; very few are older than M67. Astronomers believe that, eventually, the gravity of molecular clouds passing close by begins to shred and disperse these systems. Yet they still pose a vexing problem. Over the past few decades researchers have arrived at satisfying explanations for how the dispersal of parent clouds causes T and OB associations to fall apart. But they still have no answer for why the stars in open clusters survive cloud dispersal to remain bound together for many millions of years.

PUSH AND PULL

AS I WROTE my book on star formation, I had ample cause to wonder about the diversity of cluster forms. I saw the mystery of open clusters as part of a larger class of questions: Why does our galaxy host only a limited variety of star clusters? How does a molecular cloud "decide" what kind of cluster it is going to produce?

I considered the forces at work in star clusters. Taken together, the life stages of the three types I chose to study point to two countervailing processes: contraction, caused by the gravity of the parent cloud, and expansion, promoted by stellar winds and ionizing radiation. Each star-producing cloud is subject to these two opposing influences to varying degrees. In the case of T and OB associations, expansion eventually wins. In the case of open clusters, expansion and contraction seem to stay in balance, at least during the critical epoch during which member stars are forming.

The balance of forces in a cloud, I reasoned, thus determines its fate as well as the destiny of the stellar cluster it produces. And I suspected that the key to this balance might be the original mass of the parent cloud. As I have explained, the mass of a cloud certainly determines its gravity; the cloud's gravity, in turn, governs the rate at which it contracts. Cloud mass also determines the number of stars the cloud produces. A low-mass cloud, for example, would contract slowly, causing a gradual increase in its density that would produce a smattering of ordinary stars. Later, winds from those stars would gradually strip away the cloud, reversing the contraction and releasing member stars into space. That scenario fits what we observe in T associations today.

At the opposite extreme, a cloud with an order of magnitude more mass would undergo a rapid contraction, forming many new stars in close proximity. Eventually this cloud's core would reach a density so great that a few massive stars would be born. Then, as we see in OB associations, harsh radiation from the massive stars would quickly disperse the cloud, and the speeding stars within would move outward.

Finally, it seems probable that an intermediate range of cloud masses exists for which the two effects are comparable. These clouds would contract at about the same rate at which they lose mass. The result is a molecular cloud containing an ever increasing fraction of young, tightly knit stars but no truly massive ones. Even when stellar winds drive away the cloud, the gravitational attraction among these closely packed stars themselves would be enough to keep them bound for a very long time in a configuration not unlike the one astronomers call an open cluster.

CLOUD CONTRACTION

MY FORCE-BALANCE THEORY described how the starting mass of a parent cloud could determine the interplay of contraction and expansion in, and thus the evolution of, the resulting cluster. Yet although astronomers can observe expansion and dispersal directly in OB associations, no one had found evidence that molecular clouds ever contract at all, let alone in the ways my theory suggested. Such contraction would surely occur in the very first stages of cluster formation, but the youngest stellar groups—the embedded clusters—resisted direct examination. I would have to figure out a way to demonstrate that more mature clusters had undergone contraction long ago.

I gained a clue from work done in the late 1950s by astronomer Maarten Schmidt of the California Institute of Technology. Schmidt observed that the birth rate of new stars depends on the density of the surrounding gas. So, I reasoned, if a parent cloud had in fact contracted in the past, its density would have increased, and the rate of star formation would have accelerated, too. My theory therefore posited an acceleration of star formation in the early life of every stellar group.

To test that prediction, I needed to figure out how to measure historical star-formation rates in clusters. Fortunately, the theory of stellar evolution provides a way to do just that. Among many other things, the theory describes how young stars that are not yet burning nuclear fuel—such as T Tauri types—behave over time. T Tauri stars are about as massive as our sun, and they are just as luminous. But instead of shining because of nuclear fusion, they radiate the heat generated by compression as their own gravity causes them to contract. With time, the rate of their compression slows, while their surface temperature climbs. The stars thus get both dimmer and hotter in a predictable pattern as they age.

If you know the surface temperature and luminosity of a T Tauri star as well as its distance from Earth, you can tell how long it has been contracting—in effect, you can tell how old it is. I realized that the collective set of ages of all these stars in a cluster would reveal the star-formation history of the group—when and at what rate the member stars formed over time.

It was not difficult to apply this method to nearby stellar groups, for which the required data are most readily available. Palla and I found that, for all groups that still possess copious cloud gas, the total star-formation rate has been increasing with time. In 2000, for example, we published data showing that the rate of star formation in the Orion nebula cluster accelerated for millions of years before its parent cloud dispersed. This finding encouraged me to believe that my assumption was correct: early in their history, all cluster-forming clouds probably *do* contract.

In 2007 then graduate student Eric Huff, now at Ohio State University, and I constructed a theoretical model of the parent cloud of the Orion nebula cluster. Our model included the forces of contraction and expansion postulated by my theory. In computer simulations based on the model, the simulated cloud contracted, just as we predicted it would. We then applied an empirical prescription known as the Schmidt-Kennicutt law, derived from Schmidt's observations and many subsequent ones, to show how the increase in density in a parcel of the cloud over time would affect the local star-formation rate.

Our modeling yielded an accelerating rate of star formation that matched the acceleration Palla and I had derived from ages of stars in the Orion nebula cluster. This additional finding further corroborated the force-balance theory's assumption that parent clouds contract in the early stages of cluster evolution.

CLUSTER EXPANSION

UNFORTUNATELY, the methods I used to measure and model early star-formation rates in clusters such as the Orion nebula group cannot be applied to open clusters, those strangely persistent groups that lack any trace of a parent cloud yet remain bound by gravity. Most open clusters are just too old; their epoch of contraction and star formation—which lasted for just a few million years—amounts to a tiny fraction of these clusters' total lifetimes. The tools for discerning stellar ages do not have nearly the resolution needed. And we cannot yet simulate the parent clouds of open clusters, either; the clouds dispersed so long ago that we cannot even guess at their masses or behavior. So far the early stages of open-cluster evolution remain inaccessible even to indirect observation.

It is possible, however, to model the evolution of an open cluster whose parent cloud has already vanished using so-called N-body simulations. In such simulations, the computer solves the complex, interlocking equations that describe the motion of multiple objects under the influence of their mutual gravitational attraction. This approach has elucidated what happens in open clusters *after* the initial star-forming contraction proposed by my theory and has provided some unexpected insights into the forces that shape cluster expansion.

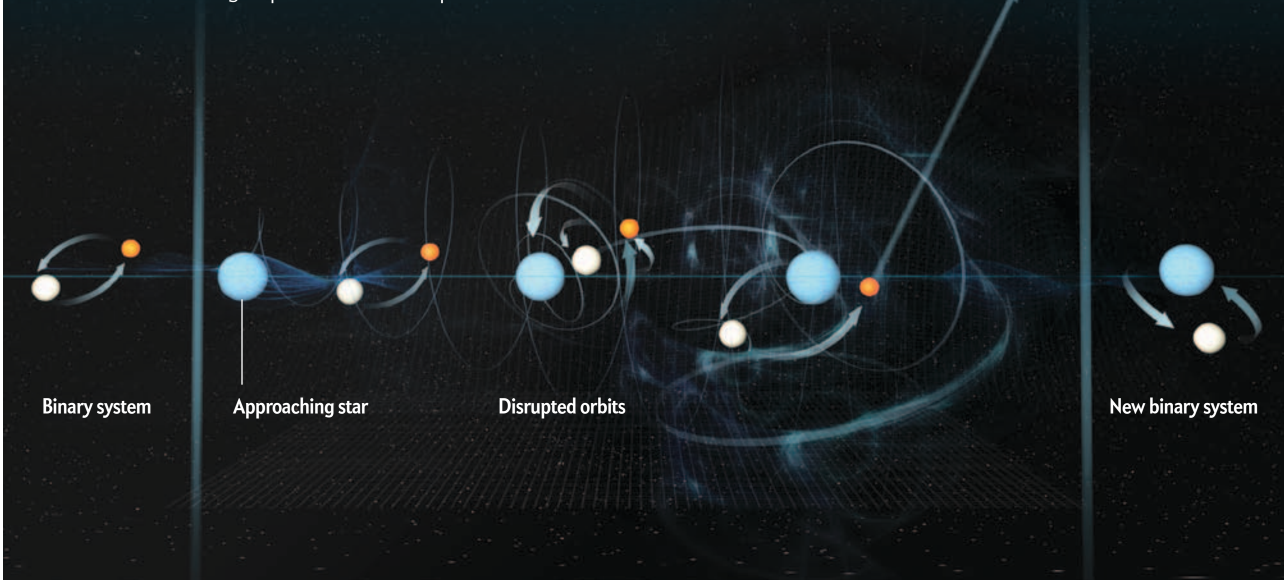
Although open clusters are remarkably stable, they are not static. The mutual gravity among member stars creates a constant, slow churning, as the orbiting stars weave in and out of one another like bees swarming in a hive. N-body codes describe this gravity-induced dance, and they are so efficient that they can simulate the evolution of a 1,200-member group such as the Pleiades on a standard desktop computer. Several years ago my graduate student Joseph M. Converse, now at the University of Toledo, and I took this numerical path to elucidate the history of the Pleiades. Our strategy was to guess an arbitrary initial configuration for the cluster and then to let it evolve for 125 million years. We compared the resulting simulated cluster with its actual counterpart and changed the initial conditions until the N-body simulation produced a group that resembled the real thing.

What we saw surprised us. It seems that while remaining gravitationally bound, the Pleiades cluster has expanded, more or less uniformly, since its cloud dispersed. The stars in their busy orbits move away from one another at a stately, steady pace. This result conflicts with prior analyses, which had predicted that the stars in open clusters would slowly segregate into an inner clump of heavier ones and an outer envelope of relatively light ones. This pattern of segregation is called dynamical relaxation, and it is the standard description of how gravitationally bound clusters evolve over time. Globular clusters, for example, are known to behave this way. Yet even when we let our N-body simulation run for 900 million years into the future, expansion continued uniformly, showing what an inflated but still intact Pleiades will look like at the age of a billion years.

This finding suggests that the classical analysis overlooked some critical factor in the balance of forces shaping cluster evolution. What drives the uniform expansion of open clusters? Converse and I demonstrated that the key is binary stars: pairs of close, orbiting companions that are quite common in stellar groups. Simulations performed by Douglas Heggie, now at the University of Edinburgh in Scotland, showed in the mid-1970s that when a third star approaches such a pair, the three engage in a complicated dance, after which the lightest of the three is usually ejected at high speed. The ejected star soon encounters other members and shares its energy with them, increasing those stars' orbital velocities and effectively "heating up" the cluster. In our N-body simulations, it was the energy from these binary encounters that caused the open cluster to expand—albeit so slowly that the expansion could easily go unnoticed by astronomers.

A Binary Pas de Trois

In computer simulations, open clusters continue to expand slowly for hundreds of millions of years. The author proposes that this expansion is fueled by binary systems, pairs of orbiting stars that are quite common in star clusters (*below*). First, a passing star enters and disrupts a binary's orbit. After a complicated gravitational dance, the lightest of the three stars gets ejected at great speed. The ejected star goes on to encounter other stars in the cluster, transferring its momentum as it passes by. This energetic exchange speeds up the other stars, enlarging their orbits and pushing the boundaries of the group farther out into space.



ENDURING MYSTERIES

MY INVESTIGATION of star clusters offers some evidence for my proposal that the original mass of a molecular cloud determines both the structure of a cluster and its evolution. The work also offers promising directions for future research. For example, astronomers should look for ways to observe the uniform expansion of open clusters predicted by my studies.

But my findings also serve to highlight the many things we still do not know about star clusters in general. Despite the advances in computer simulations, we do not yet have the tools to model how certain regions of parent clouds become dense enough to form stars. And several decades of radio and infrared observations have failed to reveal the patterns of internal motion in these clouds. The birth phase of stellar groups—a phase that takes place within the thick dust of embedded clusters—remains shrouded in mystery.

Yet the force-balance model my colleagues and I developed can help us figure out more details about this phase and other aspects of cluster evolution. We want to verify, through a combination of analytic studies and N-body simulations, that a cloud losing mass at the same rate as it contracts will indeed produce a gravitationally bound system resembling an open cluster. We also want to use modeling to explore how nascent T associations might reverse the cloud contraction and then disperse into space. Do stellar winds really play the pivotal role astronomers have assumed, for instance?

The impact of this research will extend far beyond the clusters themselves. Although the study of stellar groups in the Milky Way was long a backwater of astronomy, it is fast becoming central to other research. Some astronomers believe, for example, that the sun formed in a crowded OB association and that the close presence of neighboring stars perturbed the surrounding disk of gas and dust in ways that shaped our solar system. The molecular clouds that spawn clusters are also important players in the evolution of the interstellar medium and of galaxies as a whole. Star clusters may thus hold the key to a better understanding of the entire universe: from the birth of our solar system to the past and future of all that exists beyond it. SA

MORE TO EXPLORE

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SCIENTIFIC AMERICAN ONLINE
Take a virtual flight through the Orion nebula cluster, complete with gas clouds, stars and very young planets at **ScientificAmerican.com/mar2013/orion**