The beat of young stars
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neurons. Furthermore, long-term depression (weakening of specific glutamate synapses) was lost in DADR2 neurons.

Schwartz *et al.* identified the neuropeptide galanin as the link between the selective changes in glutamate receptor function in the nucleus accumbens and the reduced motivation to work for a palatable taste reward. Decreasing galanin 1 receptor expression in the nucleus accumbens with RNA interference prevented both the behavioral and glutamate receptor changes induced by persistent pain. Furthermore, preventing NMDA-dependent long-term depression both blocked the pain-induced reduction in AMPA receptor function in DADR2 neurons and blocked the reduction in motivation to work for food. This supports a causal link between the reduction in the excitability of DADR2 neurons and the reduced motivation to work for a reward.

By identifying a critical circuit element, Schwartz *et al.* have taken a vital step toward solving the fundamental neurobiological problem of action selection in the presence of conflicting motivations. It will be informative to relate the activity of DADR2 neurons to the effort expended to obtain food in awake behaving animals and to determine how the presence of ongoing pain changes this activity. Further work is also needed to define the behavior-relevant circuit, first by identifying the input pathway to the galanin-releasing neurons in the nucleus accumbens that mediate the change in glutamate receptor function in DADR2 neurons. To understand why reduced excitability in DADR2 neurons reduces the motivation to work for palatable food, it will be essential to determine how they act on their downstream targets. ■

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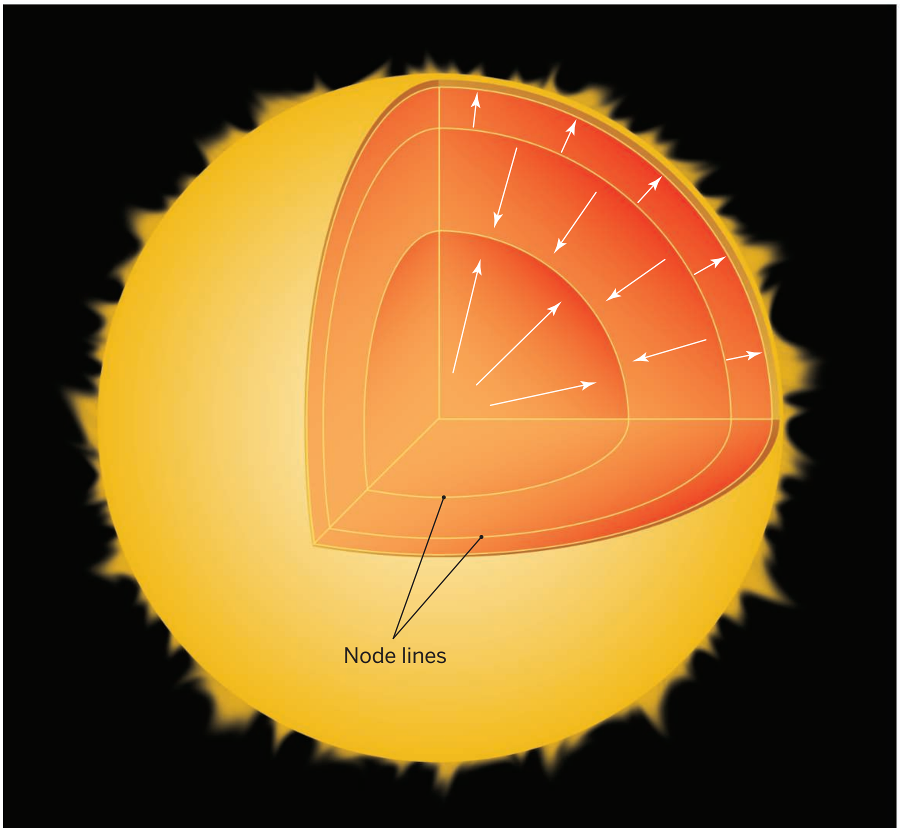

Oscillations inside a young star. Adjacent layers contract and expand periodically. At the node lines, gas remains stationary.

ILLUSTRATION: FIGURE COURTESY OF M. MARCONI; ADAPTED BY P. HUEY/SCIENCE

ASTRONOMY

The beat of young stars

Pulsations from young stars provide a new chronometer for stellar evolution

By **Steven Stahler**[1] *and* **Francesco Palla**[2]

A star is a ball of gas held together by the compressive force of self-gravity and supported from within by thermal pressure. For most of a star's life, this dynamical balance is stable; perturbing the star does not lead to explosion or collapse, but to oscillation about its equilibrium configuration. Such perturbations arise constantly from small motions within the star itself. Consequently, stars of many evolutionary phases exhibit periodic fluctuations in their luminosity (see the first figure). On page 550 of this issue, Zwintz *et al.* (*1*) report on oscillations of stars so young that they are not yet fusing hydrogen into helium. Expanding on earlier studies of such pre–main-sequence stars (*2*), Zwintz *et al.* find that the observed frequencies of oscillation of a star vary with its age, and do so in the way that theory predicts. Thus, the oscillations potentially provide a new chronometer—something greatly needed in the field of early stellar evolution.

The standard way to assess the age of a star is to measure two quantities: its luminosity, L, and its effective (or surface) temperature, T_{eff}. L is a measure of the total power emitted by the star, which is inferred from the measured flux on Earth, together with the distance to the star. T_{eff} is determined from a high-resolution spectrum of the starlight. The pattern of absorption lines reflects specific wavelengths where the flux is diminished because of absorption by atoms in the stellar surface. Given L and T_{eff}, the star can then be placed in the Hertzsprung-Russell (HR) diagram (see the second figure). The

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star's position in the diagram is the indicator of both its age and evolutionary phase.

As stars evolve, both L and T_{eff} change. Thus, the point representing a star will move within the diagram. These paths are predicted by theory and are called pre–main-sequence tracks (*3*). Physically, the young star is contracting, and its diminishing surface area changes its energy output, which comes from the contraction itself. All tracks eventually land on a curve known as the main sequence, where hydrogen ignites and halts contraction. Note that stars of higher mass contract to the main sequence relatively quickly because of their stronger self-gravity.

In principle, assigning an age to a pre–main-sequence star should be relatively straightforward. After using observations to place the object in the HR diagram, the evolutionary track is identified that passes through that point. The star's age—that is, how long it has been contracting—and its mass can then be read off. Applying this procedure not just to one star but to a whole cluster, the resulting collection of ages and masses yields the star formation history of that group.

In reality, however, the situation is more complicated. Young stars are surrounded by copious amounts of dusty cloud gas, which both dims and reddens their light before it reaches us. Discerning the star's true intrinsic luminosity and surface temperature can thus be difficult. In addition, many of these stars have circumstellar disks that may periodically dump matter onto the stellar surface. This accretion process releases energy, which could be misinterpeted as part of the underlying stellar luminosity (*4*). Both problems are ameliorated with stars that either have quickly dissipated their disks or have expelled much of the nearby cloud gas.

In 1998, Marconi and Palla discovered that a subset of pre–main-sequence stars, with masses between 1 and 4 times that of the Sun, can sustain self-excited pulsations (*5*). These pulsations are driven by variations in the opacity of the star's outer layers, where hydrogen and helium are partially ionized. If the star contracts, the opacity increases. As a result, energy emanating from the deep interior is dammed up, causing the star to inflate. The opacity then falls, and the release of excess energy causes the star to shrink, thus restarting the cycle. Whether or not the mechanism operates depends sensitively on the star's effective temperature. If T_{eff} is too low, the ionization region is so deep that it cannot move overlying gas. Conversely, in a star with too high a T_{eff}, the layer is at such a shallow depth that only a small amount of the outgoing luminosity can be absorbed.

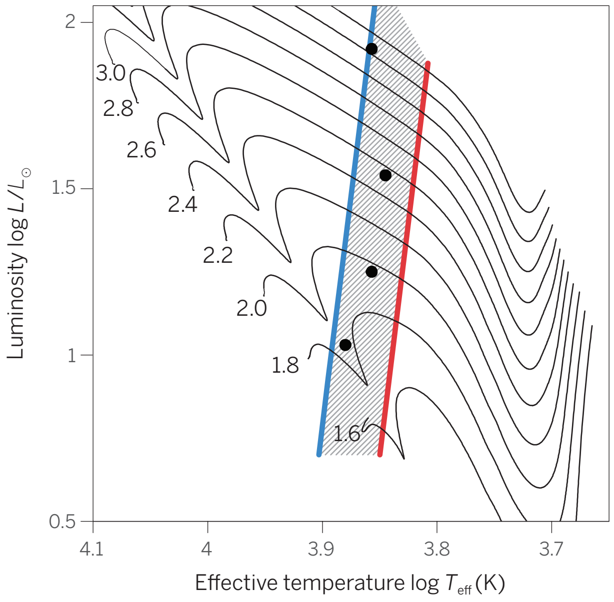
Pursuing this line of reasoning, Marconi and Palla showed that there is an "instability strip" in the HR diagram (see the figure). Pre–main-sequence stars that pass through this area are susceptible to the oscillations. Following their prediction, several dozen young pulsating stars have been found. Gratifyingly, the stars indeed all lie within the instability strip. The actual pulsation amplitudes are small, and satellite observations have greatly increased the precision of the measurements in recent years.

Any star lying within the instability strip can oscillate not just at a single frequency, but at many, just as a taut string can vibrate in many normal modes. There is an upper limit to the oscillation frequency, called the acoustic cutoff. At higher frequencies, internal pressure disturbances (that is, sound waves) do not reflect at the star's surface, as is necessary to sustain the oscillation. Instead, these high-frequency waves pass through the surface to the sparser external medium (*6*). In their sample of 34 stars, Zwintz *et al.* focused on the acoustic cutoff frequency, and found that it increases with stellar age, where the latter was gauged from a modified form of the HR diagram.

This observed trend is just what theory predicts. For any star in balance between self-gravity and pressure, a sound wave crosses it in about the same time it would take the object to freely collapse in the absence of pressure. This hypothetical free-fall time is inversely proportional to the square root of the star's mean density. It follows that the frequency of any oscillation mode is directly proportional to the square root of the density. The frequency thus should increase as the star contracts and its density rises, and this is exactly what Zwintz *et al.* found.

Although a reliable measurement of these stellar frequencies requires the precision and sensitivity of a space-based telescope, the resulting age is not fraught with the uncertainties that have plagued the traditional determination of L and T_{eff}. Thus, the path lies open to a new determination of stellar age. Of course, the new chronometer must first be calibrated, through observations of stars that both oscillate and are relatively free of circumstellar matter. The chronometer will be most useful for young clusters populous enough to contain several stars in the proper mass range. Zwintz *et al.* have already started down this road, observing nine members of the NGC 2264 cluster and finding evidence for a substantial age spread in this group.

The finding of Zwintz *et al.* already suggests the utility of the new chronometer. If there is indeed an age spread in NGC 2264, then the parent cloud forming the cluster did so over an extended time. Other clouds presumably spawn stars in a similarly protracted manner. Over the past 15 years, it has been argued that the clouds actually collapse quickly (in a free-fall time) and form their stars in a single burst. Any apparent spread in stellar ages is illusory, an artifact of the various uncertainties mentioned earlier (*7*). A new and more precise chronometer should settle the issue, and thus advance our knowledge of early stellar evolution. ■



Pulsating young stars in the Hertzsprung-Russell diagram. The solid curves are pre–main-sequence tracks for stars of different masses, here indicated in solar units. The shaded area is the instability strip, as found by Marconi and Palla (*5*). Solid circles represent some of the known pulsators. From top to bottom, the stars range in age from about 1 to 10 million years.

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