The birth and death of STAR CLUSTERS IN THE Milky Way

Steven Stahler

Simple though admittedly speculative considerations explain why most of our galaxy's stellar nurseries are highly fragile but a few survive for a remarkably long time.

Stars are not sprinkled randomly across the sky, but rather exhibit clear patterns. The well-known constellations, established in antiquity, arise mostly from the chance juxtaposition of objects at very different distances. Other groups of stars visible to the naked eye, however, represent true physical associations. One famous example is the Orion Nebula Cluster, depicted in figure 1, whose many individual stars become distinct with even a modest telescope. Another, shown in figure 2, is the Pleiades, located in the constellation Taurus.

Only a small minority of stars exist in such clusters within the disk of our Milky Way galaxy. The true significance of those groups becomes apparent once their member stars are located in a Hertzsprung–Russell (HR) diagram, which plots stellar luminosity versus surface temperature T_s. To gauge the luminosity, one needs to have not only the observed flux from the star over a range of wavelengths but also the distance to the cluster that harbors it. The surface temperature can be determined via measurements of either the relative depths of spectral absorption lines or the ratio of fluxes observed in different wavebands. Most stars in nearby clusters are amenable to such measurements and so may be placed in the HR plot.

Figure 3a shows the result of the exercise for the Orion Nebula Cluster. Many of the cluster's stars lie along the main sequence, the locus for mature stars that are fusing hydrogen into helium at their centers. But when $\log(T_s)$ falls below 3.7 or so, the distribution of stars lifts off from the main sequence. The objects in that region of the diagram, the so-called T Tauri stars, are in the pre-main-sequence phase of evolution. Possessing masses comparable to the Sun's but still too young to fuse hydrogen, they slowly contract while their interiors heat up.

During that contraction, the stars' luminosities fall and their representative points slide down the HR diagram. The position of a star in the plot thus reveals how long the star has been contracting—that is, how old the star is. Counting the number of stars with various ages yields the cluster's history, as illustrated in figure 3b. The figure clearly shows that the stellar formation rate has been increasing over the past 10 million years.

Stars with relatively low T_s also have low masses. Since their self-gravity is weaker, they contract more slowly. Evidently, the Orion Nebula Cluster as a whole is young enough that its lowest-mass members are still in the pre-main-sequence phase. Indeed, the uplift in the stellar distribution at $\log(T_s) \approx 3.7$ pinpoints the cluster's age to be about 2 million years; that's much younger than our Sun, for example, which is 4.6 billion years old.

Some assemblages of stars, known as globular clusters because of their compact appearance, are truly ancient, born along with or soon after the Milky Way and currently orbiting outside the galactic disk. Groups within the disk, however, are younger than individual unclustered stars. The Milky Way has been creating new stars for billions of years, at an average rate of about 10 per year. Counting up the stellar population in nearby young clusters and noting the birthrate of such groups in the neighborhood of our Sun leads to the far-reaching conclusion that all stars form in clusters.[1] Relatively few stars are in clusters at present, so most groups must have dispersed early on. What astronomers observe now are either groups that have not yet dispersed, like the Orion Nebula Cluster, or ones like the Pleiades, whose stars are held together by their mutual gravitational attraction.

How does Nature form star clusters? The question is distinct from the ostensibly similar question of how individual stars form. Astrophysicists have long known that Sun-type stars originate in relatively

Steven Stahler is a research astronomer at the University of California, Berkeley.

Figure 1. The Orion Nebula Cluster. The multicolored glow in this optical image results from recombination of electrons and ions in a hot plasma ionized by a few especially massive stars that lie near the brightest portion of the image. The cluster contains nearly 2000 other cataloged lower-mass stars. The Orion Nebula Cluster is an example of the young OB associations discussed in the text. (Courtesy of NASA/JPL-Caltech/STScI.)

small gas clouds, called dense cores, about 0.1 parsec (0.3 light-years) in diameter.[2] But clusters like the Orion Nebula are larger than dense cores, with diameters of several parsecs. The astrophysics community has generally accepted that all clusters form out of gas clouds with that enhanced size. The processes that govern the dynamics of cluster-forming clouds are different from those in the dense cores they contain and, in fact, are not understood in detail. Cluster birth thus remains an active subject of investigation.

A family of three

The gas clouds that form individual stars or clusters are much too cold to emit visible radiation. We know of their existence through radio emission from such molecules as carbon monoxide. Indeed, the clouds are known as molecular clouds, since their main constituent is molecular hydrogen. Molecular clouds also contain a small admixture of solid grains that absorb the light of any young star located in the cloud and reradiate that energy into the far IR.

Because they are effectively hidden by dusty gas, the most primitive stellar groups are difficult to observe. Over the past several decades, though, IR surveys, both ground based and spaceborne, have detected dozens of so-called embedded clusters within several kiloparsecs of the Sun.[3] Their number (N) distribution as a function of mass (M) is a power law, $dN/dM \propto M^{-2}$. Intriguingly, the same power-law distribution holds for more massive stellar groups seen in external galaxies.[4] The embedded clusters themselves appear as collections of IR point sources; the radiation actually emanates from dust grains surrounding individual stars. The dust makes it difficult to ascertain the properties of the member stars, and no attempt thus far has been made to place embedded clusters in an evolutionary sequence.

Figure 2. The Pleiades. Prominent in this optical image are the massive Seven Sisters. The cluster also contains some 1200 lower-mass members. The Pleiades is an example of the open clusters discussed in the text. The haze surrounding the brightest stars is a passing interstellar cloud, not the primordial one that formed the Pleiades some 120 million years ago. (Courtesy of NASA.)

Let's shift attention, therefore, to more mature groups whose members are partially or wholly visible at optical wavelengths. Those groups, like the embedded clusters, span a wide range of masses and sizes, and they fall into three qualitatively distinct types. Those with the smallest total population are T associations, so called because they consist mostly of T Tauri stars. The total mass of their 100 or so member stars is dwarfed by that of the parent molecular cloud.

At the opposite extreme are the most populous young groups, with several thousand members. Most of those, too, are T Tauri stars, but the groups also contain at least a few especially massive objects, the O and B stars. (The names derive from the tra-

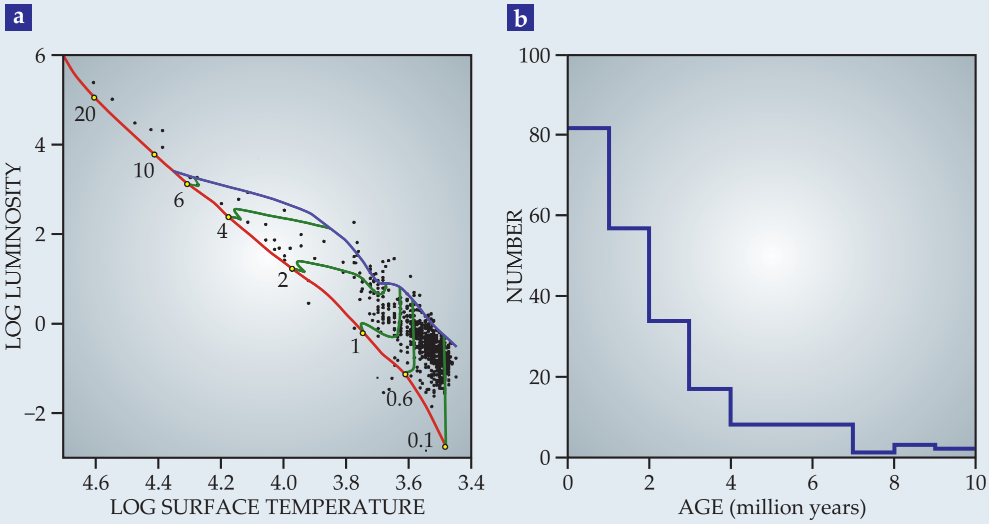

Figure 3. Star formation in the Orion Nebula Cluster. **(a)** In the Hertzsprung–Russell diagram, each dot represents a star in the cluster. The red curve is the main sequence, where mature stars lie. The numbers on the main sequence indicate stellar masses in units of the solar mass. The blue curve is the birth line, on which pre-main-sequence stars first appear. The connecting green curves indicate theoretical tracks for evolving, pre-main-sequence stars. With such theoretical input, one can determine the age of a star by its position in the plot. The luminosity on the vertical axis is relative to solar luminosity; the temperature on the horizontal axis is in kelvins. (Adapted from F. Palla, S. Stahler, *Astrophys. J.* **525**, 772, 1999; see also L. A. Hillenbrand, *Astron. J.* **113**, 1733, 1997.) **(b)** The number of stars in million-year age bins reveals that the rate of star formation has been increasing over the past 10 million years. The data for this histogram were derived from 300 pre-main-sequence stars appearing in the plot shown in panel a. (Adapted from ref. 17.)

ditional classification scheme; the O and B classes are the hottest.) Those members drive strong winds from their surfaces and, in the case of the especially rare and luminous O stars, emit harsh UV radiation that ionizes the parent molecular cloud. Thus the entire group, known as an OB association, is the site of violent activity. The fierce glow of the Orion Nebula Cluster, evident in figure 1, comes from the recombination of electrons and ions in a plasma ionized by a quartet of massive stars known as the Trapezium. One star in the Trapezium, θ^1 C, has 40 times the mass of the Sun.

The third cluster type is an intermediate category, more populous than T associations but sparser than OBs. Those so-called open clusters typically contain several hundred stars, all visible optically. The Pleiades cluster shown in figure 2 is an example that happens to lie relatively nearby. Open clusters are dense enough that the stars themselves hold the system together by virtue of their mutual gravity. They are also the rarest of the three types. Only 1 in 10 stars is ever part of an open cluster.[5] The remaining 90% spend their youth in either T or OB associations.

How associations die

What circumstances determine whether an embedded cluster lying deep within a molecular cloud evolves into a T association, an open cluster, or an OB association? Considerable insight about the birth problem can be gained by examining the *end* of a cluster's life. Again, astrophysicists generally accept that all young groups eventually disperse, thereby creating the galactic field population. How does that dispersal actually take place?

The depiction of the Orion Nebula Cluster in figure 1 portrays much more vividly than any equations how that particular system will meet its end. The Trapezium stars have ionized a considerable portion of the parent cloud that spawned the cluster. Ionization raises the temperature and pressure of the gas so that it rapidly expands. Observers have actually witnessed that expansion via the radio emission that accompanies high-level transitions of hydrogen—for example,[6] from the $n = 86$ level to $n = 85$. The blueward Doppler shift of the spectral lines reveals that the cooling gas is streaming toward Earth at several kilometers per second.

Once the gas departs, so does the main gravitational force that keeps the cluster together. The stars then drift apart. The outward drift is not yet apparent in the Orion Nebula Cluster, but it is evident in slightly older OB associations that are completely devoid of gas. Images of such associations taken decades apart show visible displacements of the stars and demonstrate that the group as a whole is dispersing.[7] After about 10 million years, the OB association, whose O stars have already died out, blends into the galactic field.

The central region of the Orion Nebula Cluster has the highest density of stars in our portion of the Milky Way. Other young OB associations in the galaxy are similarly crowded. With such a high density, it would seem that the stars' mutual gravity would be sufficient to keep the group intact, even after the gas departs. And yet all aging OB associations in the Milky Way disperse—a conundrum I call the OB paradox.

The sparsest of stellar groups, T associations, also die relatively quickly. Indeed, their age, as gauged by the distribution of members in the HR diagram, rarely exceeds 3 or 4 million years. How those associations dissolve is less clear, since observers do not directly witness the dissolution of the parent clouds.

No massive stars exist to ionize and heat the gas of a T association. However, ordinary solar-type stars, when they are young, emit bipolar winds. Figure 4 shows such a molecular outflow. The active star, embedded in the dense core at the center of the image, drives a high-velocity jet of hot gas from its surface. That jet, not visible in the figure, entrains cloud material and creates the observed outflow of cold, molecular gas.[8]

Molecular outflows are almost certainly responsible for dispersing the parent cloud and ultimately liberating the T association. Such has long been the consensus of astronomers, and no plausible alternative mechanism has yet been proposed. However, as I have noted, no one has observed the dispersal of a T-association cloud. Indeed, it is not easy to see how the highly collimated outflows inflate the entire parent cloud instead of simply boring holes in it. Theorists have made little progress on that issue and must await future observations.

Mysterious open clusters

The rarest type of group—the open clusters—is also the longest lived. The Pleiades, for example, has an age of 120 million years, about equal to one rotation period of the Milky Way. The equally well-studied Hyades Cluster, also located in Taurus, is 630 million years old, and a few observed systems have ages of several billion years.[9]

What accounts for the longevity of those groups? Unlike T and OB associations, open clusters are indeed bound by the gravitational pull of their members. That is, an individual star orbits within the changing potential well that is created by all its neighbors. A star is so tiny compared to interstellar distances, even within dense clusters, that the probability for two stars to suffer a direct collision is negligible. On rare occasions a star will gain enough kinetic energy to escape the cluster altogether. Except for that circumstance, the system of interlocking orbits remains intact. Computer simulations show that the mean radius of the Pleiades has actually increased slowly with time and will continue to do so in the future.[10]

The Pleiades age is roughly the median for galactic open clusters. Older systems are relatively rare, because they are being torn apart by the tidal gravity of passing clouds. At least that is the theory, [11] as first proposed by Lyman Spitzer Jr in the 1950s, long before the discovery of molecular clouds. As with T associations, no one has directly observed the death process in open clusters. Nonetheless, Spitzer's theory remains plausible.

The members of open clusters are Sun-type stars that, when young, eject bipolar flows like that shown in figure 4. Accepting that such flows disrupt the parent clouds of T associations raises the question of why they don't cause the demise of open clusters within 10^6 years rather than 10^8 or 10^9 years. That is the essential mystery. Somehow the clusters become sufficiently compact early on that they survive gas loss and thereafter remain intact as gravitationally bound systems of mutually orbiting bodies.

Resolution of the OB paradox

To recap, cluster origin and evolution contain two puzzles: the surprising fragility of OB associations and the equally surprising resilience of open clusters. Both types of stellar group suffer heavy gas loss early on, either through rapid expulsion by massive stars or through gradual erosion by stars of ordinary mass. Why are their fates so different?

Given today's powerful computers, it might seem a straightforward matter to numerically simulate the birth of a cluster within a large cloud, include the wind and ionization feedback from young stars explicitly, and thus solve both puzzles. But such an undertaking lies far in the future. The biggest problem is that theorists do not fully understand the balance of forces within the parent molecular cloud.

All clouds massive enough to form clusters are held together by their own gravity. They are cold enough, with temperatures a mere 15 K or so, that ordinary gas pressure cannot support them against collapse. Yet although astronomers hold a range of opinions on the issue, most agree that the clouds are not in headlong, global collapse. The clouds are permeated by the interstellar magnetic field, and wavelike perturbations of the field stir up the gas. That magnetically mediated turbulence creates an effective pressure that helps to support the cloud at least temporarily, but a fully quantitative account is still lacking.[12]

Nevertheless, it is possible to make progress in understanding the evolution of the stellar cluster it-

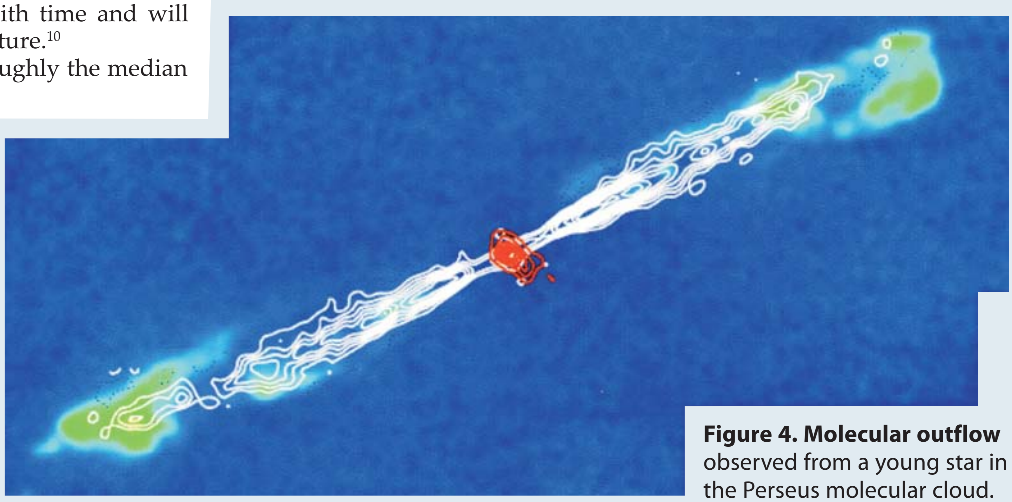

Figure 4. Molecular outflow observed from a young star in the Perseus molecular cloud. The thin, elongated, white contours show emission from relatively cold carbon monoxide gas. The green patches, which arise from radiation by hydrogen molecules heated to several thousand kelvin, show where shocked gas is located. Near the center, tight red contours represent heated dust in the dense core surrounding the young star driving the outflow. (Adapted from F. Gueth, S. Guilloteau, *Astron. Astrophys.* **343**, 571, 1999.)

self. For that purpose, simulators have traditionally represented the cloud solely by a gravitational potential well within which the stars orbit. They track those orbits using *N*-body codes. To represent gas loss, they smooth out the potential well until eventually the potential gradient vanishes—that is, until the gravitational force from the cloud disappears.[13] That approach is best suited for simulating the early evolution of OB associations, during which gas is expelled relatively quickly. Under those circumstances, the detailed manner in which the potential well flattens, and even the well's initial shape, is probably not of great importance.

Researchers have performed many such numerical experiments over the years and through those efforts have resolved the OB paradox. For the association to dissolve, it is essential that the parent cloud be relatively massive, so that stars inside it are moving rapidly. A typical orbital velocity, as described in box 1, is the virial value $(GM/R)^{1/2}$, where M and R are the cloud mass and radius, respectively, and G is Newton's gravitational constant. After gas expulsion, M drops by a factor of 100 or so, but R and the stellar orbital velocity remain the same. The stars thus quickly achieve supervirial velocities, and the cluster flies apart, even if the stellar density was initially high.

Is the assumption of a massive parent cloud plausible? Indeed it is. Within the past 15 years, observers have pinpointed the specific environments that spawn O stars.[14] Those are the IR dark clouds, especially dense clumps of molecular gas that are situated inside giant cloud complexes weighing some 10^5 solar masses. In retrospect, it is entirely reasonable that the most massive clusters form out of the highest-mass clouds, and observations bear out that expectation.

Interestingly, the argument that resolves the OB paradox fails when applied to the most massive groups of all, the super star clusters seen in some external galaxies. With stellar populations of up to 10^6, those behemoths must have had hundreds or even thousands of O stars, yet many have survived for more than 100 million years.[4] Understanding their longevity is another task for the future.

Star-formation efficiency

A tacit assumption in the resolution of the OB paradox is that the total mass of stars produced is only a small fraction of the parent cloud mass. In other words, the cloud must have a low star-formation efficiency for the resulting cluster to disperse following gas expulsion. Theorists have attempted to turn that argument around to explain the stability of open clusters in the face of gas loss. They suppose that the parent cloud forms stars with relatively *high* efficiency. Then dispersal of the remaining gas would not be such a catastrophic event for the stars. Although the assumption of high formation efficiency is probably unwarranted, the argument does provide insights that may eventually lead to a deeper understanding of cluster formation.

A young cluster can, in principle, survive intact, provided gas expulsion from its parent cloud is both rapid and limited in extent. To formulate the argument quantitatively, imagine an idealized spherical cloud quickly expelling a portion of its mass. If the total energy of the system is negative for the post-expulsion configuration, the system remains gravitationally bound. Application of the virial theorem shows that such is the case if the cloud expels less than half its original mass; box 1 gives the details.

Computer simulations of stars orbiting in vanishing potential wells confirm the result suggested by the box calculation: If the parent cloud of an open cluster can turn more than half its mass into stars prior to gas expulsion, then the loss of gas will not disrupt the system. Other numerical experiments have shown that a somewhat lower star-formation efficiency can result in at least a remnant bound cluster. If only a third of the cloud mass becomes stars, then most of those stars fly off into space following gas dispersal. However, there is a continuous distribution of stellar speeds. About 10% of the stars, those with sufficiently low velocities, remain as a bound kernel.[15]

But do open clusters really arise from clouds that produce stars with a relatively high efficiency? It is difficult to empirically assess the star-formation efficiency of open clusters, since most observed systems have already lost their molecular gas. How-

Box 1. Rapid mass loss from a gas cloud

Imagine a perfectly spherical cloud of mass M and radius R. Its total energy E is the sum of the kinetic and gravitational-potential contributions:

$$E = \frac{1}{2}MV^2 - \eta\frac{GM^2}{R}. \tag{1a}$$

Here, V is the typical internal velocity of fluid elements, G is Newton's gravitational constant, and η is a pure number of order unity whose precise value depends on the cloud's density profile. The cloud is gravitationally bound, so E is negative.

If the cloud is in dynamical equilibrium, it also obeys the virial theorem. That is, the kinetic energy has half the magnitude of the gravitational potential energy. Thus,

$$E = -\frac{\eta}{2}\frac{GM^2}{R} = -\frac{1}{2}MV^2. \tag{1b}$$

Suppose now the cloud quickly loses an amount of mass ΔM. During that brief event, the characteristic velocity V_0 and the radius R_0 do not have time to change. However, the energy changes from its initial value E_0 to

$$E = \frac{1}{2}(M_0 - \Delta M)V_0^2 - \eta\frac{G(M_0-\Delta M)^2}{R_0}. \tag{1c}$$

With the help of equation 1b, equation 1c may be expressed as

$$E = E_0\left(1-\frac{\Delta M}{M_0}\right)\left(1-\frac{2\Delta M}{M_0}\right). \tag{1d}$$

The second factor in equation 1d indicates that E becomes positive, and the cloud unbound, if ΔM is greater than $M_0/2$. Conversely, the condition that the cloud remain bound following gas loss is that ΔM be less than $M_0/2$.

ever, observers can readily determine the apportionment of stellar and gas mass in nearby T associations, such as the one in Taurus. The efficiency there is only a few percent, provided one counts up the full mass of the parent cloud, including regions of comparatively low density.[16] In any event, it is unlikely that the similar clouds spawning open clusters have the far greater efficiencies of 50% or even 30%. We must seek another explanation for the stability of those groups.

How clusters and clouds might evolve

The total population of a typical open cluster is not large enough for it to have ever contained O stars. Thus a second problem with the provisional explanation for open-cluster stability is that gas expulsion in a cluster's early history is actually relatively slow. Even in the absence of a detailed model for wind erosion, one can investigate how a cloud containing stars responds to such gradual mass loss. As in the rapid-expulsion case, the virial theorem and energy considerations give a straightforward result; box 2 presents the calculation. The bottom line is that the cloud remains gravitationally bound but expands during the erosion process. For a simplified spherical cloud of mass M and radius R, the product MR remains constant in time.

Because the open clusters observed today are relatively dense, their parent clouds probably did not expand as they began to expel gas. Evidently, the simplified calculation in box 2 is not fully adequate for that case. However, a cloud harboring an aging T association might well expand as its member stars dissolve into the galactic field. Although no observational evidence indicates such expansion, it is a possibility that I will keep in mind as I now attempt to sketch a broader picture of cluster formation.

Early in their lives, all cluster-forming clouds probably contract slowly under the influence of their own gravity. As mentioned earlier, true free-fall collapse is braked by the internal turbulence associated with magnetic waves. Again, no observations directly reveal that early contraction, but two empirical findings together do suggest that it occurs.

To appreciate the first one, return to the HR diagram for the Orion Nebula Cluster shown in figure 3a. Just as the position of a star in the diagram gives it age, so the aggregate positions of many stars in a group yield the overall age distribution, as discussed in connection with figure 3b. Evidently, the formation rate has increased over time. (In the relatively recent past, star formation in the cluster has actually stopped because of gas dispersal, but the time resolution of the plot is too coarse to show that falloff.) The star-formation histories of many other clusters show a similar rising rate.[17]

The second empirical finding is that the local star-formation rate within a cloud tends to increase with the ambient gas density. That well-established trend was first discovered in the 1950s, through observations of stars in the solar neighborhood.[18]

Taken together, the two results suggest that the density of all molecular clouds initially rises, which yields an accelerating rate of star formation. In the most massive clouds, the density rise is especially sharp and produces a centrally crowded star cluster, one that is dispersed after O stars ionize the gas. In clouds of more modest mass, gravitational contraction competes with expansion via wind erosion.

Figure 5 summarizes the above ideas in schematic images of cloud and cluster evolution. Figure 5a shows a massive cloud that initially contracts vigorously. Eventually the cloud effectively destroys itself by producing ionizing O stars; the resulting OB association expands freely. Figure 5b presents a cloud of relatively low mass. It may contract weakly at first, but eventually it loses so much mass by wind erosion that it reexpands and creates a dissolving T association. In the intermediate and evidently rarest case, depicted in figure 5c, the contraction of the cloud and its erosion by winds proceed at comparable rates. The end result is a compact, bound stellar system—an open cluster. Future observations and theoretical calculations can test the story told by the figure and help complete our understanding of cluster birth and evolution.

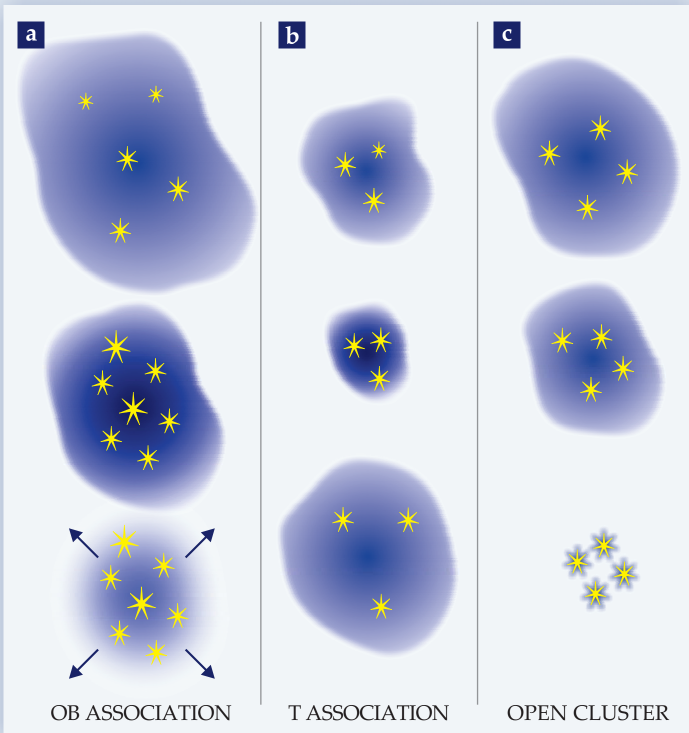

Figure 5. A speculative theory of cloud and cluster evolution. **(a)** A massive cloud contracts vigorously, creating new stars all the time. When its central density in stars and gas gets high enough, a few especially massive stars are born. Those so-called O stars ionize and disperse the cloud, freeing the entire stellar population as an expanding cluster called an OB association. **(b)** A cloud of relatively low mass contracts weakly at first, as it creates a T association. However, it later reexpands as stellar winds erode material, and the stars disperse. **(c)** A cloud of intermediate mass loses material via wind erosion as it contracts. The final product is the gravitationally bound system known as an open cluster.

Box 2. Slow mass loss from a gas cloud

As in box 1, consider a spherical cloud with mass M and radius R. Its energy E is given by equation 1a in that box. Now suppose that a small mass dM is removed. The characteristic fluid velocity V and the radius will adjust in response to the mass ejection, but those internal alterations don't affect the total energy of the cloud; any change in cloud energy is attributable solely to mass loss.

Differentiating equation 1a with respect to M yields

$$\frac{dE}{dM} = \frac{1}{2}V^2 - \frac{2\eta GM}{R}. \tag{2a}$$

Since the mass loss is slow, the virial theorem is obeyed at all times. With the help of equation 1b from box 1, equation 2a becomes

$$\frac{dE}{dM} = \frac{3E}{M}. \tag{2b}$$

Integration yields

$$E = E_0\left(\frac{M}{M_0}\right)^3, \tag{2c}$$

where E_0 is the initial energy and M_0 is the initial mass. Again, using equation 1b, which relates E to M and R, one finds

$$R = R_0\left(\frac{M_0}{M}\right). \tag{2d}$$

Evidently, the cloud expands in such a manner that the product MR is constant.

References

1. L. Allen et al., in *Protostars and Planets V*, B. Reipurth, D. Jewitt, K. Keil, eds., U. Arizona Press, Tucson (1997), p. 361.
2. P. C. Myers, P. J. Benson, *Astrophys. J.* **266**, 309 (1983).
3. C. J. Lada, E. A. Lada, *Annu. Rev. Astron. Astrophys.* **41**, 57 (2003).
4. S. M. Fall, R. Chandar, B. C. Whitmore, *Astrophys. J.* **704**, 453 (2009).
5. F. C. Adams, P. C. Myers, *Astrophys. J.* **553**, 744 (2001).
6. M. A. Gordon, E. Churchwell, *Astron. Astrophys.* **9**, 307 (1970); C. R. O'Dell, *The Orion Nebula: Where Stars Are Born*, Belknap Press/Harvard U. Press, Cambridge, MA (2003).
7. A. G. A. Brown, G. Dekker, P. T. de Zeeuw, *Mon. Not. R. Astron. Soc.* **285**, 479 (1997).
8. J. Canto, A. C. Raga, *Astrophys. J.* **372**, 646 (1991).
9. E. Friel, *Annu. Rev. Astron. Astrophys.* **33**, 381 (1995).
10. J. M. Converse, S. W. Stahler, *Mon. Not. R. Astron. Soc.* **405**, 666 (2010).
11. L. Spitzer Jr, *Astrophys. J.* **127**, 17 (1958).
12. C. F. McKee et al., in *Protostars and Planets III*, E. H. Levy, J. I. Lunine, eds., U. Arizona Press, Tucson (1993), p. 327.
13. See, for example, S. P. Goodwin, N. Bastian, *Mon. Not. R. Astron. Soc.* **373**, 752 (2006).
14. M. P. Egan et al., *Astrophys. J. Lett.* **494**, L199 (1998); S. J. Carey et al., *Astrophys. J. Lett.* **543**, L157 (2000).
15. P. Kroupa, A. Aarseth, J. Hurley, *Mon. Not. R. Astron. Soc.* **321**, 699 (2001).
16. S. J. Kenyon, L. Hartmann, *Astrophys. J. Suppl.* **101**, 117 (1995).
17. F. Palla, S. W. Stahler, *Astrophys. J.* **540**, 255 (2000).
18. M. Schmidt, *Astrophys. J.* **129**, 243 (1959); for a study of other galaxies, see R. C. Kennicutt Jr, *Astrophys. J.* **498**, 541 (1998). ■