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J. Craig Wheeler
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# 1

# Setting the stage: star formation and hydrogen burning in single stars

## 1.1 INTRODUCTION

We look up on a dark night and wonder at the stars in their brilliant isolation. The stars are not, however, truly isolated. They are one remarkable phase in a web of interconnections that unite them with the Universe and with us as human beings. These connections range from physics on the tiniest microscopic scale to the grandest reaches in the Universe. Stars can live for times that span the age of the Universe, but they can also undergo dramatic changes on human timescales. They are born from great clouds of gas and return matter to those clouds, seeding new stars. They produce the heavy elements necessary to make not only planets but also life as we know it. The elements forged in stars compose humans who wonder at the nature of it all. Our origin and fate are bound to that of the stars. To study and understand the stars in all their manifestations, from our life-giving Sun to black holes, is to deepen our understanding of the role of humans in the unfolding drama of nature.

This book will focus on the exotica of stars, their catastrophic deaths, and their transfigurations into bizarre objects like white dwarfs, neutron stars, and black holes. This will lead us from the stellar mundane to the frontiers of physics. We will see how stars work, how astronomers have come to understand them, how new knowledge of them is sought, how they are used to explore the Universe, and how they lead us to contemplate some of the grandest questions ever posed.

We will begin by laying out some of the fundamental principles by which stars and, indeed, the Universe function.

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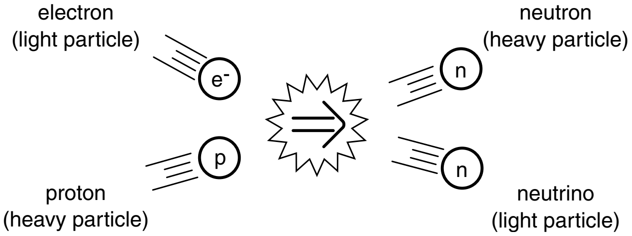
## 1.2 BACKGROUND

### 1.2.1 *The basic forces of Nature*

The nature of stars is governed by the push and pull of various forces. The traditional list of the basic forces of Nature is as follows:

- *Electromagnetic force* – long-range force that affects particles of positive (+) and negative (−) electrical charge, as shown in Figure 1.1 (top). *Protons* (p) are examples of positive charges, and *electrons* ($e^-$), negative charges.
- *Strong or nuclear force* – short-range force that affects heavy (high-mass) particles such as protons (p) and *neutrons* (n). The strong force binds protons and neutrons together in the atomic nucleus, as shown in Figure 1.1 (middle). The strong force turns repulsive at very small distances between the particles.
- *Weak force* – short-range force that affects interactions between light (low-mass) particles such as electrons ($e^-$) and *neutrinos* ($\nu$). The weak force converts one light particle into another and one heavy particle into another; for instance, as shown in Figure 1.1 (bottom).



- *Gravity* – long-range force that affects all matter and is only attractive.

The particle known as the neutrino is a special one with no electrical charge. It interacts only by means of the weak force (and gravity), that is to say, scarcely at all. Its properties and its role in nature will be explained in more detail below and in later chapters.

The results of theoretical work in the 1960s by Steven Weinberg, Abdus Salaam, and Sheldon Glashow, followed by experimental verification in the 1970s and 1980s by a large team led by Carlo Rubbia and Simon van der Meer, showed that the electromagnetic and weak forces are actually manifestations of the same basic force, which has

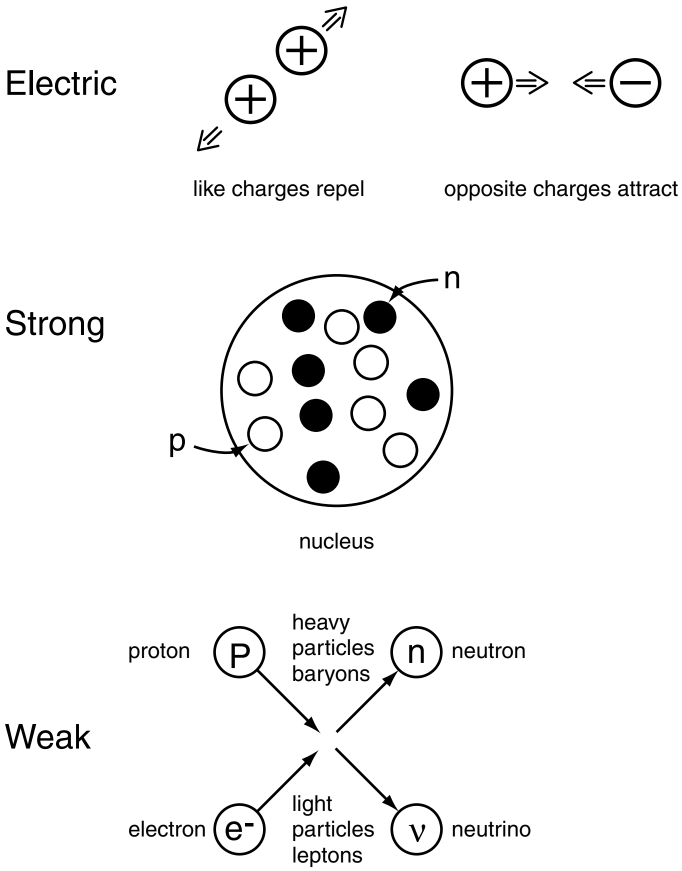


**Figure 1.1** The action of the basic forces: (top) opposite electrical forces attract, and like charges repel; (middle) the attractive nature of the strong force holds protons and neutrons together in atomic nuclei despite the charge repulsion among the protons; (bottom) the weak force causes protons to convert into neutrons and electrons into neutrinos and vice versa.

come to be called the *electroweak force*. This unification is analogous to the recognition, based on the work of Thompson and Maxwell in the nineteenth century, that electrical effects and magnetic effects are actually intimately interwoven in what we now call the electromagnetic force. Nobel Prizes are only the celebrated tip of the ferment that leads to scientific progress; however, their winners deserve their credit, and the prizes are signposts of major progress. Weinberg, Salaam, and Glashow won the 1979 Nobel Prize in Physics for their work; Rubbia and van der Meer, for theirs in 1984.

Current research is aimed at the goal of showing that the strong force is also related to the electroweak force, and that both are manifestations of some yet more fundamental force. Definite progress has already been made toward this goal of constructing a *grand unified theory*. Another dream is to show how gravity may also be understood as intrinsically related to the other forces. The story of gravity is a complex one at the heart of modern physics, and even its role in the pantheon of forces requires some interpretation. Newton interpreted gravity as a force, but, as will be elaborated in Chapter 9, Einstein's theory leads to the interpretation that gravity is a property of curved space and time, that there is no ‘‘force of gravity’’ in the sense that Newton conceived it. Recent dramatic progress has been made toward a unified picture of gravity and the other forces by envisaging particles as one-dimensional strings, rather than as points, as we will see in Chapter 12. In this evolving theory, gravity is again interpreted as a force, but one Newton would scarcely recognize. In practice, we will often refer to these forces in their four traditional categories, as given earlier, with emphasis where appropriate on the interpretation of gravity as a property of curved space.

### 1.2.2 *Conservation laws*

To a physicist, conservation does not mean careful use to ensure future supplies, but that some quantity is constant and does not change during an interaction. Physicists have learned to make powerful use of principles of conservation, which are stated in roughly the following manner: ‘‘I don't care what goes on in detail; when all is said and done, quantity X is going to be the same.’’ Conservation laws do not help to untangle the details of a given physical process; rather, they help to avoid complex details. Conservation laws are of great help exactly when the details are complicated because one can proceed with confidence that certain basic quantities are known and unchanging, despite the details. How this works will be more clear when we see how these conservation laws are used in various ways. They are employed to help understand why stars get hotter when energy is radiated away, the nature of nuclear reactions that power the stars, why stars become red giants and white dwarfs, the very existence and role of the elusive neutrino, how stars circle one another in binary orbits, why disks of matter form around black holes, and why some supernovae shine by radioactive decay. For now we will describe some of the conservation laws most frequently used in the astrophysics of stars.

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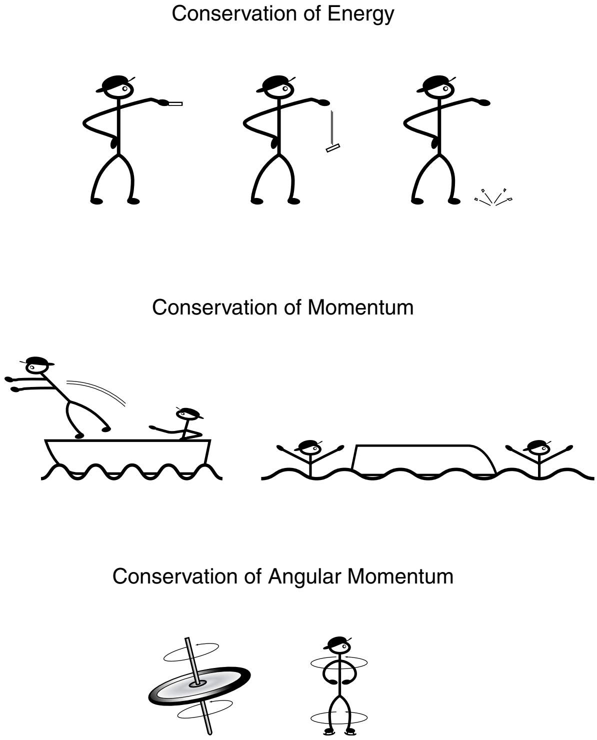
One of the most fundamental conservation laws is the *conservation of energy*. Energy can be converted from one form to another so understanding energy conservation can sometimes be tricky, but, for all physical interactions, energy is conserved. The energy can be converted from energy of directed motion to random thermal energy and from, or to, gravitational energy. Even mass can be converted to energy and energy to mass according to Einstein's most famous formula, $E = mc^2$. Despite all these potential conversions in form, the energy of a physical system is conserved. When you drop a piece of chalk, it shatters with a small crash, as illustrated in Figure 1.2 (top). The potential gravitational energy goes first into the kinetic energy of falling, then into the energy of breaking electrical bonds among the particles of chalk, and even into



Conservation of Energy

Conservation of Momentum

Conservation of Angular Momentum

**Figure 1.2** The principles of conservation: (top) dropping and shattering a piece of chalk is a complicated process, but the energy of breaking, motion, heat, and noise is exactly that gained by falling; (middle) a person leaping from a boat will send the boat and his companion rapidly in the opposite direction, illustrating conservation of momentum; (bottom) a skater drawing in his arms will spin faster, conserving angular momentum.

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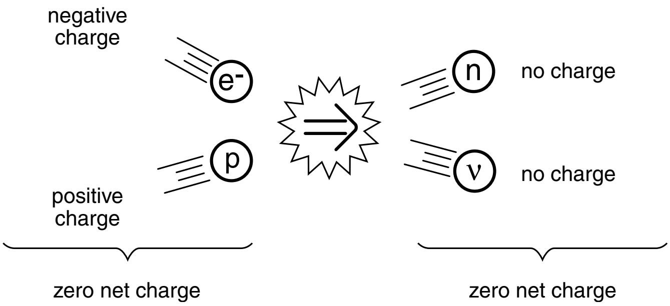
the energy of the sound waves of the noise that is made. Despite the complicated details, the total energy of everything is conserved.

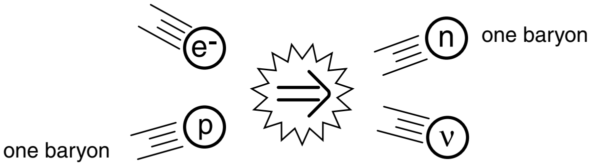
*Momentum* is a measure of the tendency of an object to move in a straight line. The measure of the momentum is not which team scored the last touchdown or goal, a common usage of the phrase in a sports context, but the product of the mass of an object with its velocity. The *mass* is a measure of the total amount of stuff in an object. The *velocity* is the speed in a given direction. Momentum characterized as mass times velocity is also conserved. A mass moving with a certain speed in a certain direction will continue to do so unless acted upon by a force. A given mass may be sped up or slowed down by the action of a force, but the agent supplying the force must suffer an equal and opposite reaction so as to conserve the momentum as a whole. Try jumping suddenly out of a boat (Figure 1.2, middle) and ask your companions if they appreciate the overwhelming verity of the principle of conservation of momentum. If you leap out one side, the boat must react by moving in the opposite direction with the same momentum as your leap. The boat will inevitably tip and leave everyone in the drink.

*Angular momentum* is a property related to ordinary momentum, but it measures the tendency of an object of a given mass to continue to spin at a certain rate. The measure of the angular momentum is the mass times the velocity of spin times the size of the object. A popular demonstration of conservation of angular momentum is an ice skater. When a spinning skater draws his arms in closer to his body, his ‘‘size’’ gets smaller. Because his mass does not change, his rate of spin must increase to ensure that his total angular momentum will be constant. In detail, this is a complex process involving the contraction and torsion of muscles and ligaments. You do not have to understand the details of how muscles and ligaments work, however, to see that the skater must end up in a dizzying spin when he pulls his arms in, and that he will slow again by simply extending his arms (Figure 1.2, bottom).

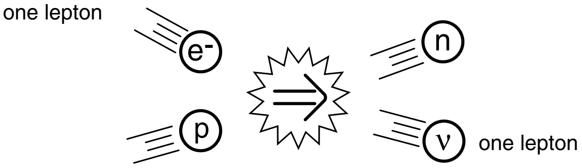
Other conservation laws are important to physics but are not reflected so easily in everyday life. An especially powerful example is that of *conservation of charge*. Electrical charge, the total number of positively and negatively charged particles, is conserved. Physical processes can cancel charges, a positive charge against a negative one, but the net positive or negative charge cannot change in a physical process. Neither positive nor negative charges can simply appear or disappear. In a reaction involving a bunch of particles, the total charge at the end of the reaction must be the same as at the beginning of the reaction. Here is an example:



Elementary particles have other properties, akin to electrical charge, that are conserved. The heavy particles like protons and neutrons that constitute atomic nuclei are called *baryons* (from the Greek "bary" meaning heavy). In a nuclear reaction, the number of baryons is conserved. The baryons may be changed from one kind to another, protons to neutrons for instance, but the number of baryons does not change. If there were four baryons at the start, there will be four at the end. The same example applies to baryons:



There are other elementary particles that do not belong to the baryon family. The ones in which we will be especially interested are the low-mass particles known as *leptons*. Electrons and neutrinos are members of this class. As for baryons, nuclear reactions conserve the total number of leptons, even though individual particles may be created or destroyed. Common reactions will involve both baryons and leptons, and both classes of particles are separately conserved. That is true in our sample reaction:



These last two conservation laws, of baryon number and lepton number, are highly accurate. These laws were once thought inviolate.

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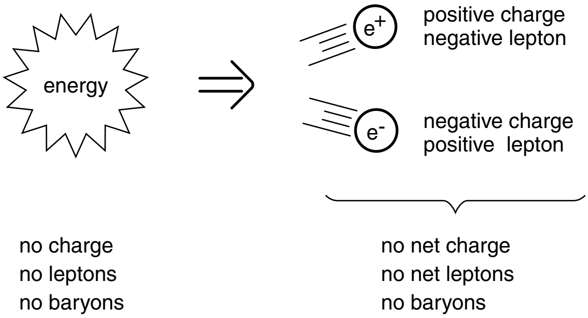
Recent theoretical developments have suggested that this is not strictly true. One of the suggestions arising from the work of constructing a grand unified theory of the strong and electroweak forces is that baryons may not be completely conserved. The big bang itself may depend on the breakdown of these conservation laws. On timescales vastly longer than the age of the Universe, baryons, including all the protons and neutrons that make up the normal matter of stars, may decay into photons and light particles. For all ‘‘normal’’ physics, and hence for all practical purposes, baryons and leptons are conserved, and we will use these conservation laws to understand some of the reactions that are crucial to understand the nature of stars.

An important offshoot of the ideas of conservation of energy, charge, baryon number, and lepton number is the existence of matter and antimatter. For all ordinary particles – electrons, neutrinos, protons, and neutrons – there are antiparticles – antielectrons, antineutrinos, antiprotons, and antineutrons. These are not fantasy propositions; they are made routinely in what are loosely called ‘‘atom smashers,’’ and more formally, particle accelerators, and they rain down continually on the Earth in the form of cosmic rays. The connection to the conservation of charge is that antiparticles always have the opposite charge of the ‘‘normal’’ particle. The antielectron, also called a *positron*, has a positive electrical charge. An antiproton has a negative charge. Because neutrinos and neutrons have no electrical charge, neither do their antiparticles; but they have other complementary properties. For instance, to make sense of the way physics works, it is necessary to consider an antielectron to count as a ‘‘negative’’ lepton and an antiproton to count as a ‘‘negative’’ baryon. In that sense, assigning the property of ‘‘leptonness’’ or ‘‘baryonness’’ to a particle is like assigning an electrical charge; it can be positive or negative and is opposite for particles and their antiparticles.

A remarkable property of particles and antiparticles is that they can be produced from pure energy and can annihilate to produce pure energy. Carl David Anderson won the Nobel Prize in Physics in 1934 for the discovery of positrons. Positrons were first created in a laboratory by applying a very strong electric field, the energy source, to an empty chamber, a vacuum. When the electric field reached a critical value, out popped electrons and positrons. You can see the connection with conservation of energy, charge, and leptons here. The energy of the electric field must be strong enough to provide the energy equivalent of the mass of an electron and a positron, twice the mass of a single electron. Because the original vacuum, even with the imposed electrical field, had no net electrical charge, the final product, the electrons and positrons, also must have no net electrical charge. For every negatively charged electron that is created in this way, there must be a particle with the opposite electrical charge, an antielectron, a positron. Likewise, the original apparatus had no ‘‘leptons,’’ just the electrical field and vacuum. When an electron and positron appear, the electron must count as plus one lepton, and the positron as minus one lepton, so that the net number of leptons is still zero, in analogy with the way one keeps track of electrical charge. Here is a schematic reaction:



This experiment can also be run backward. If an electron and positron collide, they annihilate to produce pure energy – photons of electromagnetic energy – with no net electrical charge and no net number of leptons. The same is true of any particle and antiparticle. When they collide, they annihilate and produce pure energy; all the mass disappears. This is a very dramatic example of conservation of energy and of Einstein’s formula, $E = mc^2$; pure energy can be converted into matter, and matter can be converted into pure energy. In the process, the total number of electrical charges, the total number of leptons, and the total number of baryons does not change. The total of each is always zero.

You might wonder, if antiprotons annihilate protons on contact and hence are antimatter, do they antigravitate? If I make an antiproton in a particle accelerator, will it tend to float upward? The answer is no. Energy is directly related to mass by the formula $E = mc^2$. One implication of this relation is that because mass falls in a gravitational field, energy also falls in a gravitational field. Because particles and antiparticles annihilate to form a finite, positive amount of energy that will fall in a gravitational field, so the individual particles

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and antiparticles must fall. An antigravitating particle might annihilate with a gravitating particle to produce no energy, but we do not know of any such particles. Current physics does give some hints of the existence of antigravity which we will discuss in Chapter 12.

### 1.2.3 *The energy of stellar contraction*

We can now apply these various conservation laws to stars. We will start with the principle of conservation of energy. The result is a little surprising at first glance, but crucial to understanding the way in which stars evolve.

Let us first consider the nature of a star. A star is a hot ball of gas in *dynamic equilibrium*. This means that a pressure of some kind pushes outward and balances the gravity that pulls inward. The Sun does not have the same size day after day because there are no forces on it that might alter its size; rather there are great forces both inward and outward at every point in the Sun. The structure of the Sun has adapted so that the forces just balance. The equilibrium is such that the pressure force keeps gravity from collapsing the star, and gravity keeps the pressure from exploding the star. We will see in Chapter 6 that this condition of delicate balance can be interrupted and either collapse or explosion can result, depending on the circumstances. The mass and size of a star determine the gravity and hence the pressure and heat needed to arrange the balance of forces.

The Sun and most stars we see scattered in the night sky are supported by the pressure of a hot gas. The pressure, in turn, is directly related to the thermal energy in the star. At the same time, the star is held together by gravity. As the star radiates energy into space, it loses a net amount of energy. What happens to the temperature in the star? The answer is dictated by the principle of conservation of energy.

If the star were like a brick, the answer would be simple. As energy is radiated away, a brick just cools off. Gravity plays a crucial role in the makeup of a star, however. If the star were to cool, the pressure would tend to drop, and then gravity would squeeze the star, compressing and heating it. A star responds to a loss of radiant energy in just this paradoxical way. As the star loses energy, it contracts under the compression of gravity and actually heats up! This process, illustrated in Figure 1.3, is completely in accord with the conservation of energy. One must remember only that the squeezing by gravity is an important energy source that cannot be ignored when counting