From: "The Universe Unfolding" by Ivan R. King

18 | THE STRUCTURE OF A STAR

Beneath the surface of a star is an interior that is completely hidden from our view. The hidden region contains nearly all the mass of the star, and hidden there is also the source of energy that keeps the star shining for billions of years. We can study the interior of a star only by purely theoretical reasoning. The basic principles of the theory, however, are amazingly simple, since all that they require is that the star keep itself in balance in two ways: mechanically and thermally. By analyzing these two balances, we can figure out the internal structure of the star.

The mechanical balance simply expresses the requirement that the star hold up its own weight. The star's own gravitation pulls it together and compresses it; but the more the gas is compressed, the harder it pushes back. A balance is reached when the gas pressure is just enough to support the weight. Thus the pressure at each depth within the star must be just enough to support the weight of all the overlying layers.

The thermal balance requires that the temperature everywhere inside the star be just high enough to keep the energy flowing outward. Conceptually we can start by considering the surface of the star, where a large amount of energy continually flows out in all directions into space. This loss of energy would quickly cool the star's surface, if the lost energy were not replaced by energy that flows up from below. The same is true at deeper levels; in each layer the upward-flowing energy must be replaced by an equal amount of energy from below. Ultimately, at the center of the star we must pay the reckoning; somehow new energy must be created to keep the flow going, by the burning of nuclear fuel near the center of the star, a process that we shall take up in some detail later on.

The key to understanding the thermal balance is to follow the flow of energy quantitatively. First of all, energy flows from hotter regions to cooler. Second, there is a resistance to the flow. For radiation, which is usually the mechanism that transports energy through a star, the resistance is opacity. The murky gas inside a star impedes the flow of radiation by constantly absorbing the energy and requiring it to be radiated over again. The greater the opacity, the greater is the temperature difference that is needed to drive it. Thus for a constant energy flow the temperature must rise with depth in the star, at just the right rate to keep the energy flowing upward. Using this principle, the astronomer can calculate the temperature at each level inside the star, just as he uses the mechanical balance to calculate the pressure at each level.

The principles are simple, but the practice is complicated. The precise equation for the temperature depends on the pressures, and the pressure equation depends on the temperature, and finally the pressure and temperature that result at the center must be just such that atomic nuclei under those conditions will generate the right amount of energy. The whole thing becomes a complicated computer process, but the answer eventually does come out, and the astronomer is able to calculate from first principles the entire interior structure of a star.

For a basic understanding of the universe, however, the important question is not how the astronomer behaves but rather how the star behaves. When material is put together to form a star, it adjusts its structure until these balances are satisfied: the pressure at every point balances the weight, the temperature gradient at every point is just sufficient to drive the energy flow, and the central temperature and pressure cause the atomic nuclei there to generate just the needed amount of energy. For a given chemical composition and mass, there is only one configuration that will satisfy all these conditions, and this determines what radius and luminosity the star will have. To put this differently, for a given chemical composition, a star of a given mass must have a specific radius and luminosity; there should thus be a unique sequence of radius and luminosity, depending only on the mass of the star. Translated into the HR diagram, this sequence of radius and luminosity is just the familiar main sequence. Thus, by reasoning about how a star is built, we have reached the conclusion that the main sequence is just the natural result of making stars out of different-sized chunks of the same kind of material. And it is equally clear why there should be a mass-luminosity relation.

At the same time it is easy to see why there should be stars that are not on the main sequence. These are the evolved stars, whose composition has changed at the center because they have burned all their nuclear fuel. With the composition changed in part of the star, the same balance requirements now give a different answer, and the star does not have the same radius and luminosity as a main-sequence star of uniform composition.

STELLAR ENERGY AND NUCLEAR STRUCTURE

To understand the stars fully, we must know where their energy comes from. Chemical fuel would be hopelessly inadequate for a star; a mass of coal equal to the Sun would provide the Sun's radiant energy for only 3,000 years. A more efficient process is gravitational contraction: as the material falls together to form a star, it releases energy. But contraction of the Sun from an infinite size down to its present density would provide energy at the Sun's present rate for less than 100 million years, much less than the length of time that we know life has existed on the Earth. Gravitational-contraction energy is not negligible—in fact, we shall see that it is responsible for the initial heating up of a star—but it is far from adequate for the length of an ordinary star's lifetime.

The only energy source that produces enough energy from a small mass is nuclear energy, and this is what keeps the stars shining. As we have already seen, the process that fuels nearly all the stars is the conversion of hydrogen into helium.

There are many ways of looking at nuclear energy, but certainly the easiest is to think of the nucleus as storing up energy in the forces that hold its component particles together. We can apply the same stretched-spring analogy that we used for the force holding an electron to the atom: stretching the spring stores energy, which can be released when the spring contracts. The forces between particles inside the nucleus are very much stronger than those holding the electrons. Just in the same way, however, pulling the particles into a more loosely bound state requires putting energy into a nucleus, whereas a nucleus whose particles become more tightly bound will release energy.

Physicists can measure the energy that binds a nucleus by an amazing method: they weigh it. The theory of relativity asserts that mass and energy are equivalent, according to the famous equation $E = mc^2$. Thus a nucleus that has given up energy in binding its particles tightly together should have less mass than the sum of the particles that went to make it up. It does indeed, and the difference is big enough to measure easily. Thus physicists are able, by means of mass measurements, to calculate the binding energy of each type of atomic nucleus. When one nucleus is transformed into another, the energy absorbed or released is simply the difference in the binding energies.

When all the quantities are expressed in everyday units, a little bit of mass m corresponds to a very large energy E, just because c, the velocity of light, is such a large number in everyday units. This means, conversely, that even nuclear-sized energies correspond only to small mass differences. Electronic energies also produce differences in mass, but they are a million times smaller and are therefore not practical to measure.