ASTRONOMY

Shooting for the Stars

Observations with the Kepler space telescope are revealing details of the internal structure of distant stars.

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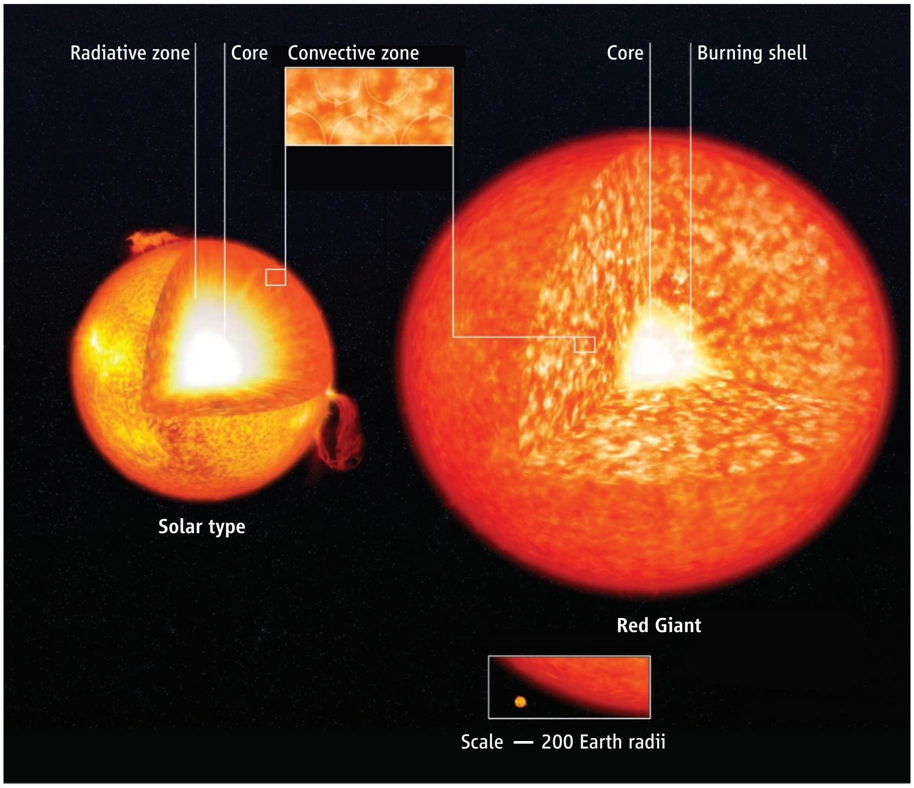

Star gazing. The convection zones of a solar-type star and a red giant. The outer convection zones in both types of stars are effective at driving pulsations.

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The primary objective of the Kepler mission is the discovery of Earth-like planets that are transiting their central stars. Its exquisite photometric precision also makes it the ideal instrument for measuring low-amplitude brightness variations in a broad range of stars. In a great many cases, these stellar variations represent modes of oscillation of the star, and their study can yield information on its interior structure. On page 213 of this issue, Chaplin *et al*. (*1*) make use of recent Kepler observations to examine the ensemble properties of more than 500 "Sun-like" stars. On page 205, Beck *et al*. (*2*) describe results for a red giant star. Finally, on page 216, Derekas *et al*. (*3*) present data on an exotic triple-star system with multiple eclipse components. Taken in combination, these latest results illustrate the power of the Kepler space telescope to probe the internal structure of distant stars.

The most familiar of the variable stars are the cepheid variables, the "Cepheids." They have been known for hundreds of years and their large changes in brightness make them easy to observe. More fundamentally, the link between their period of oscillation and their intrinsic brightness—the "Leavitt Law" or the "Period-Luminosity relation"—has made them important rungs on the astronomical distance ladder (*4*).

Although other variable stars have difficulty competing with the Cepheids in terms of brightness, they easily outstrip the monoperiodic Cepheids in terms of the number of oscillation modes they possess. The champion of these is the Sun, whose pulsation modes induce luminosity variations of only a few parts per million but whose number of excited modes exceeds a million (*5*). The reason for this contrast is the completely different driving mechanisms at work. In the Cepheids' case, the energy flowing outward through the envelope of the star is dammed up and released in a way that leads to an amplification of existing perturbations, so that small-amplitude oscillations are amplified to observable levels. In contrast, in the Sun the bubbling fluid motions in its convection zone shake the star as a whole, causing it to ring. Individual oscillation modes are damped and begin to decay after they are excited, but are continuously re-excited by the fluid motions in the convection zone, so that a balance is reached between driving and damping.

Stars whose pulsations are driven by this mechanism are termed "solarlike" pulsators, and while their amplitudes are small, they oscillate in many modes over a broad frequency range. This is fortunate because each pulsation mode samples a star's interior differently, so the more pulsation modes that are observed, the tighter the constraints placed on the internal structure. These pulsations allow us to probe a star's structure in much the same way that seismic waves on Earth allow us to sample Earth's interior. Because of this analogy, the study of a star's interior through its pulsation modes is termed asteroseismology and, for the special case of the Sun, helioseismology. Fortunately, solarlike pulsations are expected to be present in all stars having surface convection zones.

This includes main sequence stars with masses less than about 2 solar masses, as well as red giants. Chaplin *et al*. use solarlike oscillations observed by Kepler to derive distributions of the radii and masses of 500 solar-type stars. They find that the distribution of radii matches theoretical expectations but that the mass distribution shows some important differences—the observed mass distribution is wider and shifted toward lower masses. If real, this is an important result and could lead to revisions in our understanding of the initial mass distribution with which stars form, as well as the mass-radius relation. It could also point to inadequacies in our description of convection in these stars.

Beck *et al*. report a second example of solarlike oscillations, providing evidence for the detection of gravity-mode period spacings in a red giant star. Gravity modes (g-modes) are oscillation modes in which the primary restoring force is buoyancy/gravity, in contrast to pressure modes (p-modes), in which the primary restoring force is pressure.

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The oscillations that are usually observed in these stars are p-mode pulsations, which sample the envelope but do not penetrate deeply into the core. The importance of the detection of the g-mode period spacings is that g-modes do penetrate deeply into the interior; thus, they contain information inaccessible with other techniques, such as the core chemical composition, angular momentum, or density structure. This is of prime importance because models of the red giant phase of stellar evolution are much less constrained than those of the prior main sequence phase. As a result of Kepler, we may well see revisions in our understanding of red giant structure and evolution.

Rather than reporting results of stellar pulsations, Derekas *et al*. use Kepler data to study the light variations from an exotic triple star system. The bright A component of this system is a red giant star, and the B and C components form a tight binary (BC). The BC system orbits the A component. What makes this system the first of its kind is that it has two kinds of eclipses. First, stars B and C eclipse each other, and second, the BC pair and the A star eclipse each other. The eclipses provide constraints on the geometry of the system, which can then be used to test stellar models. In addition, continued observations will allow dynamical models of the evolution of the stellar orbits to be tested. In an ironic twist, the solarlike oscillations that are expected in component A (a red giant) are not detected; they are most likely suppressed by either the unusual orbital mechanics or some other aspect of this system.

Kepler is returning a treasure trove of information on the properties of stars. Although already impressive, these observations represent only the tip of the iceberg of what we will learn through continued observation with Kepler and other ground- and space-based telescopes. Future observations will test our understanding of physical processes such as convection, rotation, chemical diffusion, mass loss, and magnetic fields in stars. Because stellar evolution calculations are our basic tools for modeling the properties of all stars, whether or not they pulsate, this work will enhance our understanding of the life cycles and properties of all stars. This in turn will allow us to better understand the evolution of our galaxy and the local universe.

References and Notes

1. W. J. Chaplin *et al*., *Science* **332**, 213 (2011).
2. P. G. Beck *et al*., *Science* **332**, 205 (2011); 10.1126/science.1201939.
3. A. Derekas *et al*. *Science* **332**, 216 (2011).
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MOLECULAR BIOLOGY

Climbing in 190 Dimensions

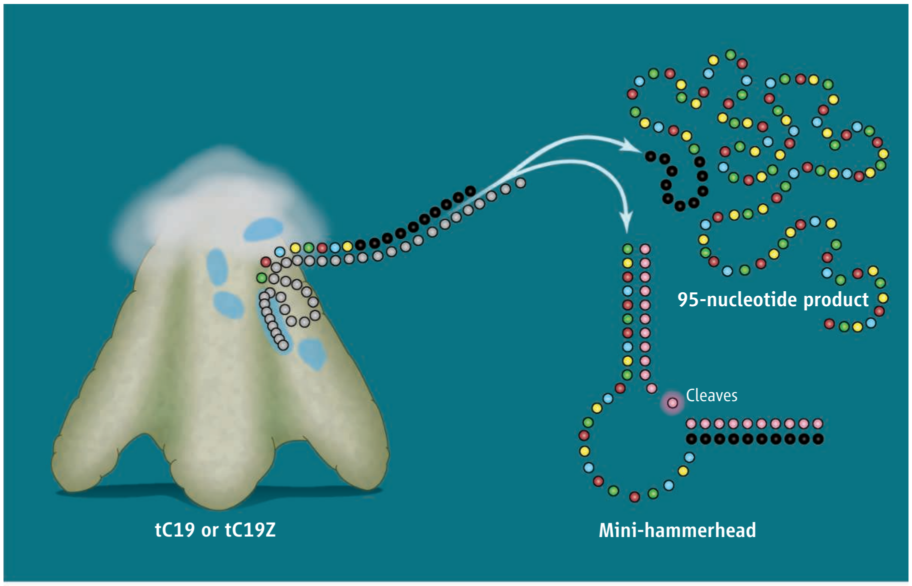
Creation of an improved RNA-copying ribozyme offers hope of realizing RNA-catalyzed self-replication.

Michael Yarus

Those who have looked at the night sky—not the dim remnant visible in cities, but the bright complexity seen in high, dark places—can appreciate the task assumed by Wochner *et al*. (*1*). On page 209, they describe the construction of an RNA enzyme (a template-dependent primed RNA polymerase) that emulates an ancient molecule that would have been crucial in the "RNA world," believed to have predated DNA- and protein-based life. To find this enzyme, they searched vast molecular populations, holding potentially many, many more RNAs than the visible universe has stars.

RNA's role in expression, and particularly in protein biosynthesis, has provided recent evidence of an ancient RNA world. One key part of this world, however, has remained lost—the ancestral RNA molecule that replicated everything, including itself. In a bid to find such a molecule, Wochner *et al*. began with the recently selected and well-studied R18 RNA (*2*). R18, however, can make templated RNAs only 14 nucleotides (*3*) or 20 nucleotides (*4*) long. These numbers frame the progress achieved by Wochner *et al*., who engineered RNA sequences that make RNAs up to 95 nucleotides long.

The crucial challenge was to explore an immense cosmos of sequence variants. R18 has 189 nucleotides, so there are 4^{189} or about 10^{114} other sequences of the same length as the initial RNA. Adding a dimension for useful synthetic activity, optimizing evolutionary potential is a problem with 190 dimensions. One must seek a peak of RNA production in



Isolating an effective RNA polymerase. (Left) The tC19 or tC19Z ribozyme (*8*, *9*), with ribozymic improvements (*1*) marked by blue patches. Template nucleotides are gray, primer is black, and products are four colors representing the four incorporated nucleotides. **(Right)** Selected RNAs produced long products (upper right, 95-mer) and an active mini-hammerhead (bottom).

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