by J. Robert Oppenheimer and George Volkoff in the late 1930s, and then Fritz Zwicky suggested that neutron stars might be created in supernova explosions.

Neutron stars remained but a theoretical conjecture until Jocelyn Bell and others discovered pulsars in 1967. Pulsars are often found at the center of supernova nebulae. They emit extremely regular, very intense pulses of radio waves. Only a spinning star with a diameter comparable to the breadth of a small city could lead to such an extraordinary extraterrestrial signal, and pulsars were quickly identified with neutron stars.

In this article, we outline much of what has been learned about Type II supernovae and describe in detail how old stars of more than 8 solar masses are thought to die. (A star's mass is always stated relative to the Sun's mass, which is 2×10^{33} grams and is denoted by the symbol $M_{\odot}$. Therefore, 8 solar masses is written as $8M_{\odot}$.) However, before we discuss the death of stars, we will digress and first discuss how those stars live.

A Star's Life

A star performs one of nature's finest high-wire acts. It carefully and continuously maintains its balance against the omnipresent pull of gravity. It is gravity that initially shapes a primordial cloud of gas[2] into a spherical star, and it is gravity that collapses and compresses the gas. Compression, however, increases both the temperature and the internal pressure of the gas. Once that pressure is sufficient to counteract gravity's pull, the star stops shrinking. If for some reason the internal pressure temporarily exceeds the gravitational force, the star will expand. The pressure will then drop, and the expansion will stop once the pressure is again equal to gravity. As long as the internal pressure can be sustained, a star will neither expand nor contract, but it will maintain a state of *hydrostatic* equilibrium, wherein gravity and the internal pressure are balanced.

But a star is also hot, with a core temperature of millions of kelvins. Heat and energy flow out from the core and through the mantle to be emitted as light from the star's surface. The star shines brilliantly. Yet for all its serene beauty, starlight is a relentless drain on the star because energy is irretrievably lost to the cold vacuum of space. If energy were not continually regenerated, the loss would cool the gas and sap the internal pressure, causing the star to slowly contract.

New energy comes from thermonuclear fusion, the process whereby two light, atomic nuclei merge to form a single, heavier nucleus. Because fusion releases a significant amount of energy, the star can counteract radiative losses simply by sustaining a sufficient fusion rate. A star achieves and maintains a *thermal* equilibrium in addition to its hydrostatic equipoise. A star's life consists of balancing the opposing forces of gravity and pressure, while simultaneously matching all energy losses with the gains produced by thermonuclear fusion.

Evidently, this state of total equilibrium cannot be maintained. The amount of nuclear fuel available to the star is finite, and as lighter elements burn, fuel slowly disappears. Initially, it is only the primordial hydrogen that burns. The burning takes place in the core, which is the hottest and densest part of the star. (See the article "Exorcising Ghosts" on page 136 for a description of the energy-producing reactions in the Sun.) In part because hydrogen burning releases a lot of energy, only a modest rate of fusion is needed to stabilize the star, and the hydrogen reserves last a long time. A star will burn hydrogen for millions to trillions of years.[3]

At some point, however, all the hydrogen in the core will have fused into helium. Because helium burning requires much higher core temperatures and densities than exist at this stage of the star's life, fusion temporarily stops. Without an energy source, the core begins to cool, the core pressure begins to drop, and gravity again compresses the star. As before, the gravitational compression does work on the stellar gas so that, somewhat counterintuitively, the loss of fusion energy leads to a *rise* in the core temperature. Once the temperature and density are sufficient to fuse helium into carbon, new energy is released, and equilibrium is quickly restored. The star still consists almost entirely of hydrogen gas, but the hydrogen now surrounds a helium gas core that is undergoing fusion.

Eventually, the helium fuel is depleted. Fusion stops, and the star cools and contracts until it is again able to initiate the burning of a new fuel. This is a repetitive process, so that the aging star will burn in succession carbon, neon, oxygen, and finally silicon. Because of the various burning stages, the star develops a layered structure consisting of many different elements, as seen in Figure 2.

However, as the elements get heavier, the amount of energy released per reaction decreases. As a result, the burning rate must increase in order to liberate enough energy to sustain the internal core pressure. In addition, neutrinos are produced much more readily within the core during the late burning stages of stellar evolution. Because the neutrinos remove even more energy from the core, they are yet another factor that leads to an increased burning rate. (See the box "The Urca Process" on page 168.)

[2]The primordial gas consists of hydrogen, some helium, and trace amounts of other light elements. This gas formed in the first few minutes after the Big Bang. See the article "Dark Matter and Massive Neutrinos" on page 180 for more details.

[3]The time it takes for a star to burn its fuel decreases rapidly as a star's mass increases. Compared with their lighter cousins, massive stars are squeezed harder by gravity and therefore require significantly more pressure to remain stable. They burn their fuel considerably faster. Whereas the Sun will live approximately 20 billion years, a 15 $M_{\odot}$ star will only live about 20 million years.