Chapter Title: Defying Gravity

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CHAPTER 4

Defying Gravity

> It seems, therefore, on the whole most probable that the sun has not illuminated the earth for 100,000,000 years, and almost certain that he has not done so for 500,000,000 years. As for the future, we may say, with equal certainty, that inhabitants of the earth can not continue to enjoy the light and heat essential to their life for many million years longer unless sources now unknown to us are prepared in the great storehouse of creation.
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> —Sir William Thomson (Lord Kelvin), in “On the Age of the Sun’s Heat,” *Macmillan’s Magazine* (1862)

Over the course of the twentieth century, geologists and geochemists slowly teased the secrets of the ages from Earth rocks, lunar samples, and meteorites. But we should keep in mind that even our very best estimate for the age of the Earth is only a lower limit. Perhaps no rocks survived the first 1 or 5 or 30 billion years of Earth history. Perhaps the Moon formed long after the Earth. Perhaps no ancient Moon rocks have survived, or perhaps the Apollo astronauts did not visit the most ancient lunar rock formations and thus did not bring back the oldest Moon rocks. Perhaps older meteorites exist but are too fragile to survive the fiery descent to Earth’s surface. Perhaps the very oldest asteroids orbit the Sun in a part of the solar system from which few or no meteorites are delivered to Earth.

If any of these “perhaps . . . ” scenarios is correct, then the radiometric ages obtained from Earth and Moon rocks and meteorites are only coincidentally coeval. And if that is the case, then the radiometric age of about 4.5 billion years we have obtained for the oldest objects yet studied might not tell us very much about the age of the Earth or the age of the Sun, let alone the age of the universe. On the other hand, the Earth, the Moon, and the meteorites may all have formed at about the same time, about 4.5 billion years ago. But what is the relationship between the age of the Sun and the age of the objects in orbit around it? If the Sun formed first and then, at a much later time, captured fully formed planets from interstellar space, there would be no relationship between the ages of the Sun and its planets. Alternatively, the Sun may have formed coevally with its planetary system. If we had a way to determine the age of the Sun, we would know the relationship between the measured ages of Earth rocks, lunar rocks, and meteorites and of the solar system as a whole. Determining the age of the Sun seems like a sensible next step as we work toward measuring the age of the universe.

In the eighteenth century, both Kant and Laplace suggested that the Sun and the planets and smaller objects that orbit it could have formed from a swirling interstellar cloud. Two centuries later, astronomers confirmed this hypothesis by identifying many such interstellar clouds that exist today and by studying the star formation process that takes place within these clouds. In general, interstellar clouds are in a precarious balance between expansion and collapse. Their internal heat generates expansive pressure while gravity from the particles of matter in the cloud works to pull the particles closer together. When an interstellar cloud cools off, its thermal pressure weakens and the cloud loses the ability to resist the compressive force of gravity. The balance tips in favor of gravity and the cloud collapses in on itself. The rotational motion of the collapsing cloud, however, prevents all of the material in the cloud from falling all the way to the center; instead, while the cloud shrinks it also flattens, forming a disk of gas and dust that revolves around the newborn star at its center. The planets that orbit our Sun formed in just such a disk.

We now understand the physics of the process of star formation well enough to know that it involves a set of associated events. The physical processes involved in the gravitational collapse of an interstellar cloud are such that the smallest particles in the disk could be almost as old as the central star; the moons and planets would form from the disk

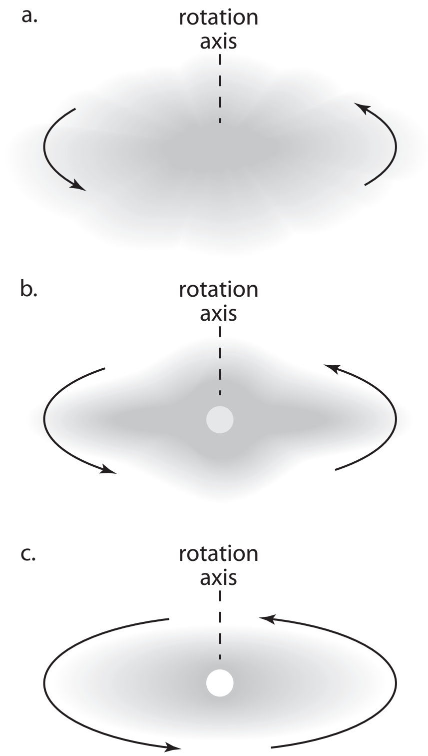

Figure 4.1. Illustration of the theory that stars form from rotating clouds of gas in space.

particles within a few tens of millions of years after the star started to form. All the astrophysical evidence supports the assertion that the Sun is older than the Earth, but only by a few million to a few tens of millions of years. The oldest meteorites could be among the very first solid objects formed in the solar system and might be almost as old as the Sun itself.

The Sun Must Have an Energy Source

The Sun is a large spherical object, made mostly of hydrogen and helium gas, that emits light. That light heats and illumines the Earth. We know the distance of the Earth from the Sun and we know the physical size of the Earth. From these two numbers, we can calculate the

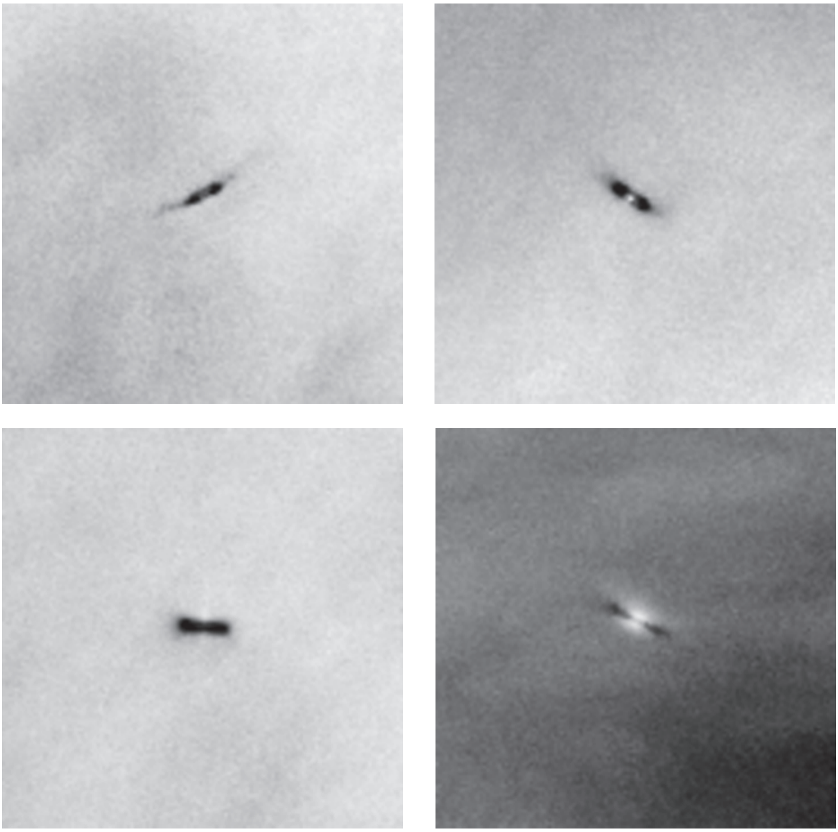

Figure 4.2. Hubble Space Telescope images showing flattened disks around newborn stars (known as *proplyds*) in the Orion Nebula. Image courtesy of NASA, ESA and L. Ricci (ESO).

fraction of emitted sunlight that is intercepted by the Earth. And from all of this information, we can calculate the total amount of energy released by the Sun every second. Simply by measuring the distances and luminosities of other stars, we can perform similar calculations for any star in the sky.

If stars radiate heat, their surface temperatures should decrease unless the heat is replenished from within. Since the interiors of stars will be hotter than their surfaces, stars will compensate for any heat lost from their surfaces through the transfer of heat from their centers to their surfaces. Unless the cores of stars have heat sources, they must cool off. If the cores cool off, the entire insides of stars should eventually cool off and the stars should contract. If contraction occurs, it should be measurable on the time scale of a human lifetime, and substantial changes should have been evident over recorded history.

The surface temperature of the Sun is not decreasing, however; and historical evidence gives no indication that the Sun has cooled over human history or even over geological history. We also see no evidence to suggest that the surface temperatures of any other stars are decreasing with time. If neither the Sun nor other stars are cooling, they therefore must be capable of generating heat from internal sources to replenish the heat radiated to space.

In the mid-nineteenth century, the German physicist Hermann von Helmholtz conjectured that if the Sun derived its heat from the oxidation of combustible materials like wood or coal, it could burn for only 1,000 years. If, however, the Sun were slowly contracting, with its outer parts settling inwards toward its core, it would generate the energy required to shine for a much longer period by converting gravitational potential energy into heat. This is the same process that heats a metal spike when you drop the head of a sledgehammer repeatedly onto the spike. Once the sledgehammer is lifted off the ground, it contains potential energy. When the head of the hammer is released, that potential energy is converted into the energy of motion (kinetic energy), which causes the hammer to drop toward the spike. When the hammer hits the spike, that kinetic energy is transferred to the spike. Some of the kinetic energy drives the spike into the ground, while some simply makes the iron atoms in the spike vibrate faster. The energy associated with the individual motions of the atoms in the spike produces what we call heat. The faster the motions of the atoms the higher the temperature of the spike. When the Sun contracts, atoms more distant from the center of the Sun fall inwards and collide with atoms slightly less distant from the center, thereby converting gravitational potential energy to kinetic energy; the conversion of potential to kinetic energy heats the outer layers of the Sun. According to Helmholtz's calculations, this process could generate enough heat to allow the Sun to shine for 20 to 40 million years. Lord Kelvin, the great English physicist and a contemporary of Helmholtz, repeated

Helmholtz's calculations and found that the Sun could be as much as 500 million years old. Presumably the Earth could be equally old. This age might be sufficient to permit rocks to form according to the natural processes outlined in Hutton and Lyell's theory of uniformitarianism. These nineteenth-century attempts at estimating the maximum length of time for which the Sun might continue to shine provided plausibility for the hypothesis that the Sun, and by inference the Earth, might be older than 6,000 years, but they did not provide an actual age for the Sun.

If the mechanism of gravitational contraction is indeed generating the Sun's energy, as Helmholtz and Kelvin proposed, that process has a testable, observable consequence: according to Lord Kelvin's calculations, the Sun should contract in diameter by about 70 meters per year. While measuring such a small change in the solar diameter was beyond the ability of nineteenth-century astronomers, such measurements are well within our twenty-first century capabilities, and we now know that the Sun's diameter is not changing. Gravitational contraction does not power the Sun.

E = mc^2

If the Sun is not changing measurably in luminosity or temperature at either its surface or its core, if the Sun is not contracting, and if the Sun is billions of years old (as it must be to match the age of the Earth), then it must have an enormously powerful internal source of energy that is able to replenish the heat lost from the core to the surface and from the surface into space. No nineteenth-century theory could identify this energy source.

English astrophysicist Arthur Eddington, in 1926, proposed a new method for energy generation in stars that was based on Albert Einstein's theory of special relativity. One tenet of special relativity is that mass (m) is equivalent to energy (E) and that the amount of energy contained by a piece of mass is found by multiplying the mass by the square of the speed of light (c^2). That is, $E = mc^2$. Effectively, $E = mc^2$ expresses two ideas: that mass is simply one way in which the universe stores energy; and that energy can be converted from one form to another if the physical conditions (temperature, density, pressure) are right. Eddington suggested that four hydrogen nuclei (four individual protons) could be combined, or fused together, to make one helium nucleus in a process called *nuclear fusion*. Since the mass of one helium nucleus is slightly less than the sum of the masses of four protons, Eddington suggested that the "lost" mass had been converted to energy, and that it was this energy that powered the stars.

In 1929, Henry Norris Russell was able to calculate the relative amounts of the elements in the atmosphere of the Sun and concluded that more than 90% of the Sun, by volume, and about 45% by mass, must be composed of hydrogen. Stars therefore had nearly inexhaustible supplies of hydrogen and so, according to the process sketched out by Eddington, could power themselves for billions of years. Aided by the discovery of the neutron in 1932 by James Chadwick and the development of the theory of quantum mechanics in the 1920s and 30s, Hans Bethe deduced the sequence of nuclear reactions that takes place in the cores of stars.

The Energy Available through Nuclear Fusion

In a sequence of reactions called the proton-proton chain, four protons (^{1}H) combine to form a single helium nucleus (^{4}He) made of two protons and two neutrons; however, this does not occur via the highly improbable simultaneous collision of four particles. Instead, the proton-proton chain involves several intermediate steps and six, not just four, protons. First, two protons collide. After the collision, one of the protons is converted into a neutron through the emission of two particles, a positron (the anti-particle partner of an electron, having the mass of an electron but a positive charge) and a neutrino (a very low-mass particle with no electric charge). The resulting particle contains both a single proton, which means that it is still a hydrogen nucleus, and a neutron, which makes the nucleus heavier than a normal hydrogen atom. This heavy hydrogen atom is known as *deuterium*, which is denoted as either ^{2}H or D.

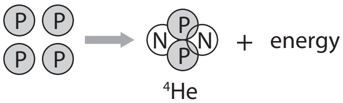

Figure 4.3. In the proton-proton chain, four protons combine to form a helium nucleus. In the process, some mass is converted into energy and a small amount of mass is converted into particles called neutrinos. This nuclear fusion reaction generates the energy that powers the Sun.

The positron will quickly find its anti-particle, an electron; and in that collision, they will annihilate one another, turning all of their combined mass into energy in the form of a high-energy gamma ray photon. The gamma ray doesn't travel far before it is absorbed by another particle, adding to that particle's energy and thereby making it move faster. Since the average speed of the particles in a gas determines its temperature, when this first step in the proton-proton chain has been repeated many times it has the effect of heating the gas at the center of the star. The neutrino has properties such that it only rarely collides with other particles (it is known as a weakly-interacting particle), so almost all neutrinos produced in this reaction fly right out of the Sun.

In the next step in the proton-proton chain, the deuterium nucleus collides with another proton to form a helium nucleus, though this is a lightweight helium nucleus with two protons but only one neutron (^{3}He; called "helium-three"). This reaction also generates a gamma ray, which will be absorbed by a nearby particle, contributing excess kinetic energy to that particle and heating the surrounding gas.

These first two reactions must each happen twice so that two ^{3}He nuclei are created. Finally, these two ^{3}He nuclei collide, forming a ^{4}He nucleus and knocking loose two protons. The combined mass of four protons is 6.690×10^{-24} g, while the mass of one ^{4}He nucleus is 6.643×10^{-24} g. The fractional difference in mass between the input and output particles, equal to 0.7 percent of the starting mass, is the amount of mass converted to energy in this process. If the entire mass of the Sun were available (which it is not) for this mass-to-energy conversion process, the proton-proton cycle could power the Sun for 100 billion years.

Critical Requirements for the Proton-Proton Chain

The collisions that power the proton-proton chain involve positively-charged nuclei colliding with other positively-charged nuclei. Positively-charged particles repel, however, so two protons (for example) are unlikely to collide except under the most extreme conditions. In fact, if two protons were propelled toward each other at low speeds, the electromagnetic repulsion exerted by each on the other would prevent the collision from happening, just as two automobile drivers driving toward each other on a single-lane country road at low speeds would likely see each other in time to avoid the collision either by slamming on their brakes or veering out of each other's way.

Let's follow the potential car crash analogy further. Under what circumstances might the two drivers be unable to avoid a collision, either with each other or with another innocent-bystander car? We can identify two preconditions that would certainly raise the likelihood of such a collision: high speeds and a high density of cars. High speeds make it less likely that a driver will have enough time to react after discovering another car in his path; high density—meaning that the parking lanes on both sides of the narrow road are packed with other cars—virtually ensures that any effort to avoid a collision with a car in the driver's lane will almost certainly cause a collision with another, nearby vehicle. If both the high speed and high density conditions are met, a collision between the two cars is inevitable.

In order for two protons to collide, they must get close enough to touch; that is, they must come closer than one nuclear diameter (10^{-13} cm). The minimum temperature required for two protons to overcome their mutual repulsion at this close distance is 10 billion K. This implies that while the surface of the Sun has a temperature of only 6,000 K, the core must have a temperature about one million times hotter if nuclear fusion is the process that powers the Sun; yet astronomers were certain, even in the 1920s, that the core of the Sun could not be much hotter than about 10 million K, which is about 1,000 times cooler than 10 billion K. They reasoned that if the core temperature of the Sun were much hotter than 10 million K, the intense pressure from the super hot gas deep inside the Sun would cause the outer layers of the Sun to expand, increasing its size much above its present diameter.

Clearly, if stars generate energy through nuclear fusion but do so at temperatures of millions of degrees rather than billions of degrees, then our simple picture of the fusion process is so far inadequate. We need to furnish two additional and crucial links. One is the consequence of what is called the *kinetic theory of gases*. In a gas—and the particles at the core of the Sun are indeed in a gaseous state—every particle moves at a different speed. Some particles move slowly in comparison to the average; others much faster. When we ask, what is the temperature of this gas? we are actually asking, what is the average speed of all the particles of which it is composed? In this distribution of velocities, known as the Maxwell-Boltzmann distribution, some particles will be moving twice as fast, some as much as six times as fast as the average. So, for example, if the temperature of the gas is 10 million degrees, a very small fraction of its particles are moving with speeds equivalent to the average velocity of particles in a gas at 60 million degrees. Thus, we do not need the temperature of the gas to be 10 billion K in order for a few particles within it to be moving at speeds as fast as the average for a 10 billion degree gas. But we do need temperatures well above 10 million K. The kinetic theory of gas makes nuclear fusion more possible, but by itself it is not sufficient to explain how fusion can take place in the Sun.

The second missing link is called *quantum tunneling*, an idea discovered by George Gamow and also, independently, by Ronald W. Gurney and Edward Condon in 1928. In the case of two protons, we can think of the electromagnetic repulsion one proton exerts on the other as a sort of energy barrier or hill that the second proton must jump over in order to bump into the first proton. If the second proton is moving fast enough, it is able to climb the energy barrier between the two protons and have enough energy left over to collide with the first proton on the other side. The quantum-tunneling concept says that there is a small

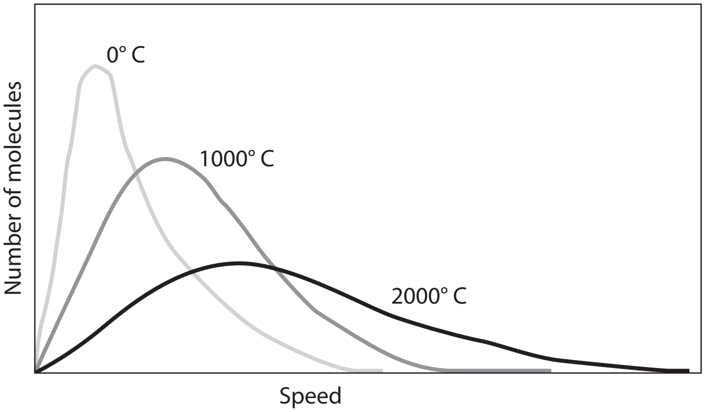

Figure 4.4. The Maxwell-Boltzmann distribution depicts the speed (*x* value) versus the number of particles in a gas moving at each speed (*y* value). As the gas temperature increases, the entire distribution broadens and shifts toward higher speeds. In the core of the Sun, only a very few particles with the very highest speeds have enough energy to participate in nuclear fusion reactions.

but real possibility that the second proton can get past—metaphorically, tunnel through—the barrier despite lacking the energy to climb over. The likelihood that two protons will collide at temperatures of only about 10 million K, without quantum tunneling, is effectively zero. But quantum-tunneling calculations indicate that though this event is unlikely, it should happen for any pair of protons once in about 10 billion years. This probability, restated, means that if I have ten billion protons, this event should happen once per year. Since the core of the Sun has an almost unfathomable number of protons (about 10 to the 55th power, 10^{55}), enough of these unlikely collisions happen every second (in fact more than 10^{38} per second) that the Sun is able to power itself through nuclear fusion reactions.

If we start at the core of the Sun and move outwards, both the temperature and density of the gas will decrease toward the surface. Outside of a critical radius, the temperature and density will be too low for any nuclear fusion reactions to take place, even with the help of quantum tunneling. The region inside this critical radius is the core of the Sun; the region outside the core is called the envelope. In the Sun, only the hydrogen located in the core can participate in the proton-

proton chain; the hydrogen in the envelope is inactive in the nuclear fusion process.

How Long Can the Sun Power Itself from Proton-Proton Chain Reactions?

Eventually, the Sun will run out of protons in its core and will no longer be able to fuel the proton-proton chain reactions. This eventuality necessarily will lead to changes in the behavior of the Sun. When energy is no longer generated in the core, the heat radiated from the surface will no longer be fully replenished from inside the star. The entire Sun will begin to cool off and contract. As we will see in Chapter Thirteen, the cooling and contraction of the core of a star will lead to a heating and compression of the core, which in turn will lead to a new set of nuclear reactions that occur at higher temperatures and pressures. Had those new nuclear reactions already begun inside our Sun, they would have produced internal changes in its structure. Those internal structural changes would cause the Sun to increase in size until it became a red giant star. As a red giant, the Sun would be larger, more luminous, and cooler at its surface. But the Sun is not a red giant, yet; therefore, it has not exhausted the supply of protons in its core.

The core of a typical star comprises about 10 percent of its total stellar mass, and about 0.7 percent of that mass can be converted to energy via proton-proton chain reactions. If we calculate the total amount of energy that can be generated by converting 0.7 percent of the mass of the core of the Sun from protons into helium nuclei, and if we divide that number by the luminosity of the Sun, we come up with the length of time during which the Sun can shine as it does today: approximately 10 billion years. We therefore may be confident that the Sun is less than 10 billion years old. But can we pin down its age more accurately?

Every second, the Sun converts a huge number of protons into helium nuclei. These conversions affect the density, temperature, and pressure in every layer of the Sun, from its center all the way out to the surface. Since the rate of nuclear reactions in the core depends on density, temperature, and pressure, these changes have a feedback effect on the nuclear fusion process itself. Slowly and steadily, these changes accumulate and affect the luminosity and temperature of the surface of the Sun, making the Sun a little bit hotter and brighter over a timescale of a few billion years. Given the mass and composition of the Sun, astrophysicists can calculate what the luminosity and surface temperature of the Sun should have been when it was born and how those parameters should evolve with time. From those calculations, we know that the Sun is neither newborn nor nearing the end of its lifetime; in fact, the Sun is about 4.5 billion years old. Were it younger, it would be cooler and less luminous. Were it older, it would be hotter and more luminous.

Our understanding of the astrophysics of the Sun has led to the conclusion that the Sun is about the same age as the oldest meteorites in the solar system. This result is independent of and consistent with our observations that stars and their planetary systems form at about the same time. We can say with confidence that the Sun and all the objects in orbit around it, from the tiniest meteorites to the Moon, Earth, and other planets and moons, all formed very nearly 4.5 billion years ago and that the universe is therefore at least that old.

In order to determine whether the rest of the universe is also 4.5 billion years old or is older, we will need to carry our investigation far beyond the confines of our solar system. Anyone who has gazed into the nighttime sky knows that the dominant objects visible to our unaided eyes are stars. Perhaps they can teach us more about the age of the universe.

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