pathway. In budding yeast, the formins Bni1 and Bnr1 are important for assembly of actin cables. Loss of formin activity leads to rapid loss of actin cables, whereas overexpression of certain segments of formin proteins leads to extra actin cables (*6, 7*). The Arp2/3 complex does not seem to be required for actin cable assembly (*6, 8*), implying that these structures may be nucleated without the help of this complex.

In the new work, Pruyne *et al.* (*2*) and Sagot *et al.* (*3*) show that the highly conserved FH2 domain of the yeast formin Bni1 nucleates the assembly of actin filaments in vitro. Biochemical and electron microscopy experiments revealed that the FH2 domain induces actin nucleation and promotes assembly of long unbranched actin filaments from their barbed ends. In contrast to Arp2/3, which binds to the pointed ends, the formin fragment appears to attach to actively growing barbed ends. Consistent with this barbed-end association of formins, Bni1 is localized in the cortex at the tip of the yeast bud, where the barbed ends are thought to reside (see the figure). With Bni1 and the barbed ends of filaments fixed into the cortex of the yeast bud, the pointed ends of actin filaments are pushed into the cell interior as monomers are added to the barbed ends. Together these exciting findings identify formins as a new class of proteins that nucleate actin.

Formins are thought to bind to multiple proteins in large complexes. In particular, they have a proline-rich domain that binds to profilin, a small protein that binds to actin monomers and stimulates their polymerization. Genetic analyses suggest that formins and profilins cooperate during actin assembly in vivo. Indeed, formin-dependent actin nucleation is stimulated by profilin in vitro, most likely through recruitment of actin monomers (*3*). Formins also bind to other actin-organizing proteins such as Bud6 and Spa2. Thus, although a small portion of a formin can stimulate actin assembly itself, their true involvement is likely to be as participants in a large actin assembly molecular machine.

These studies begin to reveal how different actin structures are formed by different nucleators. Many cells have multiple formins that carry out either specific or overlapping tasks. For instance, each of the three formins in fission yeast promotes the assembly of a specific actin structure, such as the contractile ring required for cytokinesis. A recent study in fission yeast reveals that actin nucleation in the contractile ring requires both the Arp2/3 complex and the formin cdc12p (*9*). Thus, in vivo it is possible that these two types of nucleator work together. In addition, other nucleators may exist. For instance, human zyxin may generate new actin structures in an Arp2/3-independent manner (*10*). Future studies will define which actin nucleators are responsible for directing assembly of which actin structures.

Although the new results identify formins as direct actin nucleators, many important questions remain unanswered. What is the biochemical mechanism of actin nucleation by the formin FH2 domain? How do other domains of formin proteins and other formin-associated proteins contribute to or modify FH2 domain activity? Do different formins direct the organization of different actin structures? How do formins coordinate actin assembly with other activities such as microtubule dynamics? How is actin organization regulated by the spatial and temporal regulation of formins? Clearly, the formins are an important focal point for understanding the molecular processes that direct the cytoskeletal organization of cells. Given the current pace of progress, there is little doubt that these and other questions will be straightened out in the near future.

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PERSPECTIVES: ASTRONOMY

Of Clusters and Galaxies

Christine M. Clement

Globular clusters (see the first figure) are compact assemblies of stars that are the oldest stellar systems in the Milky Way Galaxy (*1*). They play a crucial role in the study of the formation and evolution of our galaxy. But as Yoon and Lee show on page 578 of this issue (*2*), some long-held assumptions about globular clusters need to be revised.

Forty years ago, Eggen *et al.* (*3*) proposed that the galaxy formed from a homogeneous, rotating, gaseous body that collapsed into a disk (see the second figure). According to this monolithic collapse model, most globular clusters formed from condensations of gas in the spherical halo before the remaining gas collapsed. As a result, globular clusters are located primarily in the halo. Their stars have lower metal abundances than Sun-like stars because they formed at an earlier epoch when the interstellar medium was less enriched in heavy elements (*4*).

The globular cluster Omega Centauri. With about a million stars, it is the largest and brightest cluster in the Milky Way. A typical cluster contains ~100,000 stars. About 150 clusters have been identified in our galaxy.

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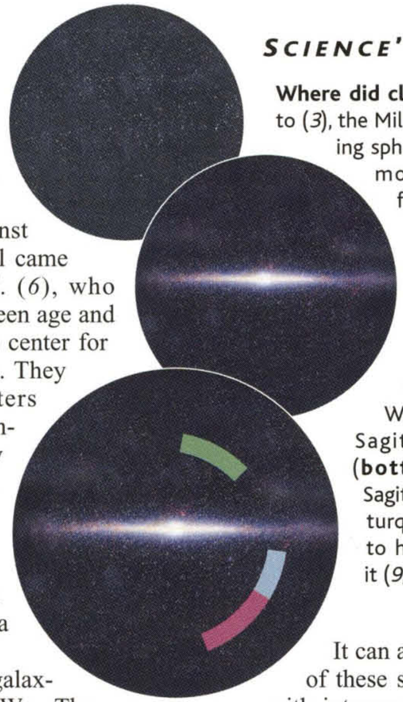
But evidence is mounting that the formation of our galaxy was less straightforward than this model suggests. Capture from other galaxies is increasingly seen as a viable source of clusters. Yoon and Lee (*2*) propose that this mechanism may explain the unusual properties of certain metal-poor globular clusters.

In a slow monolithic collapse model, the age and metal abundance of a halo cluster should depend on its distance from the galactic center—the more distant clusters should be older and have a lower metal abundance. However, Searle and Zinn (*5*) found no radial abundance gradient in the clusters of the outer halo. They argued that some clus-

The author is in the Astronomy and Astrophysics Department, University of Toronto, Toronto, Ontario M5S 3H8, Canada. E-mail: cclement@astro.utoronto.ca



Where did clusters form? According to (*3*), the Milky Way began as a rotating spherical gas cloud in which most globular clusters formed (**top**). When the cloud collapsed to form a disk, the globular clusters remained in the spherical halo (**middle**). But some clusters may have been captured by the Milky Way, for example, from the Sagittarius Dwarf Galaxy (**bottom**). Red/beige, the Sagittarius Dwarf Galaxy (*8*); turquoise, material thought to have been stripped from it (*9*, *10*). [Adapted from (*9*)]

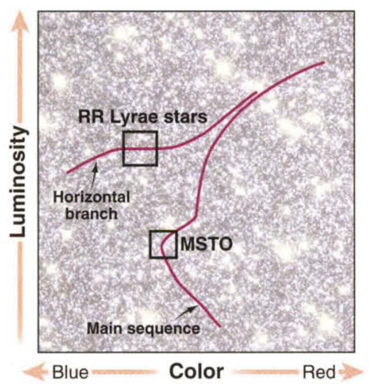
ters in the halo might have formed from gas that fell into the galaxy after the central regions collapsed.

Further evidence against the simple collapse model came from VandenBerg *et al.* (*6*), who found no correlation between age and distance from the galactic center for clusters in the outer halo. They also observed that clusters with the same metal abundance could differ widely in age. After a detailed study of a young cluster, called Ruprecht 106, Lin and Richer (*7*) proposed that it may have been tidally captured from a nearby galaxy.

Several small (dwarf) galaxies are orbiting the Milky Way. The entire Sagittarius Dwarf Galaxy is currently moving through the halo of the Milky Way (see the bottom panel of the second figure) (*8*); it contains at least four globular clusters. More recent data from the Sloan Digital Sky Survey indicate that this dwarf galaxy has had past encounters with the Milky Way (*9, 10*) and that this may be the origin of several other halo clusters.

Yoon and Lee (*2*) now propose that the capture hypothesis may address another long-standing problem: the origin of the Oosterhoff dichotomy. Many clusters contain RR Lyrae variables (see the third figure), horizontal-branch (HB) stars that pulsate on time scales of a few hours (*11*). In a study of five clusters with many RR Lyrae stars, Oosterhoff (*12*) noticed that in two clusters, the mean period was 0.55 days, but in the other three, it ranged from 0.62 to 0.66 days. These groups are now referred to as Oosterhoff type I and II, respectively. Subsequent investigations have confirmed the existence of this dichotomy, but with a broader range of mean periods in each group.

As Yoon and Lee point out (*2*), the standard theory of stellar evolution can account for the observed periods of the RR Lyrae stars in type I clusters. It can also explain the periods of these stars in type II clusters with intermediate metal abundance (their group II-a). However, it is difficult to understand why the RR Lyrae stars in metal-poor type II clusters (group II-b) have such long periods. It turns out that their long periods can be accounted for if they are younger than the II-a clusters.



Color-luminosity plot for a typical globular cluster. Main-sequence stars produce energy by thermonuclear fusion of core hydrogen. They finish their main sequence phase at the main sequence turnoff (MSTO). In horizontal-branch stars, all core hydrogen has been converted to helium, and helium fusion is the energy source. At any given time, the stars in a globular cluster are at different stages of evolution because their initial masses were different. Background: the core of Omega Centauri. [Adapted from (*16*)]

In the past, II-b clusters were assumed to be older because of their low metal abundance. However, they could be younger if they formed in another galaxy and were later absorbed by the Milky Way. The age difference between the II-a and II-b clusters proposed by Yoon and Lee is too small to be detected by conventional methods for determining absolute cluster ages (*13*). But Lee *et al.* (*14*) have devised a method for deriving their relative ages from the color distribution of HB stars (see the third figure). The method is particularly useful because HB stars are among the brightest stars in clusters and are therefore easier to observe than the fainter main-sequence stars.

Yoon and Lee first computed stellar models for HB stars with a variety of ages, chemical compositions, and masses. They also took account of the fact that HB stars in a cluster can differ widely in mass. From their stellar models, they generated color distributions of HB stars (HB population models) for a sample of hypothetical clusters. They then determined the relative ages of observed clusters by matching the population models with observations. They conclude that the II-b clusters are younger than the II-a clusters.

Having established that the II-b clusters may be younger, the next step is to find evidence that they could have been captured from another galaxy. Yoon and Lee show that most II-b clusters lie in the same plane as two nearby galaxies, the Draco dwarf galaxy and the Large Magellanic Cloud (LMC). The association with the LMC is particularly important because this nearby galaxy has globular clusters in its own halo.

The authors also provide some evidence that the II-b clusters might be moving in an orbit similar to that of the LMC [see figure 4 of (*2*)]. Existing instrumentation can, however, only measure motion in one direction: the line of sight. Motion perpendicular to the line of sight is much more difficult to detect because it involves measuring the changing position in the sky (the proper motion), and globular clusters are so far away that their positions do not change appreciably on time scales of a few years.

Future projects, such as NASA's Space Interferometry Mission, should make it possible to measure the proper motions of globular clusters and nearby galaxies. We will then be able to tell with more confidence which globular clusters have been captured from other galaxies.

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