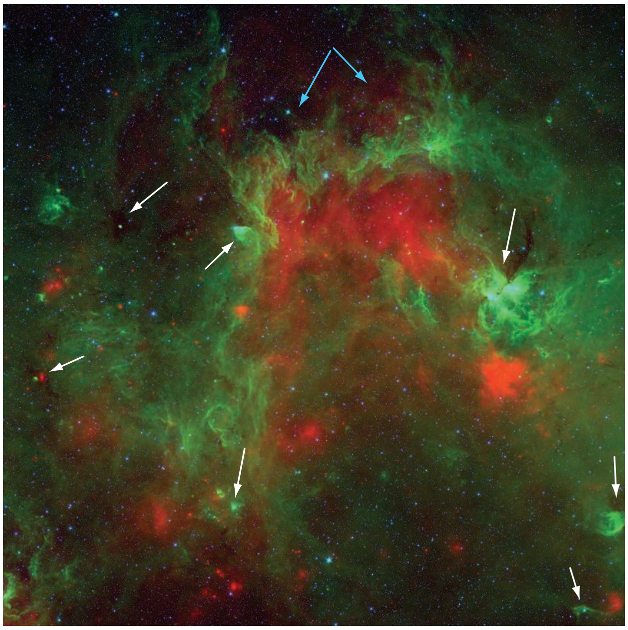
ASTRONOMY

Forming Massive Stars

Sophisticated numerical simulations can now describe the formation of supermassive stars.

Barbara Whitney

The dominant physical processes contributing to the formation of a star are gravity, rotation, and magnetic fields acting on a cloud of dense gas and dust. Magnetic fields and pressure from the gas inhibit the collapse, but once a cloud is dense enough to overcome these forces, collapse begins and gravity and rotation dominate. A starlike core forms at the center and grows as mass is accreted from the infalling gas cloud. This is just classical mechanics, mathematically formulated by Isaac Newton more than 300 years ago. For stars with a mass similar to that of our Sun, a theory for the entire sequence from a dense molecular cloud core to a hydrogen-fusion star like our current Sun has been well developed and tested with observations (*1*). For stars of about 20 to 100 solar masses, however, such a simple consideration renders them unstable, and thus a more sophisticated treatment is required. On page 754 of this issue, Krumholz *et al.* (*2*) introduce a time-dependent model that explains the physical processes involved in the formation of such massive stars.



A variety of stars. A 1.5 by 1.5 degree region on the sky (about 750 by 750 light-years in size) in our Galactic plane. Red emission shows hot dust and gas; green emission shows emission from large molecules at the surface of molecular clouds (the neutral region between the ionized hot gas and cold molecular gas). The blue sources are normal stars like our Sun. The whitish, orange, and red sources are forming stars, most of them more than 10 times as massive as our Sun. The white arrows show regions of massive (and low-mass) star formation. The blue arrows show a region where star formation appears to be inhibited, probably due to strong magnetic fields and hot temperatures caused by colliding flows of gas and dust. The structures form a ringlike shape that may have been formed by a previous generation of massive stars with strong radiation fields and winds, or even a supernova explosion. The star formation (white arrows) may be triggered by the compression in the ring caused by the previous generation of massive stars.

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For stars about 20 times as massive as our Sun, the outward pressure force exerted by photons on the grains of dust in the cloud must be considered (*3*). A simple calculation balancing gravity and the radiation force finds that this radiation pressure halts the infall onto the star once it reaches 20 solar masses. Yet, stars with masses as high as 120 times that of our Sun have been observed (*4*). For most of the 20th century, the theoretical models of star formation assumed spherical geometries, which are one-dimensional. Adding rotation to the equations makes the problem two-dimensional and leads to formation of a disk. These two-dimensional numerical models found that stars up to 40 solar masses could form from accretion through the disk, whereas the radiation pressure acts more on the polar regions (*5*). Now, it turns out that newly developed three-dimensional numerical models allow another physical process into the equations, namely instabilities, which then allow even more massive stars to form.

Krumholz *et al.* describe a three-dimensional simulation of the first 50,000 years of the collapse of a 100 solar mass cloud of molecular gas and dust in slow rotation before collapse. The slow rotation at large distances becomes fast rotation as the cloud collapses as a result of conservation of angular momentum, and thus the cloud quickly collapses into a central "proto-star" and disk in about 4000 years. Because of the large pile-up of material onto the disk, two-armed spiral instabilities form after about 20,000 years; this transports angular momentum outward, allowing more material to fall inward onto the star, increasing its mass further. After about 17,000 years, when the central object has reached about 17 solar masses, the outward radiation pressure begins to exceed gravitational force, but only in certain directions, mainly perpendicular to the disk direction, forming radiation bubbles. However, infalling material can still flow around the bubbles to reach the central object. The bubbles develop deformities, and dense fingers of material continue to fall in. These fingers are analogous to the well-studied Rayleigh-Taylor instabilities in classical fluid mechanics. The net effect is that more mass falls in than is pushed out by radiation pressure. The rate at which mass falls in is variable. In their simulation, the disk instabilities cause a second smaller star to form in the disk. At the end of the simulation, the masses of the stars were 33 and 47 solar masses, with the other 20 solar masses still in the disk and infalling envelope, and their future uncertain.

In addition to overcoming previous theoretical problems for forming massive stars, the simulation of Krumholz *et al.* reproduces an observed feature of massive stars, and that is the very common occurrence of binaries. The accretion variability predicted by the simulation caused by the instabilities should be testable by searching for variation in the observed fluxes of massive protostars.

Understanding the formation of massive stars is a fundamental goal in astronomy. Massive stars form the heaviest elements from nuclear burning in their cores and in supernovae explosions after fuel in the core is exhausted. Their winds and luminosity have a profound effect on their surrounding environments, churning up the gas and dust, and both stimulating and regulating new star formation. Examples of the turbulent processes caused by the life cycle of massive star formation (birth and death) can be seen in the figure.

The simulation by Krumholz *et al.* took about 40 days of computing time on 256 processors running simultaneously. This is

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hopefully only the beginning of even more sophisticated simulations. Many intriguing open questions remain, such as, how does the central protostar evolve as it starts nuclear burning of hydrogen in its core while its surface continues to accrete from the disk and envelope? (A more compact, hotter star will ionize the surrounding gas and have a different effect on the environment than a larger, cooler star of the same mass and luminosity.) At what point do the stellar winds and radiation disrupt the disk and envelope? Can the disk survive long enough to form planets, or is the realm of planet formation available only to low-mass stars like our Sun?

References

1. F. C. Adams, C. J. Lada, F. H. Shu, *Astrophys. J.* **312**, 788 (1987).
2. M. R. Krumholz *et al.*, *Science*, **323**, 754 (2009); published online 15 January 2009 (10.1126/science.1165857).
3. F. D. Kahn, *Astron. Astrophys.* **37**, 149 (1974).
4. D. F. Figer, *Nature*, **434**, 192 (2005).
5. H. W. Yorke, C. Sonnhalter, *Astrophys. J.* **569**, 846 (2002).

10.1126/science.1169667

EVOLUTION

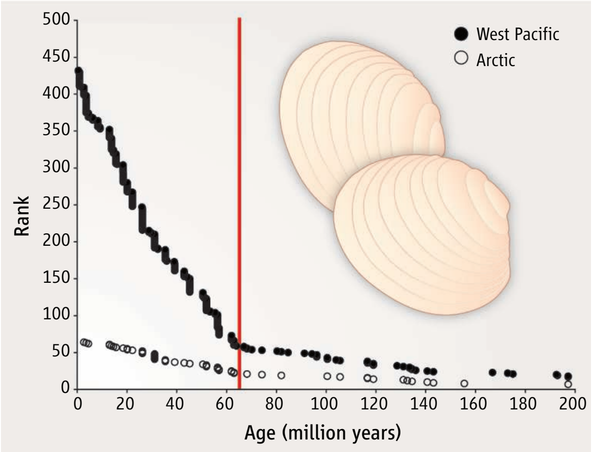
Time's Stamp on Modern Biogeography

A study of living bivalves provides clues to the evolution of biodiversity over the past 200 million years.

J. Alistair Crame

Why are there more types of plants and animals on some parts of the Earth's surface than on others, and do these patterns point to the operation of some basic laws of nature that have yet to be fully understood? Over the past three decades, answers to these questions have shifted from essentially ecological to much more evolutionary (*1*). This shift largely results from the rapid growth in phylogenetic studies, which has led to a proliferation of time-calibrated evolutionary trees, and from the advent of large, analytical databases. Using the latter, it is now possible to assemble vast amounts of spatial and temporal data on the distribution of plants and animals to establish statistically significant biogeographic patterns. On page 767 of this issue, Krug *et al.* use this approach to provide important new insights into how biodiversity evolved over the past 200 million years (*2*).

There are two critical patterns in taxonomic diversity: the trend in the total number of taxa through geologic time, and the latitudinal gradient from the tropics to the poles. These two features are undoubtedly linked. If the number of species (or genera) has increased dramatically through time (especially over the past 65 million years, referred to as the Cenozoic era), then it is almost certain that latitudinal gradients must have steepened too, because the fossil record strongly suggests that many groups originated in tropical and subtropical regions. However, if global diversity has been relatively constant for much of the past 300 million years, then the steep gradients that we see today can be regarded as essentially time-invariant features of Earth's surface. Is the strong diversity contrast between the tropics and the poles really only a feature of the youngest part of the fossil record, or has it perhaps always been there?



Age-frequency distributions of marine bivalve genera. The curves plot the ages of genera, ranked from youngest to oldest, in the tropical West Pacific and Arctic bioprovinces. The vertical line marks the K-Pg boundary at 65 million years ago. The slopes of the two provinces differ slightly before the K-Pg boundary, but diverge strongly following the mass extinction, as many more new species evolved in the tropics than in the Arctic. [From fig. S3 in (*3*)]

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According to the conventional view of biodiversity through time, biodiversity rose rapidly from 542 to 445 million years ago, followed by a somewhat irregular plateau until about 250 million years ago. A steep fall at the Permian-Triassic mass extinction event was soon reversed, and the greater part of the past 250 million years was marked by a steep rise that was barely deflected by the Cretaceous–Paleogene (K-Pg) mass extinction. The increase in the number of species through the past 65 million years alone could have been by an order of magnitude (*3*, *4*).

Our faith in this view was, however, severely tested when Alroy *et al.* published a major new database survey of the fossil record of the past 540 million years in 2001 (*5*). The new diversity curve, produced by the authors, seemed to show a much flatter diversity trajectory over the past ~140 million years. Could the canonical explosive radiation of both marine and terrestrial biotas during this time frame be an artifact of the fossil record?

Closer inspection of the Alroy *et al.* (*5*) curves reveals that the younger part of the Cenozoic record (i.e., the last 23 million years) is poorly sampled, and this is particularly so of the tropics (*6*). To counter this, Alroy *et al.* later quadrupled the size of their database and produced a new curve based on substantially better coverage, both stratigraphically and geographically, of the entire Cenozoic (*7*). This curve again shows only a very modest rise over the past 65 million years; in terms of the number of genera, the peak over the last 23 million years is only 1.74 times as high as that of approximately 400 million years ago. Furthermore, Alroy *et al.* (*7*) found evidence of steep latitudinal gradients as far back in time as 475 million years ago. Although these are shallower than those of the last 23 million years, the ratio of tropical to temperate faunas seems to be very similar. These authors suggest that gradients must have developed through time by the parallel development of both tropical and temperate faunas, and not by tropical radiations alone.

Krug *et al.* now provide a somewhat different perspective on the evolution of modern

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