CHAPTER 2

The Setting

The Big Bang and Galaxy Formation

Earth is a minor member of a system of planets in orbit around a star we call the sun. The sun is one of about 400 billion stars that make up our Milky Way. The light from this myriad of stars allows observers in neighboring galaxies to define our galaxy's spiral form. The galaxy is the basic unit into which universe matter is subdivided.

Like its billions of fellow galaxies, ours is speeding out on the wings of a great explosion that gave birth to the universe. That these major pieces of the universe are flying away from each other is revealed by a shift toward the red of the "bar code" of spectral lines of the elements in the light reaching us from distant galaxies. The close correlation between the magnitude of this shift and the distance of the galaxy from Earth tells us that about 13.7 billion years ago all the galaxies must have been in one place at the same time. The catastrophic beginning of the universe is still heralded by a dull glow of background light. This glow is the remnant of the great flash that occurred when the debris from the explosion cooled to the point where the electrons could be captured into orbits around the hydrogen and helium nuclei. The Big Bang was the impulse from which everything else in the universe has been derived. Contained in the galaxies lying within the range of our telescopes are about 400 billion billion stars. A sizable number of these stars are thought to have planetary systems.

Careful examination of the data from galaxies shows that a vast amount of matter is not accounted for in what we can see. This "dark matter" is not visible to us and is poorly understood, but it makes up almost six times as much total mass as the *atomic matter that makes up stars, planets and life. Careful measurement of retreating galaxies shows that they are speeding up with time and that the universe will not ultimately contract into a "big crunch." To explain this phenomenon requires "dark energy" that has a repulsive force that counters the effect of gravity. Some 76% of the universe is believed by physicists to be made of dark energy, relegating the material that we know and understand to only 4% of what was created in the Big Bang. While the beginning event is well established, great mysteries concerning the contents and operation of the universe remain to be understood.*

Introduction

Where the universe comes from and how it got here are the essential first questions as we delve to the starting point of Earth's history, deep in time even long before the formation of the Milky Way. Was there a beginning? When and how did it happen? In this chapter we will see that there was indeed a spectacular beginning to the universe—the origin of everything we can observe—and we can even determine when it happened. From there, everything else unfolds.

The Big Bang

The universe as we know it began about 13.7 billion years ago with an explosion that astronomers refer to as the Big Bang. All the matter in the universe still rides forth on the wings of this blast. Speculations as to the nature of this cosmic event constitute the forefront of a field called *cosmology*. What went on before this explosion is a matter that is not currently subject to scientific investigation, because every observable phenomenon in the universe (that we know of) dates from the Big Bang. No physical record of prior events remains.

To state that we know the age of our universe and its mode of origin is rather bold. Is this fanciful thinking or is there evidence? While it is remarkable that we have detailed knowledge of the beginning of the universe, the observations astronomers have made provide compelling

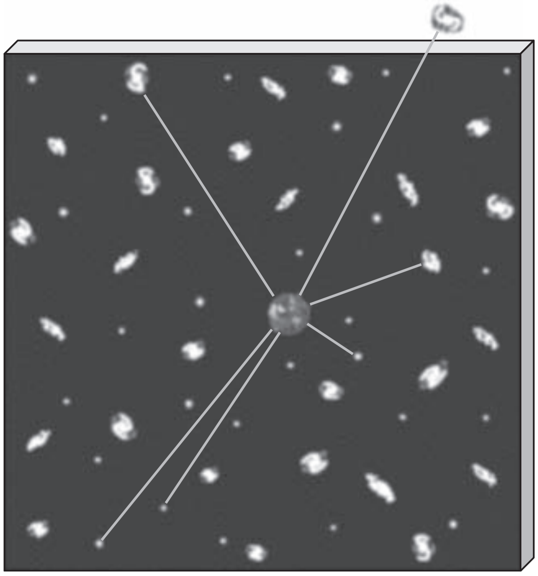


Fig. 2-1: Schematic illustration of one aspect of Olber's paradox. If the universe is infinite in space and time, then looking out into space from Earth, every line of sight ultimately hits a star or distant galaxy. If the line did not intersect light within the box, it could simply be extended further until there was an intersection. Therefore, the night sky should be filled with light, but it isn't.

support for the Big Bang theory of universe origin. On a scale of reliability that goes from 0 (idle speculation) to 10 (proven fact), this theory gets a 9.9!

Before presenting this evidence, let us consider a seeming paradox that confronted astronomers before the concept of an expanding universe was proposed. This paradox was articulated by Heinrich Olbers in 1826. To state it simply, no one was able to explain the fact that the nighttime sky is dark. The black background between the stars seemed to demand either that the universe has a finite extent or that the light from the most distant stars is being intercepted by dark matter in the voids of space. To understand this, one has only to envision a universe of infinite extent made up of luminous objects separated by empty voids. In such a universe, no matter where we looked we would see the light from some distant star (Fig. 2-1). The sky would be blindingly bright! The obvious alternative is that the universe is finite. In a finite universe, we could look between the stars into the black void beyond. Another possibility is, of course, that there are clouds of nonluminous matter floating in the voids between stars and that these clouds block the light from the more distant stars from our view.

The first alternative appeared unacceptable, because in a universe of finite extent there would be nothing to hold the stars apart. The mutual star-to-star gravitational attraction would lead to an unbalanced pull toward the "middle" of the universe. It would be as if we secured a series of balls on a great three-dimensional latticework and then connected each ball to each of the other balls with a stretched rubber band. While the balls near the center of the latticework would be pulled more or less equally from all directions, those near the edge of the lattice would be pulled toward the inside. If by magic we suddenly removed the latticework, leaving only the balls and stretched rubber bands, there would be a massive implosion as the balls streaked toward the lattice's center. Only if the lattice were infinite in extent would nothing happen. In this case the pull on every ball would be exactly balanced. The universe has no latticework to hold the stars apart, yet there they are. Hence, the finite universe explanation for the dark sky must be rejected as inadequate.

The second explanation—that the light from very distant stars is intercepted by dark clouds of dust and gas along its path to the Earth—is also unacceptable. In this situation the light from stars at intermediate distances would also be affected. We should see a glow of scattered light similar to that in the night sky over a great city or from headlights approaching through fog. No such glow is seen! So this explanation must also be rejected.

More than a hundred years passed before this cosmological puzzle was solved. In 1927 a Belgian astronomer, Georges Lemaître, proposed that the universe began with the explosion of a cosmic "egg." This clever concept neatly explained the long-standing paradox in that the force of the explosion prevents the gravitational pull from drawing the matter toward the center of the universe. It would be as if a bomb were to blow the balls on our lattice away, overpowering the pull of the rubber bands. In the absence of observational evidence, the Lemaître hypothesis would have received relatively little attention. Within two years of its publication, however, Edwin Hubble reported observations that turned the attention of the scientific world toward the concept of an expanding universe. Hubble reported a shift toward the red in the spectra of light reaching us from the stars in very distant galaxies. The simplest explanation for such a shift was that these distant galaxies were speeding away from ours at incredible speeds.

THE RED SHIFT: MEASURING VELOCITY

The light coming from the sun consists of a spectrum of frequencies. As these light rays pass into and out of raindrops, they are bent. Each frequency is bent at a slightly different angle separating the bundle of mixed light into a rainbow of individual color components. Each of these frequencies leaves a different imprint on our retina. We see them as colors.

Isaac Newton in the seventeenth century did a number of experiments with light, forming rainbows by passing sunlight through a glass prism. Light rays passing through such a prism are bent according to frequency. As shown in Figure 2-2, the red light (that with the lowest frequency detectable by our eyes) is bent the least, and violet light (that with the highest frequency detectable by our eyes) is bent the most. What we see as white light is actually a combination of all the colors in the visible spectrum.

Astronomers have long used prisms (and more recently diffraction gratings) in their telescopes as a means of examining the color composition of the light from distant galaxies. Rather than producing a continuous spectrum, the light from stars is broken up by dark bands that mar the otherwise smooth transition from red to orange, to yellow, to green, to blue, and to violet. The dark bands are produced by the absorption of

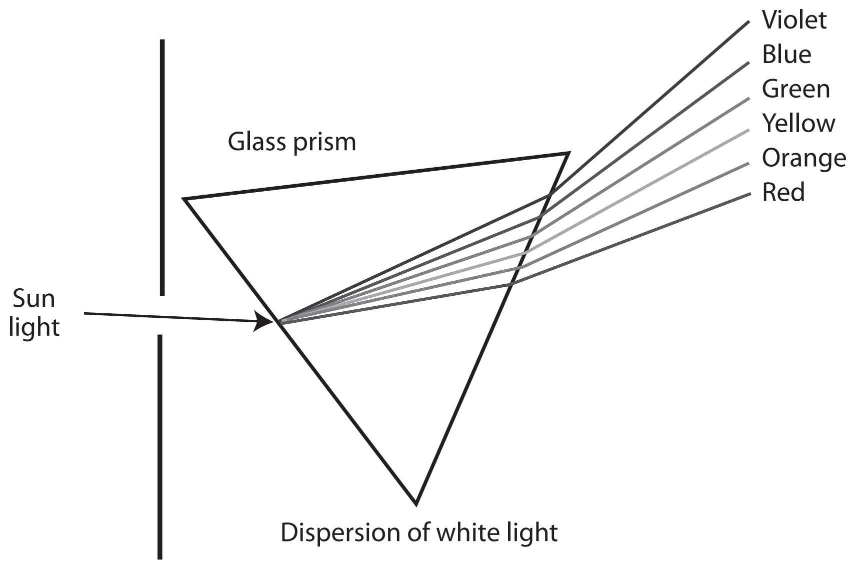


Fig. 2-2: Light rays passing through a prism are bent according to frequency. The red light (that with the lowest frequency detectable by our eyes) is bent the least, and violet light (that with the highest frequency detectable by our eyes) is bent the most.

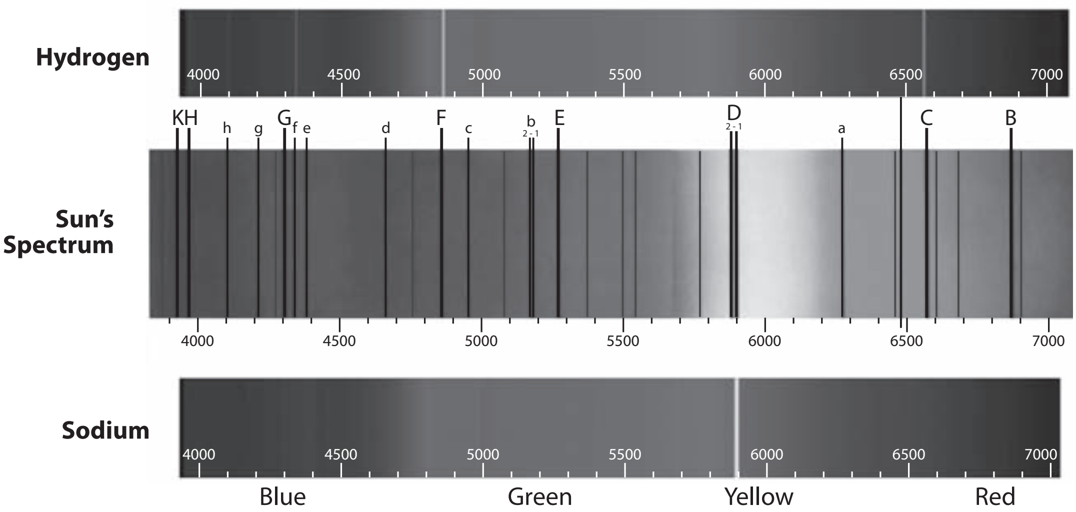


Fig. 2-3: A portion of the spectrum of the sun, called the *Fraunhofer spectrum* after its discoverer, compared to portions of emission spectra of hydrogen and sodium. The *C* and *F* lines of the Fraunhofer spectrum are created by hydrogen in the sun's atmosphere; the dark *D* lines in the yellow are the most prominent lines of the sodium spectrum. Other lines are produced by absorption by other elements. See also color plate 3.

certain frequencies of light by the element-containing halo of gas surrounding the star that is producing the light. A packet of light can interact with an atom only if it has just the right energy to lift one of the atom's electrons from one of its permitted energy levels to another. While transparent to some frequencies of light, the excitation of elements in the gas absorbs other frequencies so that specific wavelengths of light do not get through. Early spectra identified only the most prominent lines (Fig. 2-3). When examined in detail, thousands of lines became apparent. Most do not completely blacken the rainbow; they produce a weakening of the intensity of the light at that frequency. This weakening is the result of partial absorption of the departing light by the star's "atmosphere," depending on the abundance of the element.

Astronomers originally took an interest in these bands because they offered a means of making chemical analyses of the star's halo of gas. Unlike Earth, whose atmosphere has a composition that bears no relationship to that of its crust or interior, the composition of a star's atmosphere is close to that of its bulk. Each partially darkened line in the spectrum represents a single element. Using laboratory arcs as a means of calibration, astronomers were able to estimate the relative abundances of the elements making up the atmospheres of neighboring stars. Since

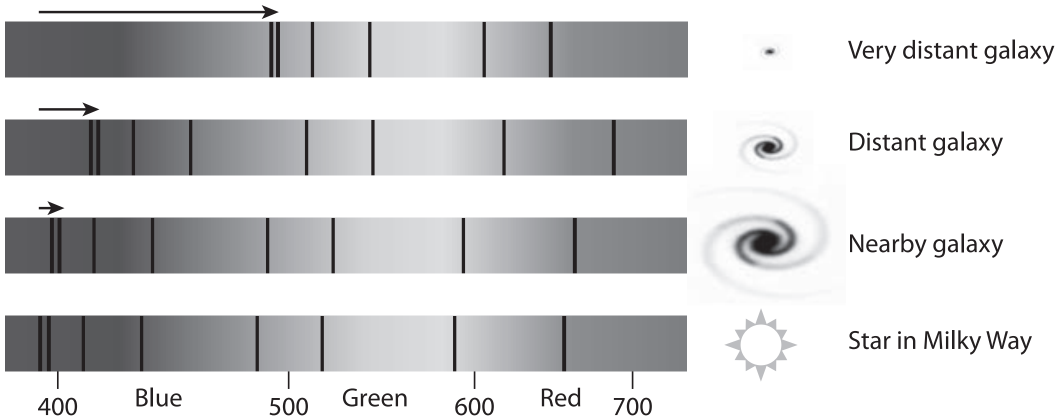


Fig. 2-4: Schematic illustration of how the spectral lines of distant stars shift toward the red (the right-hand ends of the spectra). The bottom spectra represents a nearby star in our galaxy and the spectral lines correspond with the wavelengths we could observe for the elements on Earth. For nearby galaxies, which appear large in a telescope, the spectra are shifted slightly toward the red. For distant galaxies, which appear very small in the telescope, the red shift is much greater. Arrows indicate the extent of the red shift for each spectrum.

all stars contain at least some of all the elements, the characteristic lines become a fixed "bar code," with spacings and relative intensities controlled by the fundamental characteristics of atoms (see Fig. 2-3).

As bigger and better telescopes become available, astronomers were able to extend their chemical analyses to more distant objects. It was here that the great discovery came. When astronomers looked at very distant objects, they found that the characteristic "bar code" shifted with respect to the rainbow background. For example, patterns of lines that were in the blue part of a spectrum taken from the sun would instead be found in the green part of the spectrum for the light from a distant galaxy; a line that appeared in the yellow part of the sun's spectra would appear in the orange part of the distant galaxy's spectrum, and so forth. The "bar code"—the spacing and relative intensity of lines—remained the same. But it looked as if someone had lifted the whole set of dark lines off the background rainbow, moved it toward the red end, and then replaced it. More startling was the finding that the more distant the object, the greater the shift toward red (see Fig. 2-4).

We can understand how this occurs if we first grasp what we will refer to as the "train-whistle concept" (physicists call it the *Doppler shift*). Those who have indulged in train watching may remember that most engineers of express trains blow their whistles as they roar through local stations. Anyone standing on the platform experiences a strange sensation as the train passes. The pitch of the whistle suddenly drops! It drops for exactly the same reason that the lines in the spectra for distant galaxies shift. Since the whistle situation is a bit easier to comprehend, we will consider it first.

Sound travels through the air at a velocity of 1,236 km/hr. If the train passes through the station at 123 km/hr, then the frequency of the sound impulses on the listener's ears would be 10 percent higher as the train approaches and 10 percent lower after it has passed by. This phenomenon is easily understood if we substitute for the train's whistle a beeper that gives off one beep each second. Were an observer to count the beeps from a train stopped down the tracks, he would get 60 each minute. Were he to count the beeps from a train speeding toward him at 123 km/hr, he would hear 66 each minute. Were he to count the beeps from a train speeding away from him at 123 km/hr, he would hear only 54 beeps per minute. The ear counts the frequency of sound waves hitting our eardrum. When the source of the sound is receding, each beat is further away and has to travel further to reach the eardrum, so the ear detects a lower frequency and sends to the brain a lower pitch.

If a source of light is receding, the "pitch" of its light is also lowered. However, as light travels at a staggering 1,080 million km/hr, the frequency of light reaching us from a speeding train is not significantly changed, because to have an effect the speed of retreat has to be a significant fraction of the speed of transmission. So if we observe a shift toward red in the spectrum of the light reaching us from a distant galaxy corresponding to a 10% reduction in frequency, the galaxy must be speeding away from us at the amazing speed of 108 million miles an hour!

MEASURING DISTANCE

As stated above, the more rapidly a galaxy is retreating, the larger will be the shift of its light toward the red. Examples of spectra observed from a series of galaxies are shown in Figure 2-5. The great discovery that followed the discovery of the red shift was that those galaxies that exhibit the greatest red shift are also the farthest away. This discovery required a series of developments that gradually led to a robust distance scale.

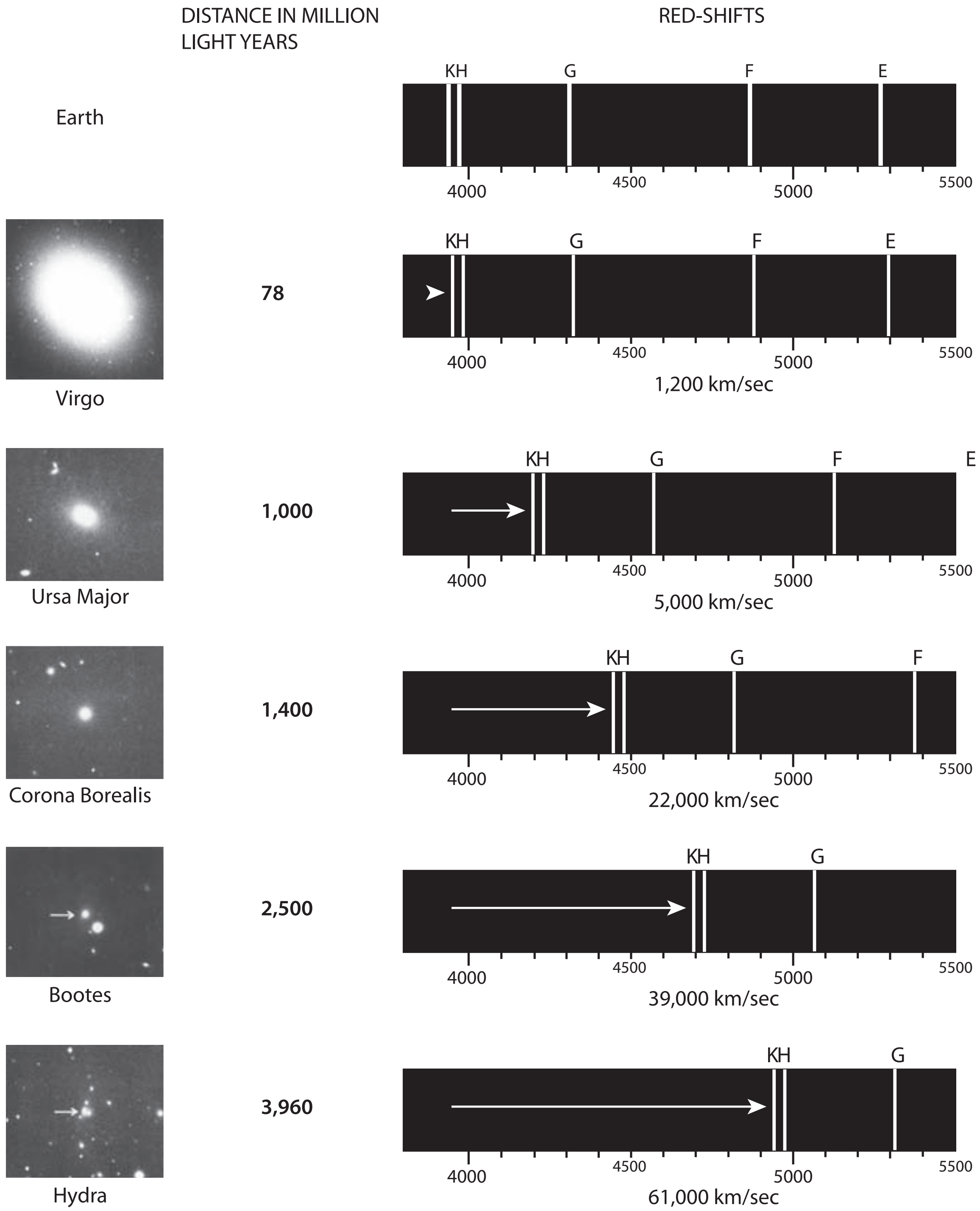


Fig. 2-5: Galaxies and their light spectra: On the left are shown photos of five galaxies taken with the Hale Observatory telescope. As these objects are probably similar in size, Virgo must be located much closer to Earth than Hydra. Also shown, on the right, are schematic light spectra from the galaxies, compared to spectral lines as measured on Earth. The horizontal white arrows show the displacement of an easily identified pair of dark lines from its position in a light spectrum for the Sum (or for a laboratory arc). The recession velocities corresponding to these arrow lengths are given. As can be seen, the more distant the object, the greater is recession velocity. (Images courtesy of California Institute of Technology)

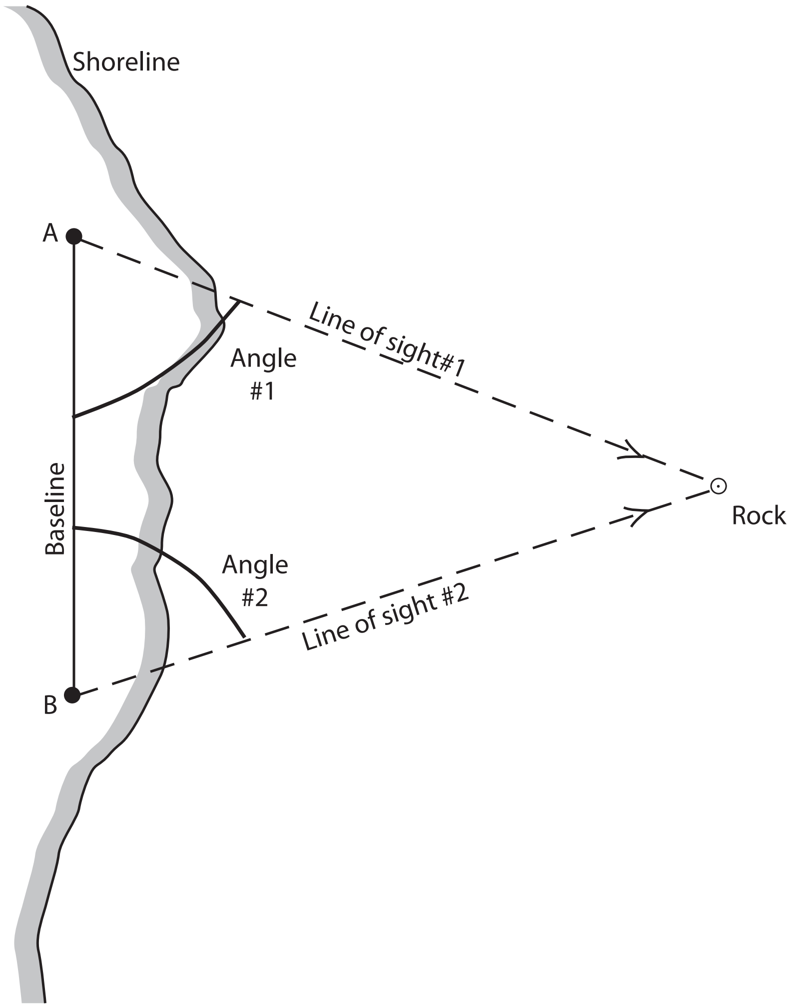


Fig. 2-6: Illustration of how geometry can be used to determine the distance to far away objects. The surveyor observes the distant rock out in the ocean from the ends of a baseline on the shoreline of known length and notes the angles between baseline and the lines of sight. He can then compute the distance through trigonometry.

Distances are far more difficult to measure than velocities—sufficiently difficult that it is beyond our task here to try to grasp exactly how it is done. A few paragraphs will suffice to show the general principles.

As do all surveying schemes, measurements out into space start with a baseline (Fig. 2-6). If a surveyor wants to measure the distance of an object that he cannot easily reach (like a rock out in a lake), he sets up a baseline on shore and measures its length. He then observes the rock from both ends of the baseline and notes the angle between the line of sight and the baseline. Simple trigonometry allows him to calculate the distance to the rock.

As can be seen from Figure 2-7, the ranges of distance confronting the astronomer are staggering! The astronomer boldly starts by using

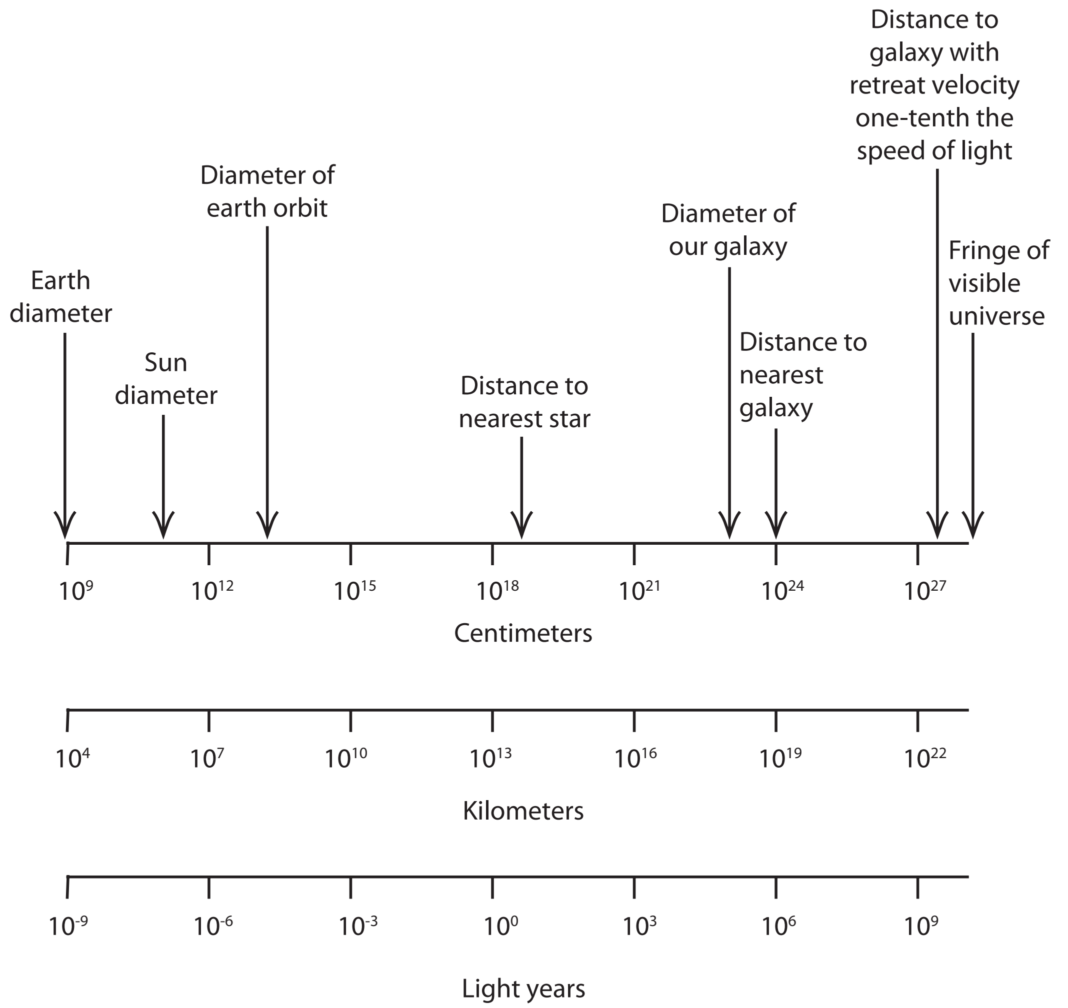


Fig. 2-7: Distance scales. Astronomers must cope with distances ranging over 19 orders of magnitude.

Earth's orbit about the sun as his baseline. By making observations of objects in the sky from the extremes of the orbit, the astronomer can use the triangulation method to measure the distance of "rocks" out in space. Even with this seemingly gigantic baseline, this proves to be a very tough task. The baseline is 3×10^8 km long. Even the nearest star is 4×10^{13} km away. Thus, it is akin to measuring the distance of a rock 10 km off the coast using a baseline only 1 cm long!

Through the use of a very accurate technique called *parallax*, the distance to a few thousand of our nearest neighbor stars can be determined using Earth's orbit as a baseline. This method, however, is limited to a very, very small portion of our own galaxy.

The baseline was greatly extended by showing that our own sun is rushing through our galaxy at a rather large rate of speed—6×10^8 km/yr.

In this way an ever-growing baseline far longer than Earth's orbit affords has been established. It would be as if a surveyor were driving along a shore road in a truck, periodically taking sightings on a distant island. From the truck's velocity and the elapsed time, he could determine the length of his growing baseline. In a related but more complicated way (called *statistical parallax*), astronomers have been able to measure the distances of stars out to about 3×10^{15} km. Even so, all these stars reside in our own galaxy.

Finding the distance to galaxies beyond our own posed a problem so formidable that the trigonometric approach had to be abandoned. Nature, however, provided an alternative approach, which astronomers hit upon and exploited. Some of the stars in our galaxy show regular pulsations in their luminosity. Hence, they are more like lighthouses than headlights. These stars show a range of blinking rates. The important characteristic is that stars that blink at the same rate have the same luminosity. It's as if the Coast Guard decided to have all its lighthouses use "light bulb" strengths related to their turning time. For example, all lighthouses with 100,000-watt bulbs would turn once each minute; those with 200,000-watt bulbs would turn twice a minute, and so forth. The variation in intensity of these stars is large—almost a factor of 10, so they are quite easy to spot even in galaxies other than our own (Fig. 2-8).

The astronomers jumped on this relationship and reasoned that blinking stars visible in nearby galaxies probably followed the same rules: from the blinking rate the luminosity of the star could be estimated. By comparing that luminosity at the source with the intensity of light seen from Earth, the distance of the star, and hence of its hosting galaxy, could be determined. This "headlight" method is a quantitative version of how we intuitively judge the distance of an approaching car on a dark highway. As automobile headlights have similar luminosities, we judge the distance of an oncoming vehicle by the brightness of its headlights. The distances to the nearby galaxies could be estimated by the differences between the intensities of light received from these distant blinkers and the intensity of light received from one of its cousins in our own galaxy, whose distance had been determined by trigonometry. Knowing the distances of these nearby galaxies, the astronomer could then from trigonometry determine their diameters. A "map" showing the Milky Way and its neighboring galaxies and clouds of gas and dust is shown in Figure 2-9.

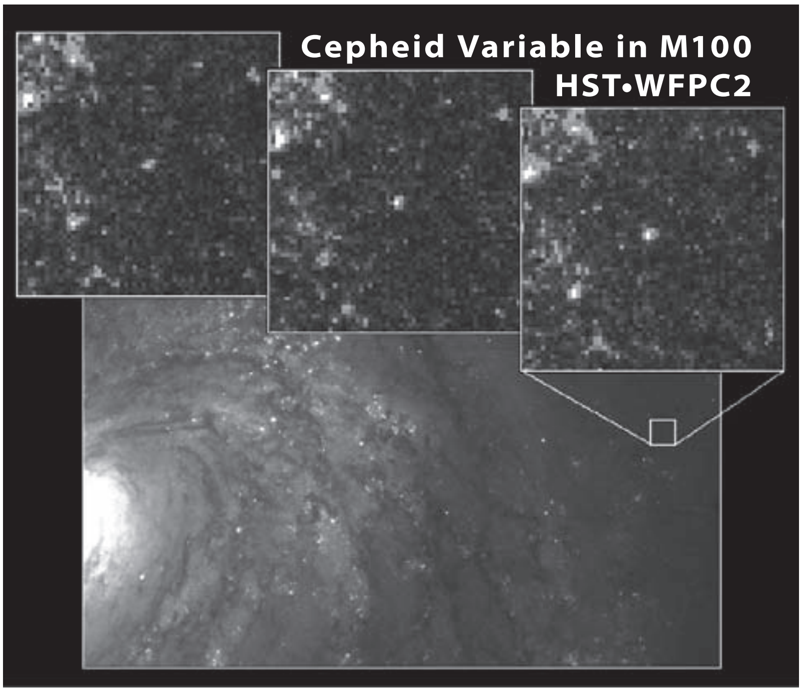


Fig. 2-8: Illustration of the change in magnitude (intensity of light) of a pulsating star in a nearby galaxy. The squares at the top are blowups at three different times of the small region in the galaxy identified by the small box in the lower image where one of these stars, centered in the boxes, can be identified. (Courtesy of NASA; http://apod.nasa.gov/apod/ap960110.html. Credit: NASA, HST, W. Freedman (CIW), R. Kennicutt (U. Arizona), J. Mould (NU))

Unfortunately, the galaxies that show significant red shifts are so far away that even our biggest telescopes cannot resolve individual stars, though much more distant galaxies have been able to be measured by this method using the Hubble telescope, which avoids the interference of Earth's atmosphere by residing in space. For the most distant galaxies, however, the whole galaxy appears only a bit larger than a nearby star. Thus, no individual pulsing stars can be identified and the lighthouse method is not applicable.

The last step out into space is then taken by using the size of the galaxy itself. More often than not, galaxies are found in clusters. Astronomers have carefully studied the sizes of the galaxies in nearby clusters. As with the sizes of people (and cars), they follow some simple rules. The assumption is made that the galaxies in very distant clusters have a similar spectrum of sizes and brightness as the ones in "nearby" clusters. For example, the distance of a car can be estimated not only from the brightness of its headlights but also how far apart they seem to us. While

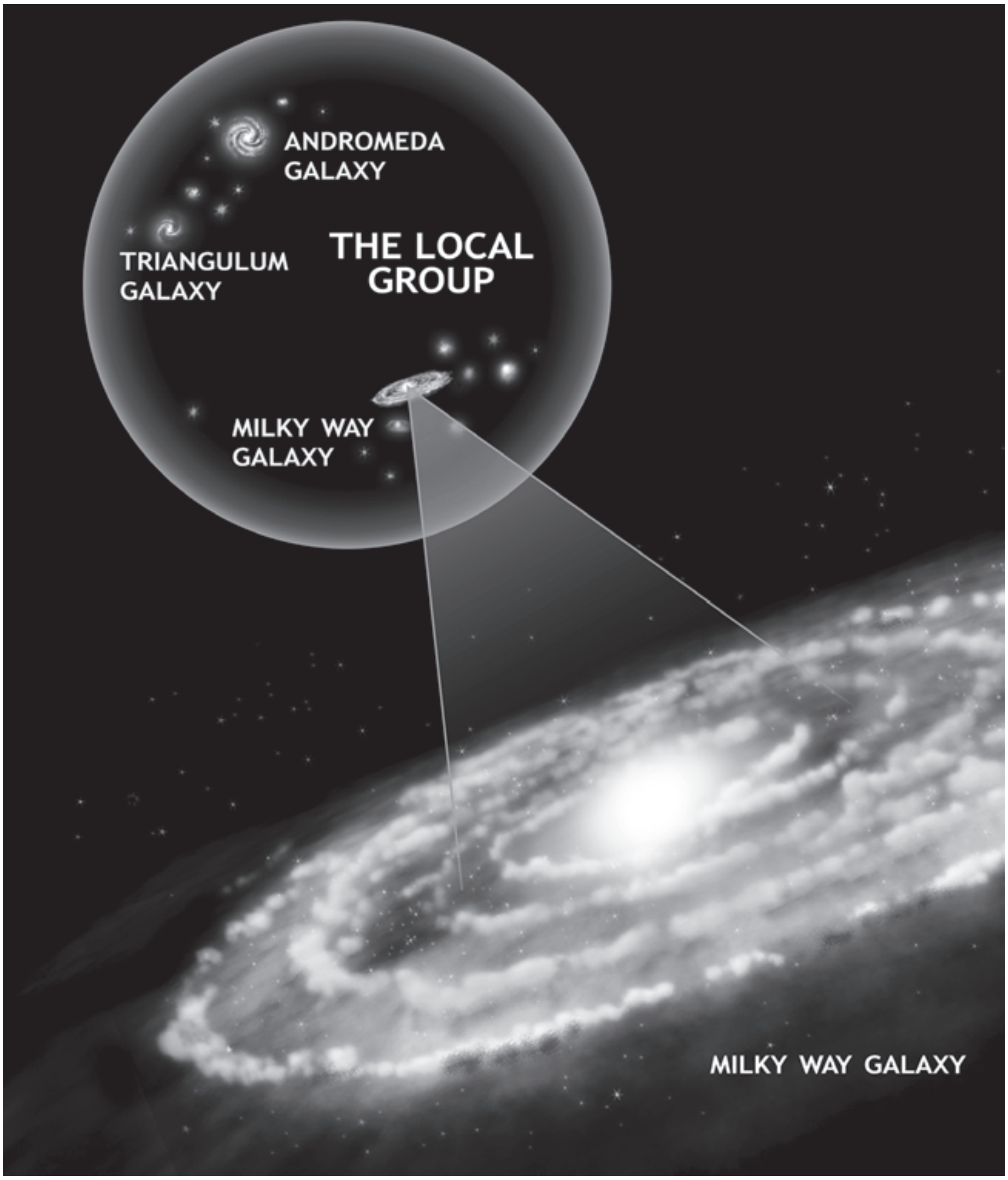


Fig. 2-9: Illustrative map showing the Milky Way and its nearest neighbor galaxies and clouds of gas and dust. The Andromeda Galaxy, with one trillion stars, is 2.5 million light years from the Milky Way. (Courtesy of NASA/CXC/M.Weiss; http://chandra.harvard.edu/resources/illustrations/milkyWay.html)

there is some variation, we will not be far off with this method. Like the automobile driver, the astronomer infers the distance of these clusters by the sizes of their individual galaxies.

Recently, astronomers have improved on this approach by observing a certain class of supernova explosions in distant galaxies. Such events occur in any given galaxy roughly once each century. Thus, each decade about one in every ten galaxies is lit by such a strong flash of light that it can be observed. These flashes are thought to be excellent headlights.

THE VELOCITY-DISTANCE RELATIONSHIP: DATING THE BEGINNING

Having determined both velocity and distance for galaxies throughout the universe, astronomers can then make a graph with the distance of the galactic cluster on one axis and the velocity at which it is receding from us on the other axis. As shown in Figure 2-10, when the observations for various galactic clusters are plotted on such a graph, the points form a linear array. A factor of 10 increase in distance is matched by very nearly a factor of 10 increase in recession velocity. What is the significance of this striking relationship?

The significance of the distance-vs.-red shift relationship is that it is what would be expected for galaxies that were once all together at the same time and place. Consider, for example, a birthday party where

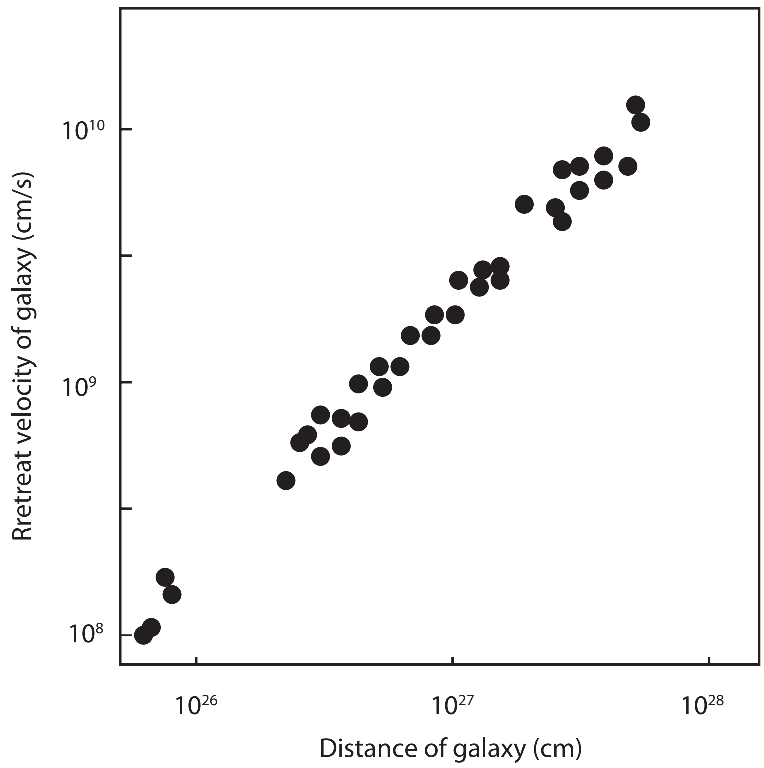


Fig. 2-10: Relationship between galactic distance and galactic recession velocity. Each point represents a distant galaxy (or cluster of different galaxies). Since the distances range over a factor of 100, a logarithmic rather than linear scale is used.

everyone leaves at exactly the same time. Some people walk home at 4 km/hr, others cycle at 10 km/hr, others drive at 50 km/hr, and one takes a helicopter at 500 km/hr. Imagine that they all travel for an hour in a straight line but heading off in different directions. After one hour, the walkers are 4 km away, the cyclists 10 km away and so on. Plotting the speed of their retreat vs. their distance from the party house would produce a straight line, and the slope of the line gives the time they left the party. It is also true that plotting the distance from any one of the groups would lead to the same result, so everyone who was at the party would produce a graph with the same slope, because they were all at the party and they all left together. The farther two groups are from one another, the faster they must be moving apart. The same thing happens in three-dimensional space. If we turn time around and move the various galaxies backward at the rates they are observed to be retreating, all come together at the same time! The actual date can be obtained from the distance (from our galaxy) and the rate of recession (from ours) of any distant galaxy.

So this simple diagram both shows us that all the galaxies were together at one point in time and gives us that time, which is the age of formation of the universe. Since one axis is cm and the other is cm/sec, the slope is time (or 1/time). The ratio of distance to recession velocity yields an age for the universe. The result is that the matter in the universe is flying outward on the wings of an explosion that occurred about 13.7 billion years ago.

In Figure 2-11 the evolution of the distance-velocity relationship is depicted. Were we to have lived only 5 billion years after the Big Bang, the line depicting the velocity-distance trend would have been about three times steeper than the one we obtain today. This is because the retreat velocity for any given galaxy remains nearly the same, while the galaxy's distance from us increases.

A natural question that arises from this reasoning is, Where is the center of the universe? A train analogy in Figure 2-12 shows why the velocity/distance relationship tells us nothing about this. Observers on night train A speeding along one track see a light mounted on top of train *B* speeding along another track. They also hear train B's whistle. They know this train left the central station at the same time their train did. From the strength of its light they determine the distance of train B.

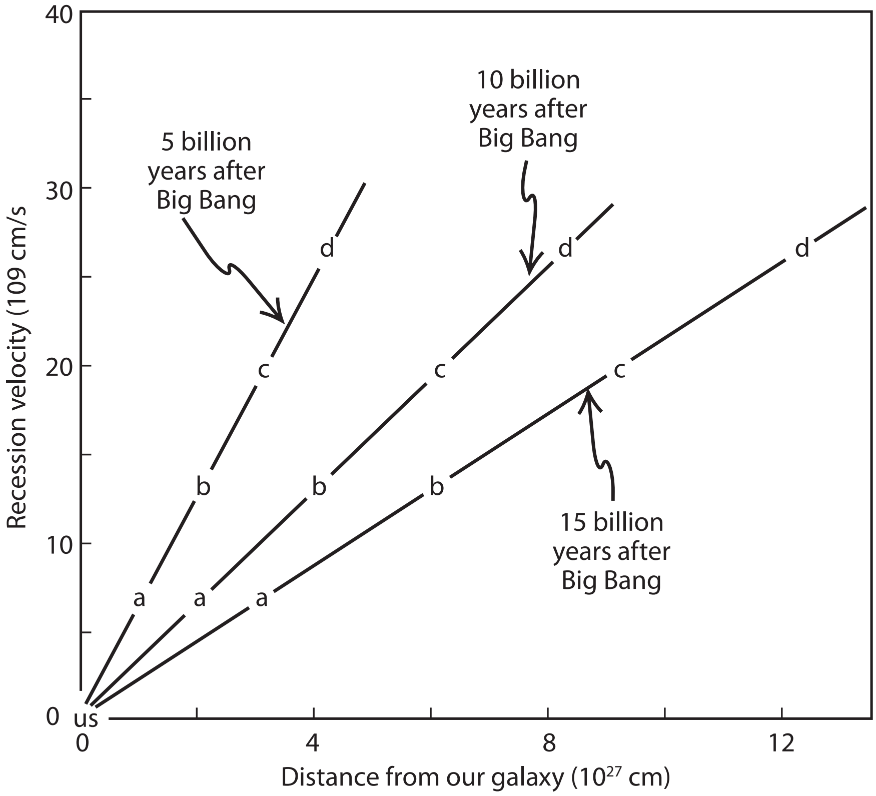


Fig. 2-11: Evolution of the distance-velocity relationship. Each of the four galaxies a, b, c, and d moves away from us at a different velocity. These velocities have remained nearly constant through time. However, as the universe becomes older, the distance separating these galaxies from us increases. Some 15 billion years after the explosion, they are three times as far away as they were 5 billion years after it.

From the pitch of its whistle they know that it is moving away from them and the exact speed of this recession. Knowing only this much, the observers could not determine where the central station is located. Neither can astronomers locate the center of the universe.

Added Support for the Big Bang Hypothesis

Additional support for the Big Bang was provided by the discovery that the universe has a nonvisible background glow. To understand this glow it is necessary to realize that all objects above absolute zero emit radiation that is diagnostic of their temperature (see Fig. 2-13 for a description of the various temperature scales). This radiation, called *blackbody radiation*, can be used to estimate the temperature of distant objects. The wavelength of emitted radiation decreases as the temperature increases.

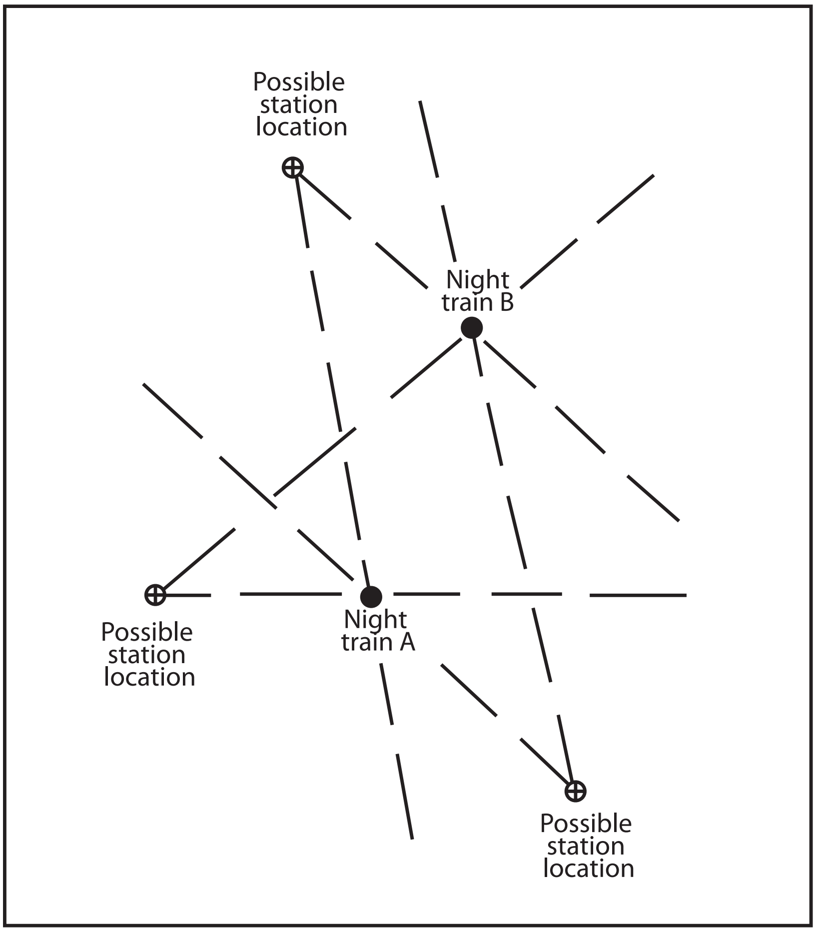


Fig. 2-12: The train analogy. Passengers on night train A sight the beacon of night train B, which left the central station at the same time they did. From its brightness they determine the distance between the two trains. They also hear the whistle. From its pitch they determine the speed at which the two trains are moving apart. However, unless they have some other information (e.g., the direction in which their train is going and the speed at which it moves along the track), there is no way for them to determine where the central station is located. Of the infinite number of possibilities, three are depicted here.

At very low temperatures, the radiation is not visible. But as the temperature gets above a few hundred degrees C, the wavelengths start to enter the visible range, and the object glows a dull red. At higher and higher temperatures the object turns orange, then white hot, and so on. It is not a single wavelength of radiation that is emitted, but a characteristic pattern that is completely diagnostic of the temperature of the object. This is apparent on the dark coils of an electric stove, for example. As the coils get hotter, the radiation emitted changes wavelength. At first the coils remain dark because the emission is in the infrared, where our eyes are not sensitive. Then they glow a dull red as some of the radiation

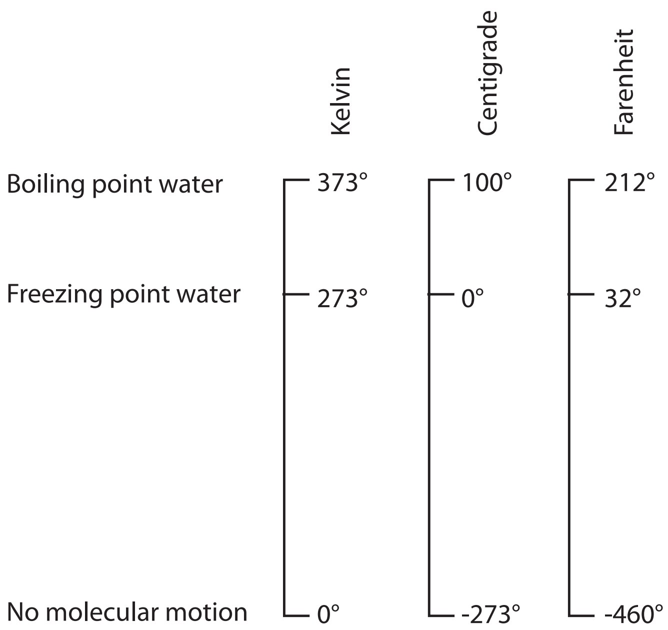


Fig. 2-13: Description of the three temperature scales. Absolute zero on the Kelvin scale is the temperature of no molecular motion. In everyday life in the United States used the Fahrenheit scale is used. The centigrade scale is used by most other countries in the world.

reaches the visible range. If they get too hot they are almost white, as many colors of the visible spectrum are emitted. Measuring the detailed pattern of radiation from a distance can tell us the temperature of the object. For example, Earth gives off radiation characteristic of its surface temperature of about 288°K. This radiation is centered in the infrared range. The sun gives off radiation characteristic of its surface temperature of 5700°K. This radiation is centered in the visible range.

That's the background. The surprising data was obtained by physicists Robert Wilson and Arno Penzias of the Bell Laboratory in New Jersey, who for other reasons were experimenting with an detector that was very sensitive to very long wavelength radiation—electromagnetic waves in the 0.1- to 100-cm range (i.e., microwaves) When they happened to turn their instrument toward the heavens, they found that although no visible light can be observed in the dark voids between stars and galaxies, there is a nonvisible glow. Looking at the detailed pattern of the radiation, they were able to show that this universal glow was the same as that emitted by an object whose temperature is 2.73° above absolute zero . After the Wilson and Penzias discovery, subsequent work, including very precise measurements from satellites, has demonstrated with

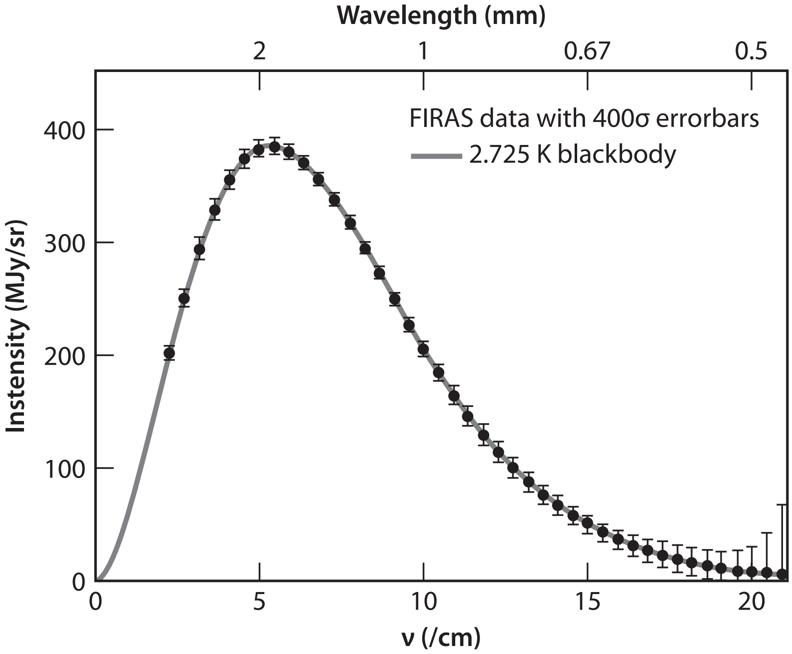


Fig. 2-14: The cosmic microwave background of the Universe determined by the far infrared absolute spectrophotomer on the COBE (Cosmic Background Explorer) satellite. The universe glows with radiation in the microwave range. By measuring the intensity of this glow at many wavelengths, it can be seen that the spectrum corresponds exactly with blackbody radiation from a material with a temperature of 2.725 + 0.002°K. The temperature corresponds extraordinarily well with the Big Bang theory. (Courtesy of NASA;http://lambda.gsfc.nasa.gov/product/cobe/firas_overview.cfm)

great precision that the relative intensities of the various wavelengths of radiation in this range are consistent with this very cold glow (fig. 2-14).

What is the source of the universal blackbody radiation? Shortly after the Big Bang, a great flash of light appeared when the protons and electrons in the expanding universe cloud cooled to the point where they could combine into neutral atoms. At that time the universe was only about 100,000 years old and the gas had a temperature of about 4,000°K. The reason why this light, which was given off from a gas at 4,000°K, appears now to have been given off by an object about 1,500 times cooler (that is, one with a temperature of 2.76°K) has to do with the expansion of the universe since that time. While the computation of the magnitude of this "cooling" is too complex to be described here, to the physicist it is exactly as expected. Hence, the discovery of the afterglow of the Big Bang is taken by physicists as a strong confirmation of the Big Bang hypothesis.

As we shall learn in the next chapter, universe matter right after the Big Bang consisted almost entirely only two elements, hydrogen (H) and helium (He). By careful modeling of the Big Bang, physicists have been able to calculate what the proportions of hydrogen and helium should have been from the atomic reactions that took place. The calculated proportion of 10:1 corresponds with the observed H/He ratio in the universe.

The combination of these different and independent lines of evidence—the velocity/distance relationship of galaxies, the background radiation of the universe, and the chemical composition of the universe all combine to support the Big Bang hypothesis of the universe's origin.

An Expanding Universe and Dark Energy

The universe has been expanding from the beginning, counterbalanced by an inevitable gravitational force. This led to the idea that gravity might be strong enough to gradually slow the expansion to zero, and then a grand contraction would occur, leading to a "big crunch" and even a possible oscillation of the universe. Could this be shown from observations? The launch of the Hubble Space Telescope in 1998 provided the necessary data, as well as the surprising and completely unexpected result—that the expansion has been accelerating. Theorists have striven to come up with possible explanations for this result, and the various ideas come under the name of *dark energy*. Dark energy is not a minor phenomenon; to explain the observations, it must make up some 70% of the universe! Furthermore, it has the opposite effect to what we perceive as matter and energy and exerts an expanding force on the universe that is able to overcome gravitational attraction.

A further problem is that all the visible matter in the universe is insufficient to account for the mass that is required to explain various cosmological observations. The remaining, invisible mass is referred to as *dark matter*. Dark matter is also not trivial, but makes up about six times as much mass as "normal" matter. Dark matter is not in stars, planets, or back holes. Physicists know what it isn't, but are not sure what it is!

All our discussion in the remainder of this book will be referring to what we call "normal" matter and energy. This world that we can see and discuss turns out to be only ~4% of the composition of the universe

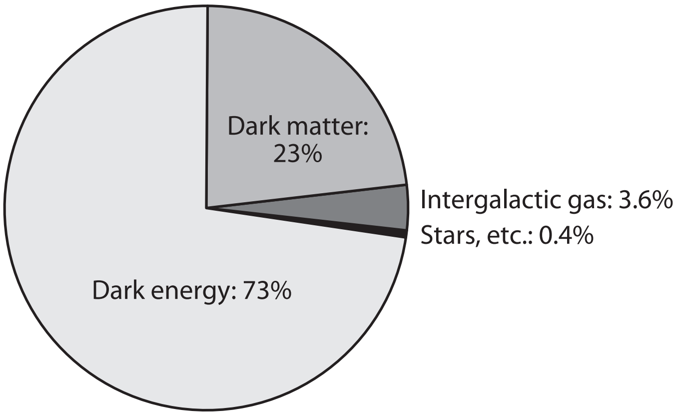


Fig. 2-15: Pie chart illustrating the composition of the universe. All the matter that we can directly observe and will be discussing in this book makes up only 4% of the universe.

(Fig. 2-15). As we continue with our discussion of what is known, and the questions about what is known, it is also useful to reflect on the fact that the unknown remains far greater than the known.

Aftermath of the Big Bang

About 100,000 years after the Big Bang, when the expanding matter had cooled to the point where the heretofore free electrons could become entrapped in orbits around the positively charged nuclei, helium and hydrogen gas formed. This gas was lighted only by the afterglow of the Big Bang. At this point the universe was a dull place indeed. No galaxies, no stars, no planets, and no life were to be found. There were only molecules of gas in a rapidly expanding cloud.

Then, for reasons as yet not entirely understood, the cloud began to break up into a myriad of clusters. Once formed, these clusters remained as stable units bound by their mutual gravitation. Each of these clusters in turn evolved into one or more galaxies. Within these galaxies the gas further subdivided to form many billions of brightly burning stars. The universe was no longer dark!

While these early stars are by now either dead or lost among their younger counterparts, we can be quite sure that they had no Earthlike planets. The reason is that Earthlike planets cannot be formed from hydrogen or helium. Elements not present in the young universe are required. Thus, the next step in our journey to habitability will be to see where and how the remaining ninety elements formed.

Summary

Human beings have always been interested in looking for knowledge and inspiration in the heavens. Natural curiosity and questions such as, "What is the spectrum of the sun and how does it compare to stars?" and "How far away are the stars?" led to unexpected discoveries. Distant galaxies have their element "bar code" of spectral lines shifted to the red, requiring that they be moving away from us at great rates of speed. Most surprisingly, the speed of retreat correlates with the distance, suggesting a common origin at the same time and place 13.7 billion years ago. This inference from direct observation obtained unexpected support from another observation based on curiosity, the answer to the question, "Does the universe emit any background radiation?" The blackbody radiation then turned out to be striking confirmation of the Big Bang. Subsequent understanding of nuclear physics led to another confirming prediction in the H/He ratio. All of these combine to make the Big Bang one of our fundamental pieces of knowledge of where we come from, and when it happened.

In the last decade, further observations from the Hubble Space Telescope show us that all the matter that we can observe makes up but a small fraction of the universe. Much remains to be discovered in our exploration of the universe.

Supplementary Readings

Frank Durham and Robert D. Purrington. 1983. *Frame of the Universe*. New York: Columbia University Press.

William J. Kaufman III. 1979. *Galaxies and Quasars*. New York: W. H. Freeman & Co.

Joseph Silk. 2001. *The Big Bang*, 3rd ed. New York: W. H. Freeman & Co.

Steven Weinberg. 1977. *The First Three Minutes*. New York: Bantam Books.

Richard Panek. 2011. *The 4 Percent Universe: Dark Matter, Dark Energy, and the Race to Discover the Rest of Reality.* Boston: Houghton Mifflin Harcourt.

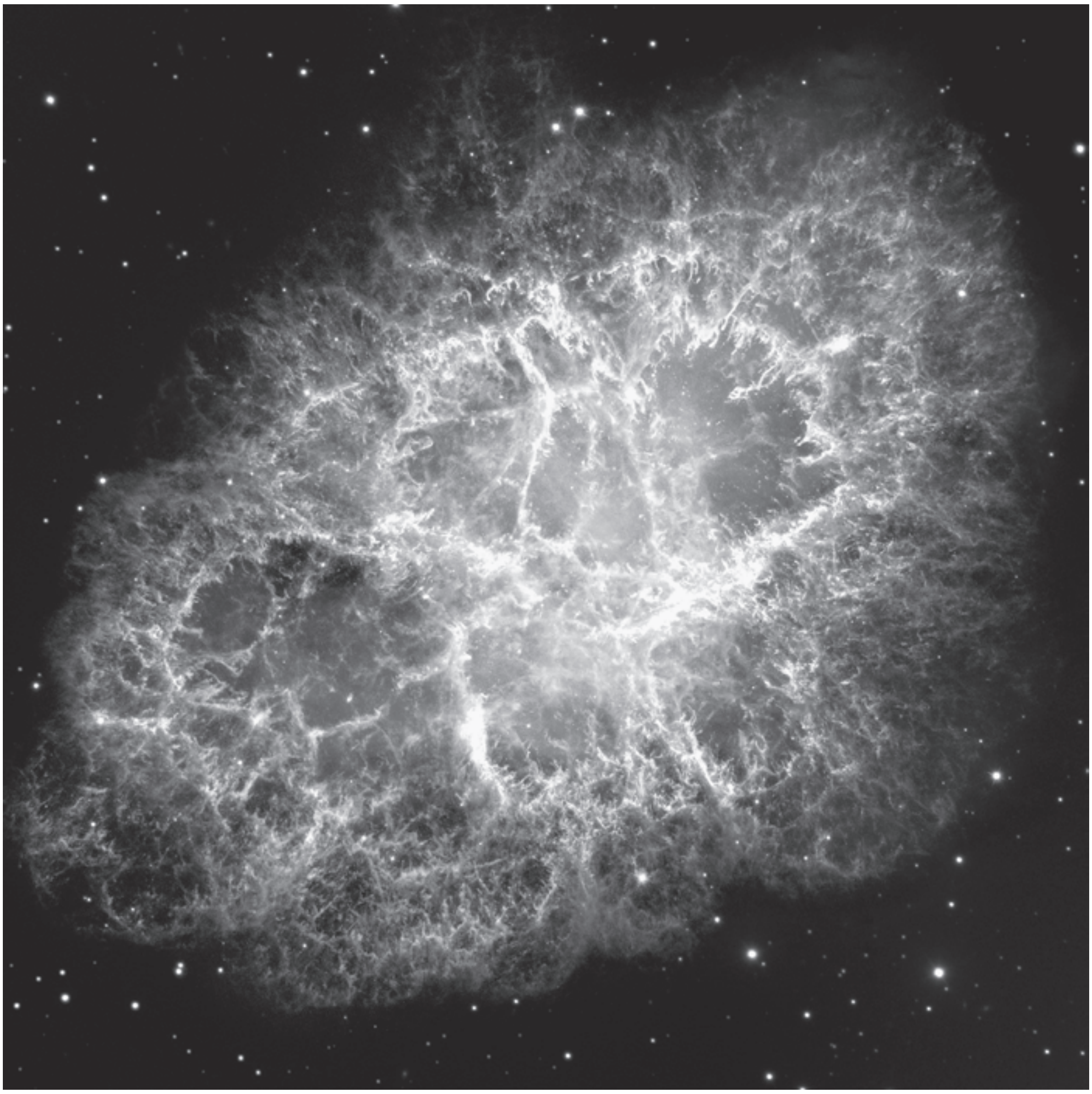


Fig. 3-0: The Crab Nebula, a supernova remnant in the constellation of Taurus, 6500 light years from Earth. The nebula is the expanding cloud that began with the supernova recorded by Chinese and Arab astronomers in 1054. The expansion rate is about 1500 km/sec, and the nebula is currently about 11 light years across. The size of our solar system out to the planet Neptune (~0.001 light years) would only be the size of a tiny spot on the image. The nebula was the first to be associated with a historical supernova explosion. (Courtesy of NASA, ESA, and Allison Loll/Jeff Hester (Arizona State University). Acknowledgment: Davide De Martin (ESA/Hubble))

CHAPTER 3

The Raw Material

Synthesis of Elements in Stars

During the explosive birth of our universe only two elements were formed in abundance: hydrogen and helium. Were this the end of the story, no planets and life could have appeared in the history of the universe. Our planet and the sun contain all the elements, so the other ninety elements in the periodic table must have been produced over the history of the universe. Stars are the universe's element production factories. Stellar interiors are so hot that atomic nuclei can interact and fuse together, emitting massive energy and making heavier elements in the process. Nuclear fusion, however, can occur only up to nuclei with 56 atomic particles, which is the element iron (Fe). Stars that reach this point then explode, creating heavier elements in the process and casting forth into neighboring regions of the galaxy a mixture of all ninety missing elements. The frequency of these awesome explosions in galaxies like our own Milky Way is about one per thirty years.

Evidence that supports this origin is imprinted in the relative abundances of the elements that make up our solar system. For example, the high relative abundance of iron is consistent with the fact that it is the ultimate product of the nuclear fires at the centers of stars. Element production in stars is also demonstrated by the existence of the spectral lines imposed by elements with very short radioactive half-lives. The radioactive decay of 78-day half-life cobalt (Co) with 56 nuclear particles (^{56}Co) dominates the light given off after a supernova explosion, demonstrating element production of heavy elements during such an event. The element technetium (Tc) is also found in stellar spectra. Since all the isotopes of Tc are radioactive with short half-lives, Tc can be present only in matter freshly produced by a nuclear furnace.

Because supernovae happen relatively frequently, the history of individual explosions can be monitored. Chinese astronomers observed a supernova in 1054. The debris cloud from this explosion continues to expand and is now known as the Crab Nebula (see frontispiece). Through the course of our galaxy's history, the formation and demise of about 100 million red giants has converted about 2% of the galaxy's hydrogen and helium into heavier elements. Contained in this 2% are the ingredients needed to build planets and form life. The processes of element creation are common to stars in all galaxies, and the raw material for planets and life is omnipresent in the universe.

Introduction

By cosmic standards, our Earth and its fellow terrestrial planets are chemical mavericks. They consist primarily of four elements: iron (Fe), magnesium (Mg), silicon (Si), and oxygen (O). By contrast, we look out on stars that are made up almost entirely of two different elements, hydrogen and helium. For the universe as a whole, all elements other than hydrogen and helium are small potatoes; taken together they account for only about 2% of all of the 4% of matter that is not dark matter or dark energy.

Despite their rarity, the elements other than H and He are prerequisites for habitability. A habitable planet must have a solid or liquid exterior and an abundance of the element carbon (C). Objects made primarily of hydrogen and helium gas offer no solid base. Hence, high on our agenda must be an understanding of how elements heavier than hydrogen and helium were formed and how these elements were separated from the bulk gas and forged into rocky planets. In this chapter we tackle the first of these problems.

The Chemical Composition of the Sun

All stars form from the gravitational collapse of clouds of gas. Since the lion's share of the matter in the collapsing clouds ends up in the star itself, the star's chemical composition must be representative of the parent cloud. If we could somehow determine the chemical composition of the sun, we could constrain the composition of the galactic matter from which the sun formed.

As noted in Chapter 2, our information about the composition of stars comes from the dark lines in its spectrum that result from absorption by chemical elements in the atmosphere of the sun through which the light passes. The extent to which the light corresponding to each line is muted in the rainbow is a measure of the abundance of that particular element in the sun's atmosphere. Fortunately for stars like our sun, except for hydrogen and helium, the atmosphere is thought to have a composition nearly identical to that of the star's interior.

The strength of the lines can then be converted into the relative abundance of elements in the sun's atmosphere. By "relative abundance" we mean the ratio of the number of atoms of a given element to the number of atoms of a reference element. By convention, astronomers use silicon as the reference element. The relative abundance of an element is stated as the number of atoms of that element for each 1 million atoms of silicon. These abundances are plotted versus element number on the graph in Figure 3-1. This graph has a logarithmic power of 10 scale. For example, helium atoms with a relative abundance lying between 10^9 and 10^{10} on this scale are 10 billion times more abundant than bismuth (Bi) atoms with a relative abundance lying between 10^{-1} and 10^0.

Other than the dominance of the abundances of hydrogen and helium over those of the other ninety elements, a prominent feature of the graph is the general decline in abundance with increasing element number. Superimposed on this decline are several obvious features. One is that the abundance of the element iron is 1,000 times higher than would be expected were the decline smooth. A second is that the elements lithium (Li), beryllium (Be), and boron (B) have abundances many orders of magnitude lower than would be expected were the decline smooth. A third is that the abundance curve has a saw-toothed appearance because elements with an odd number of protons are generally less abundant than their even-numbered neighbors. These characteristics of the abundance curve provide hot clues regarding the mode of origin of the elements heavier than hydrogen and helium.

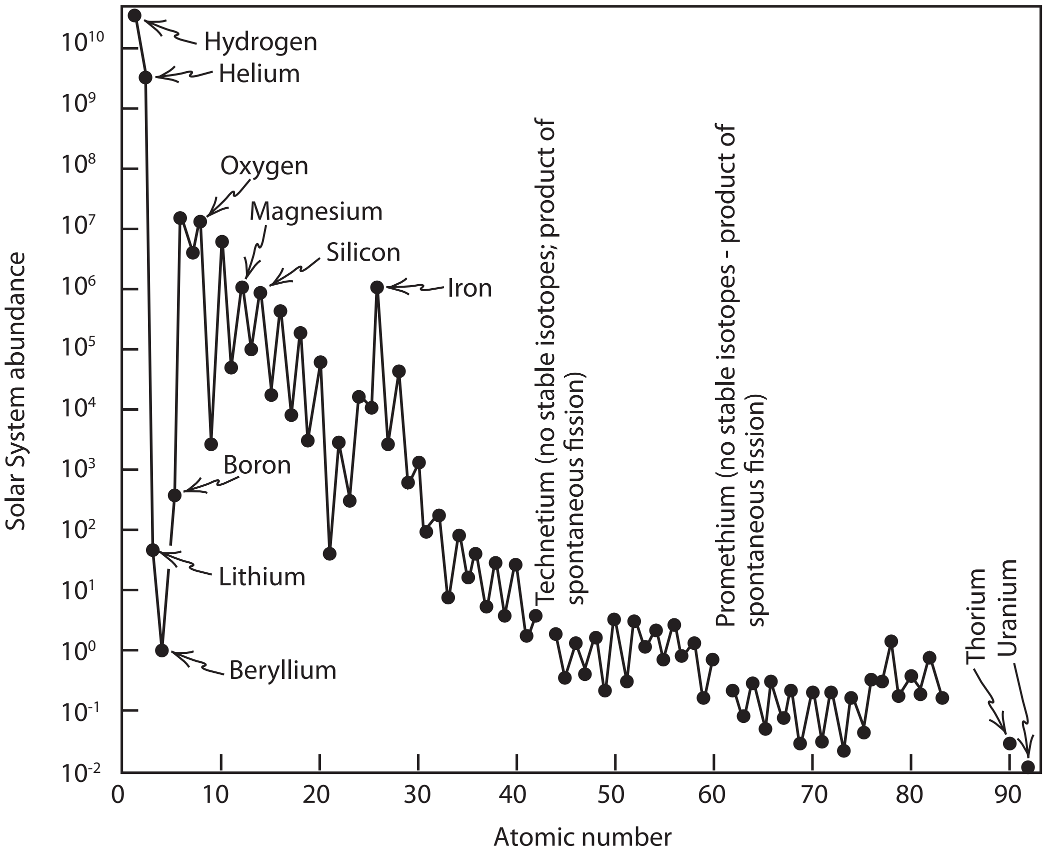


Fig. 3-1: Relative abundances of the elements in our sun: as the abundances range over 13 orders of magnitude, they must be displayed on a power of 10 (logarithmic) scale. The abundance of each element is expressed as the number of atoms per million (i.e., 10^6) atoms of the element silicon. The gaps in the sequence of technetium and promethium represent elements that have only radioactive isotopes and are, therefore, absent in a relatively low temperature star such as the sun.

Hydrogen, Helium, Galaxies, Stars

Physicists conjecture that at the instant of the Big Bang, all matter must have been contained in a very compact blob. The pressures and temperatures in this primordial blob were so high that stable combinations of neutrons and protons could not exist. Within seconds after the explosion, however, such combinations could and did form. At one time it was hypothesized that the blend of elements we see in our sun might have been generated entirely during the first hour of universe history. But subsequent work has shown that the only elements produced in significant amounts during this very early phase of universe evolution were hydrogen and helium. The others were produced billions of years later, inside giant stars.

The hydrogen and helium gas produced during the Big Bang eventually agglomerated into megaclouds. These megaclouds organized into the spiral and elliptical shapes we see in distant galaxies. Some of the gas in these newly formed galaxies in turn broke into far smaller subclouds that collapsed under their mutual gravitation into stars. So through their telescopes astronomers see a host of galaxies, each defined by billions of stars. Through careful observation, astronomers have been able to show that the process of star formation continues. They see new stars forming and old ones dying. By observing stars of all sizes and in all stages of their evolution, astronomers have been able to map out the history of these objects. Interwoven with this evolution is the conversion of hydrogen and helium to heavier elements. It is here, rather than in the Big Bang, that we must look for the production of the iron, magnesium, silicon, and oxygen of which Earth is largely comprised.

Again one might ask, How do scientists know that the elements heavier than helium were born in the centers of stars? As we shall see, a rather impressive case can be made. No jury could deny it. Like the Big Bang theory, the *stellar synthesis* theory of element origin gets a ranking of 9.9 out of a possible 10.

DESCRIPTIVE ATOMIC PHYSICS

In order to comprehend the case to be put forth in support of the stellar synthesis hypothesis, we need to consider some of the simple facts about the architecture of atomic nuclei.

Each atom has a compact nucleus made of neutrally charged neutrons and positively charged protons (e.g., see Fig. 1-1). This nucleus carries nearly all of the atom's mass and is incredibly small, only about 10^{-15} m in diameter. A fluff of negatively charged electrons fly in complicated orbits around the central nucleus and give the atom its size but add almost nothing to its mass. The diameter of this electron cloud is about 10^{-10} m (i.e., the atom is 100,000 times bigger than its nucleus). The electrons are held in captive orbits by the electrical attraction of the positively charged protons in the nucleus.

The power of the electrostatic force that keeps the protons and electrons together can be appreciated by comparing it to the power of gravity. A paper clip rests on a countertop because of the gravitational pull of the entire Earth. If a very small magnet is placed just above the paper clip, the paper clip jumps up to the magnet, because the electrostatic attraction of the little magnet is stronger than Earth's gravity. By measuring such forces accurately, physicists find that the electrostatic force is 10^{36} times stronger than gravity! The only reason that large objects like Earth do not exert a powerful electromagnetic force is because the negative and positive charges of atoms exactly cancel each other out, making gravity the potent force for very massive objects. For tiny objects like an atom, gravity has no power, and the electrostatic force is essential.

Just as opposite charges attract, charges that are the same repel—two similar poles of a magnet repel each other if we try to put them together. This repulsive force doubles for every factor of two decreases in distance. This feature of the atom prevents two positively charged nuclei from approaching one another during normal chemical interactions. The electrons manage because they occupy such a large volume and can avoid one another. Normal chemistry depends on attraction as well as repulsion.

So far so good, but a little reflection leads to quite a paradox. Given the power of the electrostatic force and its large increase with decreasing distance, how can the multiple positively charged protons in the nucleus stay together in such a small volume? The repulsive force must be enormous! Given the huge repulsive forces that exist in the nucleus, some much stronger force must exist to hold the protons together. This "strong force" is 138 times more powerful even than electromagnetism, but it operates only over very short distances. It is analogous to glue, a force that can operate only when two objects "touch" one another. Because of this property of the strong force, physicists gave the particle that carries the force the name *gluon*. So imagine, for example, two powerful magnets that repel one another, with superglue on their surfaces. As they get closer and closer they are repelled ever more strongly, but if we get the surfaces to touch, the superglue holds them together despite the electrostatic repulsion. The relative power of these forces in the universe is shown in Table 3-1. Gravity that is so important to us is so puny in comparison to other forces!

Table 3-1

The Four Fundamental Forces			
Name of force	Relative strength	Distances over which it operates	Where it is important
Strong force	1	10^{-15} m	In the atomic nucleus
Electromagnetic force	1/137	Infinite	Everywhere
Weak force	10^{-5}	10^{-17} m	Nuclear particles
Gravity	10^{-39}	Infinite	Well beyond the atomic scale, large masses needed

At low temperatures, the repulsive power of the nucleus keeps atoms separate, and interactions between atoms occur by the sharing of electrons to form chemical compounds. During such chemical reactions, only the character of electron orbits changes; the nucleus remains intact. These reactions occur at temperatures of tens to thousands of degrees centigrade. To make nuclear reactions occur, the nuclei need to get so close together that they "touch," allowing the strong force to exert its power. This can happen only if the nuclei have very high velocities. Velocity increases with temperature, so very high temperatures are necessary. To ignite the nuclear fires, temperatures of 50 million degrees or more must be achieved—no simple task for planetary beings. Only by accelerating charged particles in mighty cyclotrons or by setting off nuclear explosions can physicists create these high temperatures. This is why the alchemists dedicated to making gold from less valuable elements failed. They had no means by which to start a nuclear fire!

The places in the universe with natural furnaces with the temperatures required for nuclear fires are at the centers of stars. Every star must have such a fire at its core; otherwise, the star could not shine. Stars are the alchemists of the universe, where one element can be converted to another.

To understand which nuclides might be manufactured in stars, we must be aware that only certain combinations of neutrons and protons form stable units. The power of the repulsive force helps us to understand the important role of neutrons—they keep the protons separated from one another, reducing their electrostatic repulsion. Neutrons and protons also have a special relationship to one another, which is that they can be converted one to the other. Neutrons that are isolated are unstable, and they decay to a proton plus an electron (a hydrogen atom) with about half the neutrons decaying approximately every ten minutes. And given the right inducement, protons can convert to neutrons by capturing an electron—so the proton-neutron configuration of the nucleus is convertible in terms of the proportions of each. Neutrons are useful because they separate protons, but neutrons left to themselves decay. Protons are held together by gluons, but prefer to be separated. If the nucleus has too many neutrons, they decay to protons; if too many protons, they decay to neutrons. This balance causes stable nuclei to have roughly coequal amounts of both particles.

This balancing act in the nucleus leads to a *band of stability*, where there is no further preference for conversion of one nuclide to another. Figure 3-2 shows that out of all the possible neutron/proton combinations, relatively few are in this stable category. The rest are *radioactive*, and given enough time, will spontaneously transform into one of the stable combinations. The pathways for these transformations are shown in Figure 3-2.

There is one further aspect to stability of the nucleus. If the nucleus gets too large, there are so many protons that electrostatic repulsion becomes large enough for the nucleus to eject protons and neutrons. ^{209}Bi is the stable nuclide with the most neutrons and protons. All nuclei with more than 209 particles are radioactive. At first nuclear parcels, like a helium nucleus containing two protons and two neutrons, are ejected. For still heavier nuclei, the entire nucleus falls apart, in a process called *nuclear fission*.

Those nuclides which, left to themselves, will forever remain unchanged end up making planets and life. They form a *band of stability* that traverses the chart of the nuclides running from ^{1}H at one end to ^{209}Bi at the other. The course of this band represents the most favorable ratio of neutrons to protons. This ratio is near unity for the low proton number elements. Larger nuclei become more neutron rich, with the ratio of neutrons to protons reaching 1.5 for bismuth (Bi).

All nuclei outside the band of stability are radioactive and decay to the band. Nuclei that are too neutron rich convert neutrons to protons +electrons, called *beta decay.* Nuclei that are too proton rich capture

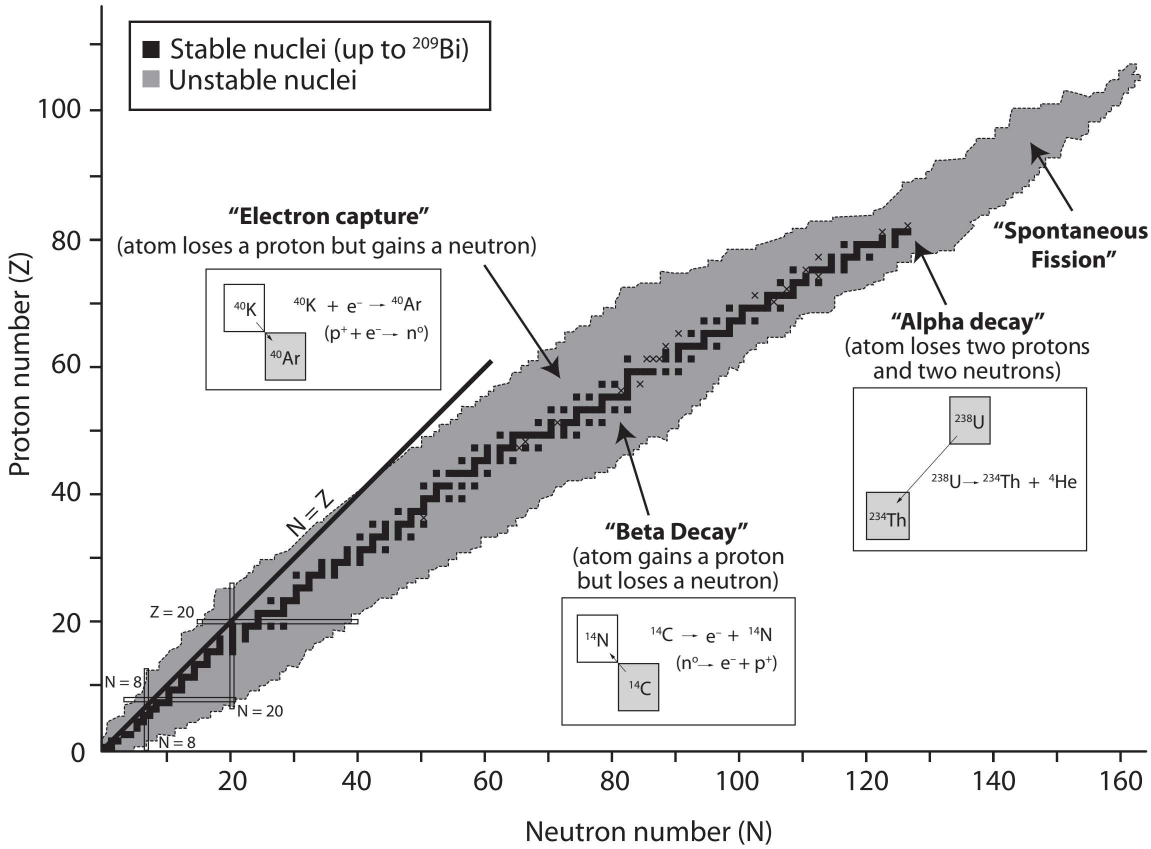


Fig. 3-2: The chart of the nuclides. Stable nuclides (the *band of stability*) are indicated by the solid black boxes. Radioactive nuclides that decay back to the band of stability with variable half-lives are indicated by the gray field. Very heavy isotopes decay by fission, where they spontaneously break up into pieces. Heavy masses decay by alpha decay, ejecting a helium atom of two protons and two neutrons. Neutron-rich isotopes decay by beta decay, converting a neutron to a proton without changing the number of nuclides in the nucleus. Proton-rich isotopes decay by electron capture, converting a proton plus electron to a neutron. The $N = Z$ line shows that at low masses the number of neutrons and protons is quite equal. Higher masses become neutron rich.

electrons to convert protons to neutrons in a process called *electron capture*. And nuclei that are too big eject a helium atom, called an *alpha particle* (because it was discovered first). Note that the first two processes do not change the number of nuclear particles in the nucleus, while *alpha decay* decreases the number of nuclear particles by four, two neutrons and two protons (Fig. 3-2).

All stable nuclides are found on Earth, in meteorites, and on other planets, so all must somehow have been produced from hydrogen and helium at the centers of stars. As we shall see, this buildup from small to large occurs in many steps. To produce a carbon atom requires only two

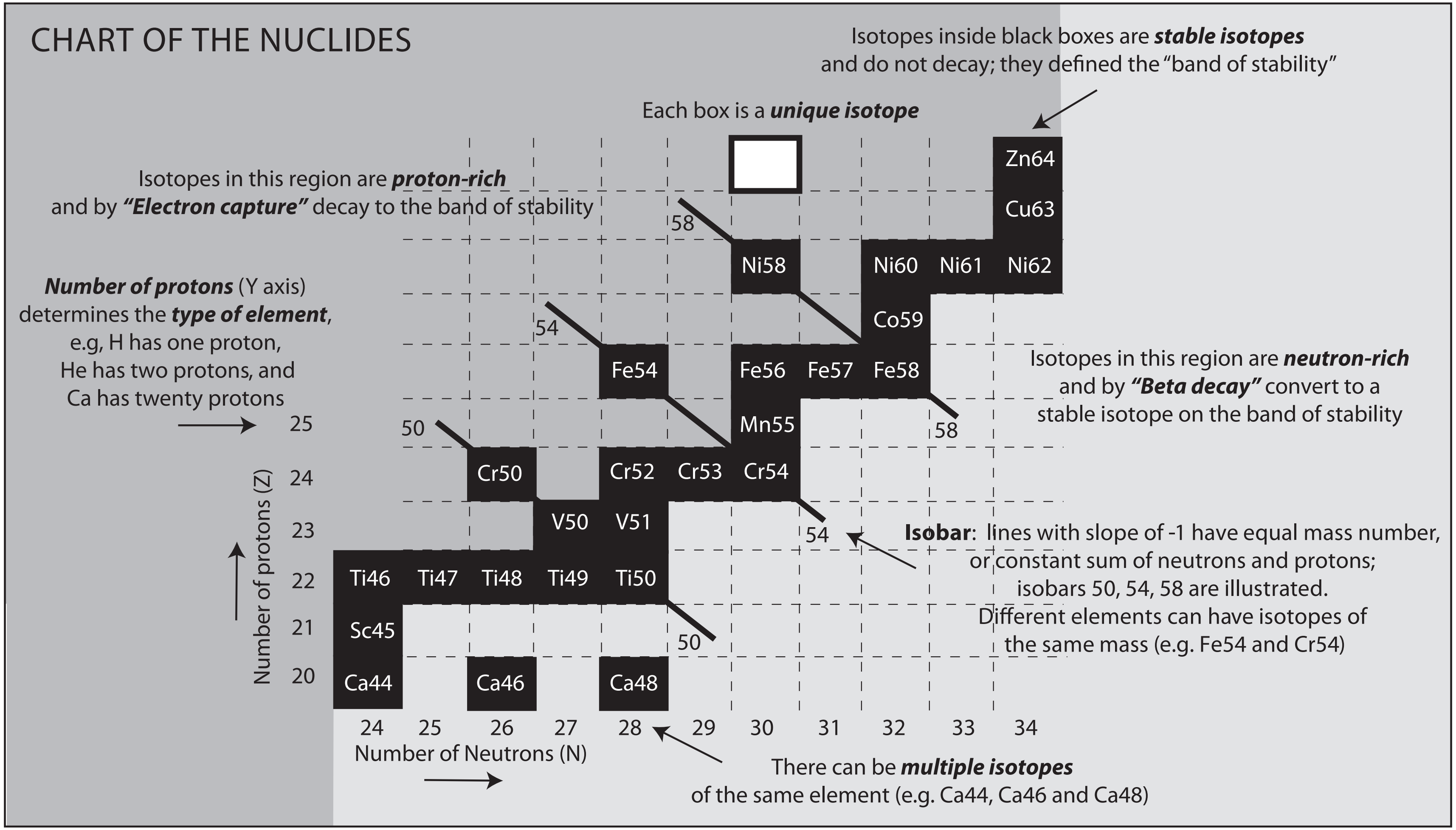


Fig. 3-3: A blowup of a portion of the chart of the nuclides illustrating similar principles as Fig. 3-2. Electron capture and beta decay occur along isobars. The number of protons determines the element identity. Elements with even numbers of protons have many more stable isotopes than those with odd numbers of protons, which usually have only one isotope. Note the very small number of stable isotopes that are "odd-odd."

steps; to produce an iron atom requires a few more steps; to produce a bismuth atom requires many more steps. It is because of this stepwise buildup that the "light" elements are produced in greater abundance than the "heavy" elements.

Element Production during the Big Bang

Let's examine what these steps are. In the fireball of the Big Bang, matter was largely in the form of neutrons. Once released from their dense confinement, neutrons underwent spontaneous radioactive decay to protons plus electrons, with half of the neutrons present decaying every 10.2 minutes—this time is referred to as the *half-life* of the decay. (For example, after three half-lives, one-eighth of the original atoms remain.) During those minutes of stability, many of the neutrons collided with a proton to make ^{2}H, an isotope of hydrogen consisting of one proton and one neutron called *deuterium*. Other collisions could lead to masses 3 and helium atoms of mass 4. At this point there is a remarkable aspect of nuclear stability, which is that no stable nucleus of mass 5 or mass 8 exists (Fig. 3-4). A helium nucleus colliding with the abundant protons or neutrons would produce no reaction. Or two helium atoms colliding would also produce nothing. Instead, only rare reactions could jump over mass 5 to produce masses 6, 7, or 8. For example, a proton and a neutron would have to have collided at the same time with a ^{4}He nucleus to produce ^{6}Li. As is the case on a pool table, in the expanding gas cloud "three-ball" collisions were far less frequent than "two-ball" collisions, so infrequent, in fact, that the number of nuclei formed that were heavier than ^{4}He was insignificant. Thus, at the end of Day One universe matter consisted almost entirely of the elements hydrogen and helium, with only very small amounts of the next three elements—lithium (Li), beryllium (Be), and boron (B). Further synthesis awaited the formation of galaxies and the formation of stars within these galaxies.

Physicists have made models of the collisions that would have occurred during the first day of universe history. They found that there would have been one helium atom for every ten hydrogen atoms.[1] This

[1] While there are 100 ^{4}He atoms for every 1,000 ^{1}H atoms, because the helium atoms are four times as massive, they account for $4 \times 100/1{,}400$, or 29% of the universe mass.

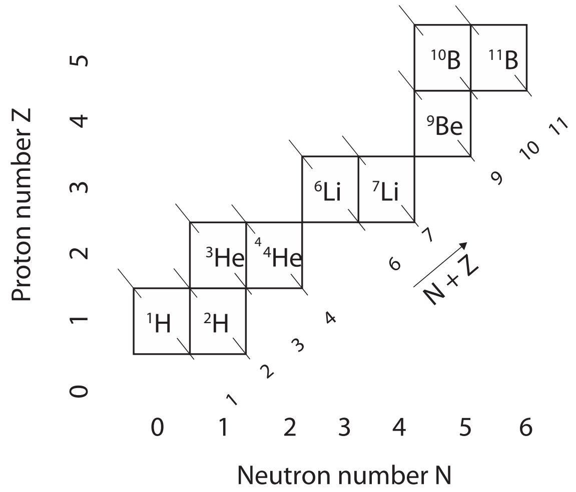


Fig. 3-4: The lower left-hand corner of the chart of the nuclides. Stable nuclides with a particle number in the 1 to 11 range. Note that no stable nuclide exists with a neutron plus proton number totaling 5 or 8. It is these two gaps in the chain that prevented element formation during the Big Bang from continuing beyond helium to any significant extent.

is about the fraction of helium seen in young stars from throughout the universe, which was the third line of evidence for the Big Bang hypothesis discussed in Chapter 2.

Element Formation in Stars

Stars are hot inside for the same reason that brake shoes on a stopping car are hot. When a moving vehicle is brought to a stop, the energy associated with its motion is converted to heat in its brake linings. During the collapse of a cloud of gas, gravitational energy is likewise converted to heat. The amount of heat produced is so vast, and the insulation provided by the enshrouding envelope of gas so effective, that the core of the protostar becomes hot enough to ignite a nuclear fire.

For the nuclei in a star to react, they must touch. To touch, they must fly at one another at such high velocities that they overcome the electrical repulsion exerted by one proton on another. It is much like trying to throw a Ping-Pong ball into a fan. A very high velocity is required to prevent the ball from being blown back in your face.

The hotter atoms are, the faster they move. Temperature is a scale for molecular motion. Touching a hot stove causes the molecules in the

Table 3-2
Conversion of mass to energy

Element	Element mass (g/mole)	Number of atoms	Total mass (g)	Mass loss	Calories of energy
H	1.008	4	4.032 g	0.029 gm	$0.26 \cdot 10^{-10}$ Joules
He	4.0026	1	4.002 g		
Si	28.0860	2	56.172 g	0.33 gm	$2.97 \cdot 10^{-10}$ Joules
Fe	55.8450	1	55.845 g		

skin of your finger to move so fast that the chemical bonds holding them in place are rent; we call this molecular damage a *burn*. For two protons to collide requires velocities equivalent to a temperature of about 60,000,000°C. Through a somewhat complicated series of collisions, four protons can combine to produce a helium nucleus (and two electrons). The helium nucleus contains two of the original protons and two neutrons. These neutrons come into being through the mergers of protons with electrons (for each proton in a star there must be one electron).

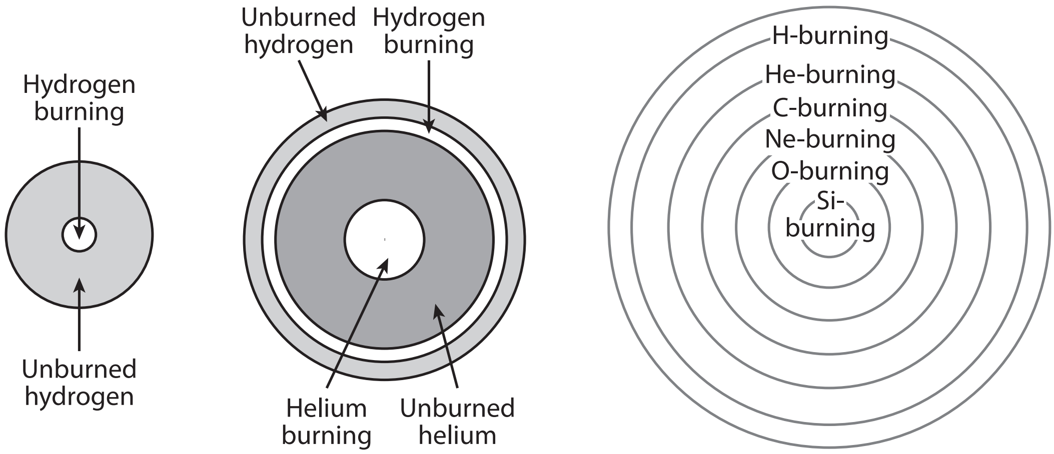
As first recognized by Einstein, for nuclear fusion to occur there must be a release of energy, and this energy release results in a reduction in mass. This lost mass reappears as heat. Indeed, the weight of a helium atom is just a little less than that of four hydrogen atoms (see Table 3-2), and this mass is converted to heat when the atom is manufactured in a star. As the proponents of fusion power are quick to point out, the amount of heat obtained in this way is phenomenal. So phenomenal, in fact, that once a protostar's nuclear fire is ignited, its collapse is stemmed by the pressure created by the escape of the heat generated. The star stabilizes in size and burns smoothly for a very long time. For example, our sun has burned for 4.6 billion years and won't run short of hydrogen fuel for several more billion years.

Most of the stars we see are emitting light created by the heat from a hydrogen-burning nuclear furnace. Thus, one might say that stars are continuing the job begun during the first day of universe history; they are slowly converting the remaining hydrogen in the universe to helium.

Our sun is small enough that hydrogen burning can take place for billions of years. Since helium nuclei have two protons, the force of electrical repulsion between them is four times the force of repulsion between two hydrogen nuclei. At the temperatures of hydrogen fusion, the velocities of the nuclei are insufficient to overcome this electrostatic repulsion. For this reason, fusion of helium atoms does not take place in small stars. Within the center of a large star, the gravitational attraction is larger, and to counter it the hydrogen fuel converts to helium relatively rapidly. So-called red giants run through their hydrogen supply in something like a million years. When the core of a red giant becomes depleted in hydrogen, the nuclear fire dims and the star loses its ability to resist the inward pull of gravity. It once again begins to collapse. The energy released by the renewed collapse causes the core temperature to rise and the pressure to increase. The higher temperatures reach the ignition temperature required for helium fusion. Then helium nuclei begin to combine to form carbon nuclei (three ^{4}He nuclei merge to form one ^{12}C nucleus). The mass of the carbon atom is less than that of the three helium atoms from which it was formed. This lost mass appears as heat. The heat from the rekindled nuclear fire stems the star's collapse, and its size once again stabilizes.

In large stars this cycle of fuel depletion, renewed collapse, core temperature rise, and ignition of a less flammable nuclear fuel is repeated several times (Fig. 3-5). A carbon nucleus can fuse with a helium nucleus to form oxygen, or two carbons can merge to form magnesium nuclei, and so forth. Each merger leads to a small loss of mass and to the corresponding production of heat. This entire process can continue as long as fusion to produce heavier nuclei produces a loss of mass and production of heat. The extra heat is needed to prevent the star from collapsing and to keep it in a stable state where expansion from heat production balances contraction from gravitational attraction.

The maximum mass that can be created by this process is isotope 56 of Fe (^{56}Fe). Above this mass, merger of nuclei does not lead to loss of mass, and instead heat must be added to nuclei if they are to merge. That is, since mass and energy are related by $E = MC^2$, the mass of nuclei heavier than iron proves to be slightly larger than the mass of the nuclei that are merged to form them. These reactions are heat sinks rather than heat sources, and therefore cannot stem the gravitational collapse of the star. For this reason, the nuclear furnaces of stars can produce only elements ranging from helium through iron. It should be noted that in-



Name of process	Fuel	Products	Temperature
Hydrogen-burning	H	He	60×10^6 °K
Helium-burning	He	C, O	200×10^6 °K
Carbon-burning	C	O, Ne, Na, Mg	800×10^6 °K
Neon-burning	Ne	O, Mg	1500×10^6 °K
Oxygen-burning	O	Mg to S	2000×10^6 °K
Silicon-burning	Mg to S	Elements near Fe	3000×10^6 °K

Fig. 3-5: Three stars with progressively hotter nuclear fires. Like our sun, the star at the left burns hydrogen to form helium in its core; this core is surrounded by unburned fuel. The middle star is burning helium to form carbon and oxygen in its core. This core is surrounded by a layer of unburned helium. Outside of this is a layer in which hydrogen burns to produce helium. Finally, there is an outer layer of unburned hydrogen. The star on the right has a multilayered fire all the way up to Si-burning to create ^{56}Fe. The approximate temperatures required to ignite the successive fuels are also given.

cluded in this range are the elements carbon, nitrogen, oxygen, magnesium, and silicon.

We are then left with two problems. First, there are many elements more massive than ^{56}Fe. How can these be produced? And second, making elements in stellar interiors is not much use for planet building if the elements remain trapped inside. There must be some distribution mechanism that allows these elements to become broadly dispersed throughout the universe. We know this must be the case not only because of the compositions of the planets but also the composition of the sun itself. The materials from which the sun formed must have included all the elements, because the solar spectrum shows that all of these elements exist in the sun itself. It is not made up only of H and He.

Before discussing the solution to these two problems, let us briefly consider the fate of smaller stars like our sun. When the core of our sun runs out of hydrogen, several billion years from now, it will resume its collapse. However, our sun is just barely massive enough to generate the temperature necessary to start a helium fire. Then, after it has burned its core helium, it will collapse into a very dense object that will cool slowly until it gives off only a dull glow. A star to which this has happened is referred to as a *white dwarf*.

Element Synthesis by Neutron Capture

The solution to the two problems of heavy element creation and element distribution is solved thanks to the numbers of very massive stars that exist. These massive stars are ten to twenty-five times the mass of the sun and have such a large gravitational attraction that very high temperatures are required to prevent their collapse. They rapidly progress to the multilayered structure shown in Figure 3-5. Once Fe forms in their core, however, no further heat production is possible through fusion, and there is nothing to prevent their further collapse. The ensuing collapse is catastrophic, bringing the iron nuclei so close together that their nuclear shells begin to interpenetrate. The resistance for further compression generates a shock wave that pushes its exterior outwards. The result is like throwing gasoline onto a hot fire. An incredible explosion occurs, tearing the star asunder. Much of the interior material is blown free of the star's gravity into the galactic surroundings (see Figure 3-0). Astronomers call these explosions *type II supernovae*. A second kind of supernova (called *type I*) evolves when a white dwarf accretes material from its companion stars. When its mass reaches a certain limit, ^{12}C and ^{16}O fuse to form ^{56}Fe, leading to a gigantic nuclear explosion.

Nuclear reactions occurring during these explosions create elements heavier than iron. To understand these reactions we must consider the one nuclear reaction that can occur at "room temperature." It is called *neutron capture*. Because the neutron has no charge, it is not repelled by any nucleus it happens to encounter; it can freely enter any nucleus, regardless of how slowly it is moving. This ability of the neutron to react with nuclides under "room temperature" conditions lies at the heart of the principle of nuclear power generation.

During the explosion that marks the death of a massive star, a host of nuclear reactions occur that release free neutrons. In the close-packed conditions inside the exploding star, the neutrons encounter a nucleus long before they get around to undergoing spontaneous decay to a proton plus an electron. Many of these encounters will be with Fe nuclei. The Fe nucleus absorbs the neutron and becomes heavier. In the supernova explosion, these neutron hits will be like bullets from a machine gun. No sooner is an Fe atom hit by one neutron than it is hit by another. The Fe nucleus gets heavier and heavier until finally it cannot absorb any more neutrons. This very brief pause in growth ends when one of the extra neutrons that have been plastered on undergoes beta decay by emitting an electron. Each neutron that decays becomes a proton and increases the atomic number by one, while maintaining the same total number of nuclear particles in the nucleus. The decay of one neutron converts the Fe nucleus to cobalt (Co). This is the first step along the chain of production of the heavy elements. The Co nucleus can in its turn absorb neutrons one after another, until it too becomes saturated. It then emits an electron and in so doing becomes a nickel (Ni) nucleus. These would be the first steps along the road from iron to uranium.

This sequence is repeated over and over again, driving matter along the neutron saturation route (Figs. 3-6 and 3-7). Because of the rapidity of the impacts, radioactivity proves to be no barrier to this buildup. The buildup zooms past bismuth and even past uranium (U) and thorium (Th), stopping only when the nuclei get so big that the neutron impacts cause them to fission. The fragments produced by a fission event are caught up in the bombardment and begin once again to move along the saturation route. The process of such rapid addition of neutrons that there is no time for decay has led to the name *r-process* (*r* for "rapid") for this mode of heavy element creation that occurs during supernova explosions.

Since we are dealing with an explosion, this bombardment is as brief as it is intense. The flux of free neutrons stops suddenly, and no more neutrons are available to be added to nuclei. All the nuclei that have been generated, however, are very neutron rich and far from the band of stability. These neutron-rich isotopes convert one neutron after another to proton plus electron until they have achieved a stable neutron-to-proton ratio (Fig. 3-7). Those nuclides heavier than bismuth emit alpha particles (He nuclei) as well as electrons, moving toward stability as isotopes of the element lead (Pb). While for most nuclides this adjustment process is quickly completed, for a few nuclides with long radio decay

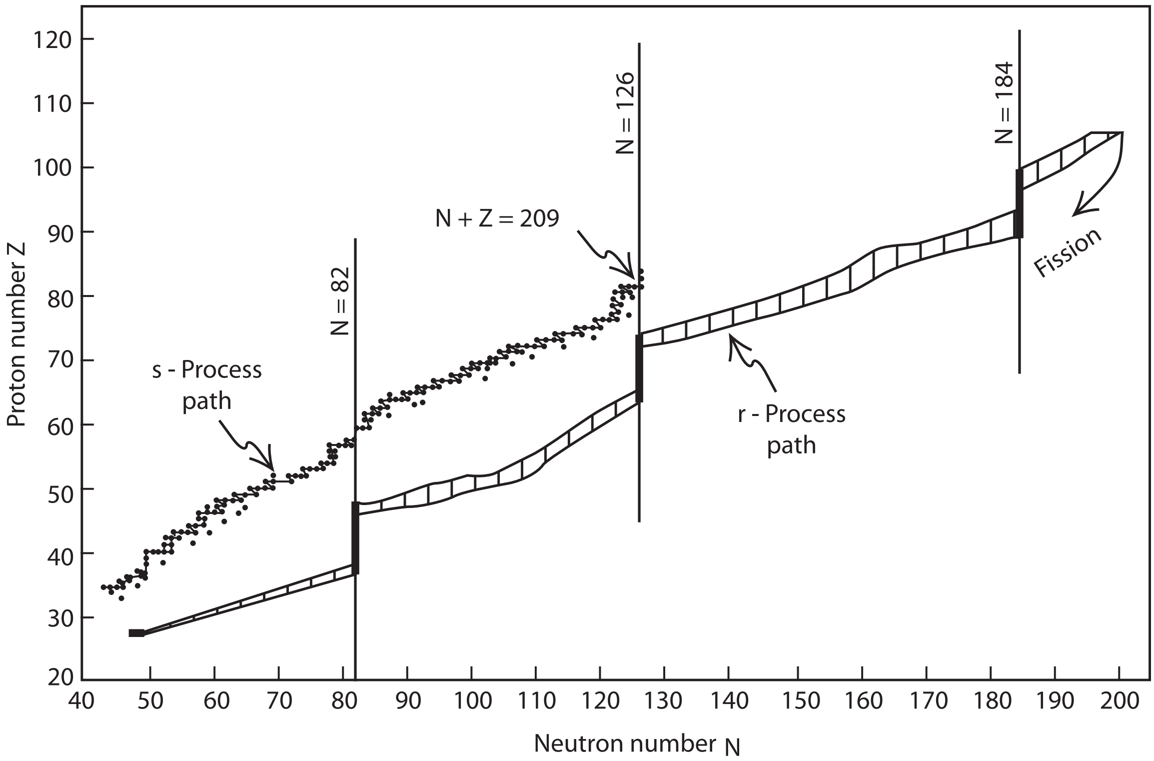


Fig. 3-6: The elements heavier than iron were built by neutron irradiation. Two quite different processes contributed to this production. One, the s-process, proceeds in a controlled way. Neutron hits are spaced out in such a way that the nuclides have time to achieve stability through beta decay. Thus, the buildup path follows the belt of stability shown in Fig. 3-2. For the same reason it terminates at ^{209}Bi, the heaviest stable nuclide. The r-process (rapid process) occurs during the supernova explosion. No sooner has a nuclide absorbed one neutron than it is hit by another. No time exists between hits for radio decay. Instead, radio decay occurs only when the nuclide becomes so neutron rich that it cannot absorb any more, as indicated by the vertically hachured band in the figure.

half-lives, the adjustment process still goes on today. As we shall see, the radioactivity of these remaining long-lived isotopes plays a very important role in the evolution of planetary interiors and will provide us with timescales for planetary processes.

It turns out that the rapid events during supernova explosions are not the only time that free neutrons that can be added to nuclei are produced. As part of the steady nuclear burn that characterizes most of a star's history, side reactions occur that release neutrons. These neutrons also can build lighter elements into heavier elements, but they do it very slowly, one neutron after another, during the relatively long process of stellar evolution. Because the neutron addition is slow, it is called the

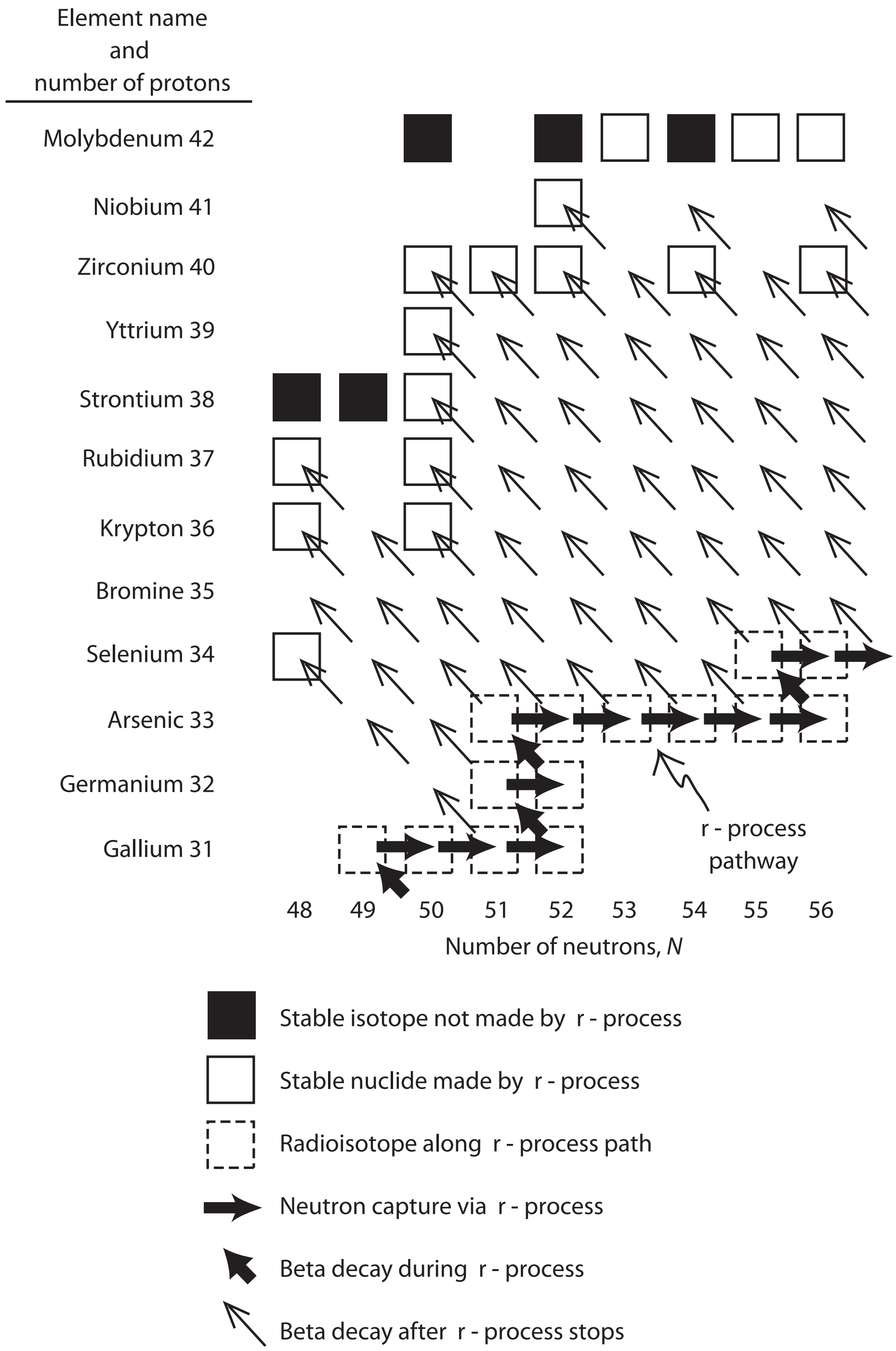


Fig. 3-7: A segment of the r-process pathway. Rapidfire neutron bombardment adds neutrons until a nuclide cannot hold any more. Only then does the nuclide undergo beta decay to become the next heavier element. This process—neutron capture to saturation followed by beta decay—is repeated over and over again, producing successively heavier elements. The r-process buildup occurs during the explosion that destroys the red giant. Hence it ends abruptly. The neutron flux stops and the highly radioactive isotopes on the r-process pathway emit beta particles one after another until stability is achieved. Note that in the case of those isobars for which two stable nuclides exist, only the neutron-rich nuclide of the pair is produced by the r-process.

s-process (*s* for "slow"). For the r-process, the frequency of neutron hits is extraordinarily high—so high, in fact, that even those nuclides with extremely short half-lives do not have a chance to undergo radio decay before being hit again with a neutron. In contrast, the neutron bombardment associated with the steady nuclear fires of stellar cores is far more leisurely. Adequate time exists between hits for all but the radioisotopes with the longest half-lives to undergo radio decay (Fig. 3-8). The s-process produces most of the stable nuclides not produced by the r-process.

The s- and r-processes combined create much of the complexity of the band of stability. As can be seen in Figures 3-2 and 3-7, there are generally two stable nuclides on each even-numbered isobar (as opposed to only one on each odd-numbered isobar). Of these two, the r-process produces only the stable nuclide with the most neutrons (Fig. 3-7). Some isotopes can be produced by both r- and s-process. Those which are neutron rich and separated from other isotopes are r-process only. Those isotopes which are shielded by a stable nucleus that is richer in neutrons along the same isobar are s-process only.

Careful inspection of the chart of the nuclides shows that there are a few nuclides that are produced by neither the r- nor the s-process. For example, in Figure 3-8, ^{58}Ni, with 28 protons and 30 neutrons, is not intersected by either the r-process or s-process path. These isotopes are found in much lower abundance than their r- and s-process neighbors. They can be produced by the *p-process* of proton addition, or by disintegration of heavier nuclei made by the r- and s-processes.

To sum up, we have seen that a diversity of processes have combined to form all the elements. The governing diagram is the chart of the nuclides, with the band of stability revealing what nuclei can survive without decay. The Big Bang makes the raw material of H and He, with small amounts of Li, Be, and B. Fusion of nuclei in stellar interiors makes more He, and the elements from C to Fe. The larger the star, the shorter the lifetime and the heavier the elements that are formed, up to Fe. Within these stellar interiors, the s-process can create some heavier elements. For the most massive stars, collapse and explosion occur, leading to the r-process, formation of all the heavy elements from Fe to U, and distribution of the elements into space where they become available for stars of subsequent generations and the planets that surround them.

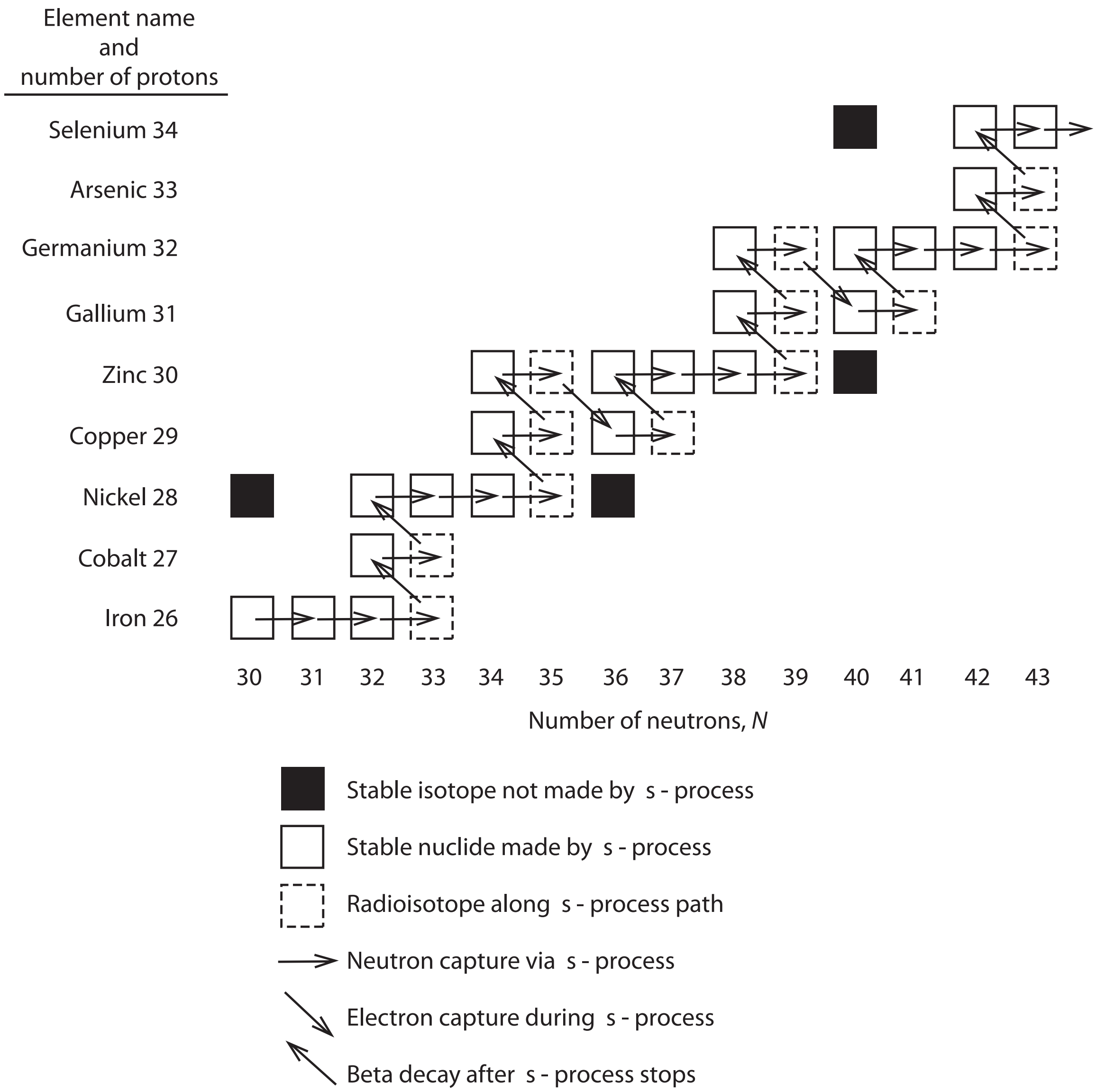


Fig. 3-8: Details of the s-process path. Each time neutron capture produces an unstable, radioactive isotope, decay occurs changing either a neutron into a proton or a proton into a neutron. Not all of the stable isotopes found in solar system matter can be produced in this way. Those stable isotopes lying below the path are produced by the r-process. Those stable isotopes lying above the path are produced by proton bombardment.

Evidence Supporting the Stellar Hypothesis

Shall we accept the progressively intensifying nuclear fires and catastrophic explosions proposed by astrophysicists to explain the synthesis of the ninety elements heavier than helium? Can this scenario be defended with hard evidence, or might it be merely a cosmic fairy tale?

Clearly, no one has ever sent a probe into the core of a star, so we have no direct evidence regarding these phenomena. There are six indirect lines of evidence, however, that are compelling. First, the only conceivable source of energy that could keep stars burning and so hot is nuclear. The pressures and temperatures of the cores of very large stars are adequate to permit not only hydrogen to burn but also helium and even heavier elements. Second, explosions of large stars have been observed (Fig. 3-9).

A third line of evidence comes from the element technetium (Tc), which is not present in Earth because this element has no stable isotopes. Nor are its dark lines present in the spectra of the light reaching us from our sun or from distant stars. The reason is that all these objects are old enough that any technetium produced in stellar interiors has long decayed away. However, the dark lines characteristic of the element do appear in the spectra associated with supernovae explosions. Technetium has two isotopes with moderately long half-lives: ^{97}Tc (2.6×10^6 years) and ^{98}Tc (4.2×10^6 years). These isotopes persist for millions of years after their production. They would have completely disappeared, however, during the 4.5×10^9 years that have elapsed since our solar system formed. The presence of the dark lines of technetium in the atmospheres of a class of objects referred to as *AGB stars* provides powerful support for the hypothesis that elements are being formed in stars.

A fourth line of evidence comes from gamma rays emitted by ^{56}Co formed from ^{56}Fe during the r-process onslaught during a supernova. These gamma rays light up the nebula created by the explosion. We know this because the nebular glow decreases exponentially following the 78-day half-life of ^{56}Co!

A fifth line of evidence comes from the relative abundances of the elements. Using experiments carried out in particle accelerators, astrophysicists have accumulated substantial data on the stability of nuclei and the forces that hold nuclear particles together. Elaborate calculations have been carried out to determine what the proportions of elements and isotopes should be if elements were produced in massive stars. These calculations reproduce very nicely the important features of the element-abundance curve.

Finally, nuclear physicists are able to produce many of the same reactions postulated for stellar interiors in particle accelerators, and of course in the hydrogen bombs, where the conversion of hydrogen to

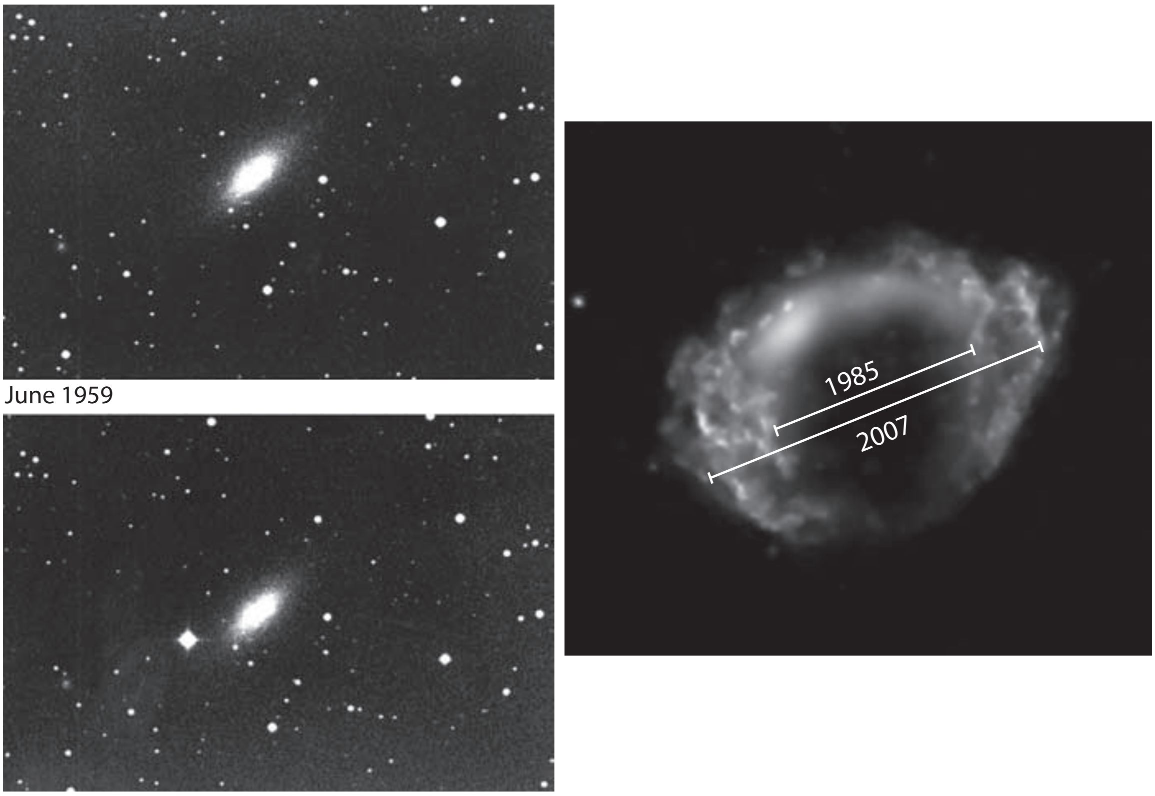


Fig. 3-9: Evidence for supernova explosions. Photographs taken before (*top left*) and after (*bottom left*) a supernova explosion. Panel on the right shows a closeup of a supernova in 1985 and 2007, revealing the rapid expansion of the cloud. (Photos on left courtesy of Hale Observatories. Right panel courtesy of NASA; http://science.nasa.gov/science-news/science-at-nasa/2008/14may_galactichunt)

helium on even a small scale has very powerful effects. The detailed reactions proposed to occur during stellar nucleosynthesis are largely susceptible to experimental confirmation.

All of these lines of evidence make nucleosynthesis in stars one of the established facts of nature, meriting a 10 on our theory scale.

The characteristics of the abundance curve are also central to the future habitability of planets, because planetary processes must be based on the elements that are abundant. For these reasons it is useful for us to examine the abundance curve in more detail.

In Figure 3-10 the nuclide abundances are plotted as a function of the number of nuclear particles. While there is great richness and complexity in the details of the element abundances, here we point out a few that are very important and easily grasped. One is the peak associated with iron (at particle number 56 in Fig. 3-10). If the stars that explode have

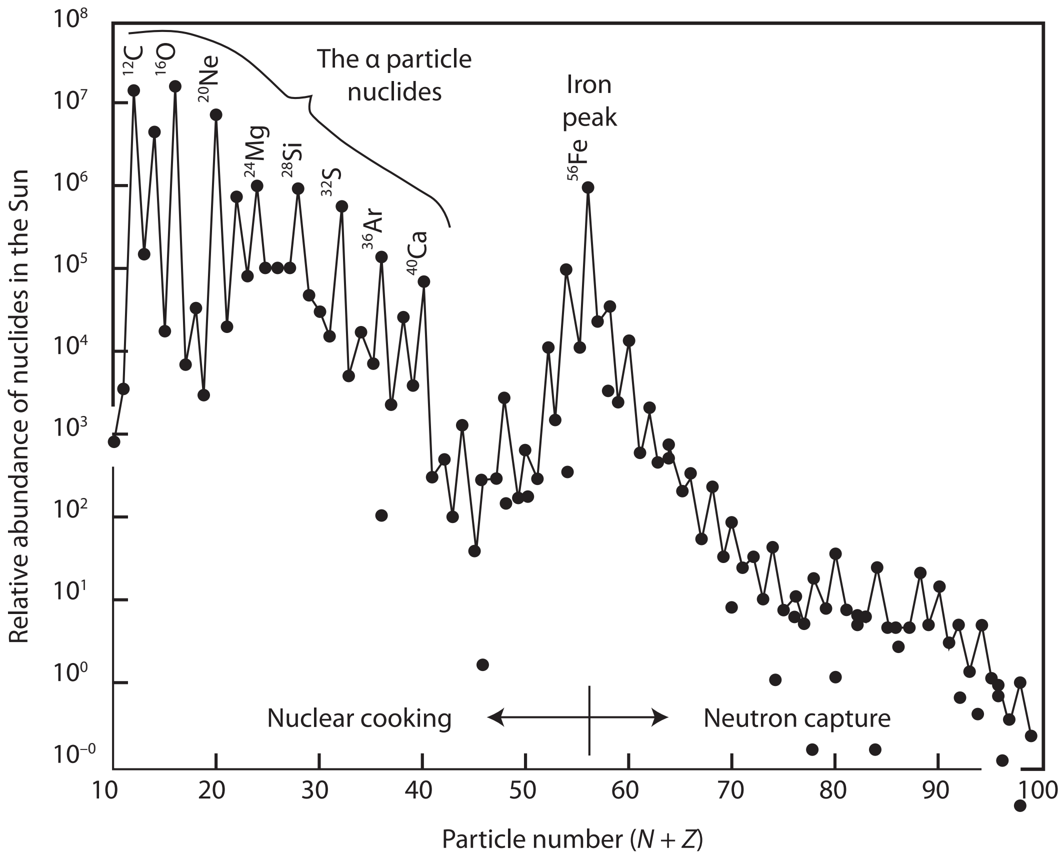


Fig. 3-10: Relative abundances of individual nuclides: In the mass range 10 to 100, nuclides with particle numbers divisible by 4 (i.e., 12, 16, 20, 24, 28, 32, . . .) have abundances far above those of their neighbors. They are referred to as the *alpha particle* nuclides. In the particle number range 50–100 the abundances of nuclides with an even particle number stand about a factor of 3 above those for their odd-numbered neighbors. Where more than one point is shown at a given mass number, two different nuclides with the same neutron plus proton number exist.

cores of iron, then it is not surprising that the major nuclide of iron (^{56}Fe) is more abundant than its neighbors in universe material. Since ^{56}Fe is the end of the nuclear fusion assembly line, its abundance will stack up as more and more stellar material is processed. One might ask, in fact, why is the iron peak not even more prominent? If all the material at the star's interior were converted to iron, then elements such as carbon, oxygen, magnesium, and silicon should be absent in the debris from supernovae. While this is the case for the star's core, it is not for the layers of gas surrounding the core. When the cores collapse to form supernova, the outer layers are still in earlier states of nuclear fusion, forming lighter elements.

Another feature of the abundances is the prominence in the mass range 10 to 40 of those nuclides with mass numbers divisible by 4. These nuclei are aggregates of the very stable ^{4}He nucleus, and are the primary products of nuclear fires. They are called *alpha-particle* nuclides, since they are made up of multiples of helium atoms.

Supporting evidence for nucleosynthesis by the processes we have described can be seen in the upper portion of Figure 3-11. Two humps appear in the element-abundance curve that punctuates the smooth decline with increasing proton number, one centered at about 55 protons and the other at about 80 protons. The same humps appear when plotted against the total number of nuclides in the nucleus (lower portion of Fig. 3-11) near masses 138 and 208. These peaks results from what physicists refer to as the magic neutron numbers 82 and 126. For example, the isotopes ^{138}Ba (56 protons, 82 neutrons) and ^{208}Pb (82 protons, 126 neutrons) are unusually abundant. It turns out that nuclear configurations involving either 82 or 126 neutrons are particularly stable. One expression of this stability is their lowered propensity to gobble passing neutrons. Thus, once formed during the s-process, nuclides with 82 or 126 neutrons are less likely to capture more neutrons and move further along the buildup chain. Because of this they were produced in higher abundance than their neighbors. In the r-process, radioactive nuclides with 82 and 126 neutrons also produce a bottleneck that causes them to be produced in greater abundance. Because the r-process nuclides are far from the band of stability, once the intense blast of neutrons is turned off, the extra neutrons are one by one converted to protons via beta decay. For example, one of these nuclides is the radioactive ^{124}Mo (42p, 82n). As it decays back to the band of stability, 8 of its neutrons are converted to protons generating the stable nuclide ^{124}Sn (50p, 74n). For this reason, the abundance peak for the r-process nuclides does not fall in the same place as that for the s-process nuclides. Rather, it is shifted toward lower particle number by 8 to 12 mass units. The existence of these twin peaks in the abundance curve provides strong support for the existence of both the r and the s neutron buildup process.

Finally, one last characteristic of the abundance curve merits comment. Both the element abundance and mass abundance plots in Figure 3-11 show a distinctive saw-toothed pattern. Odd elements and odd-particle-numbered nuclides have lower abundances than their even-

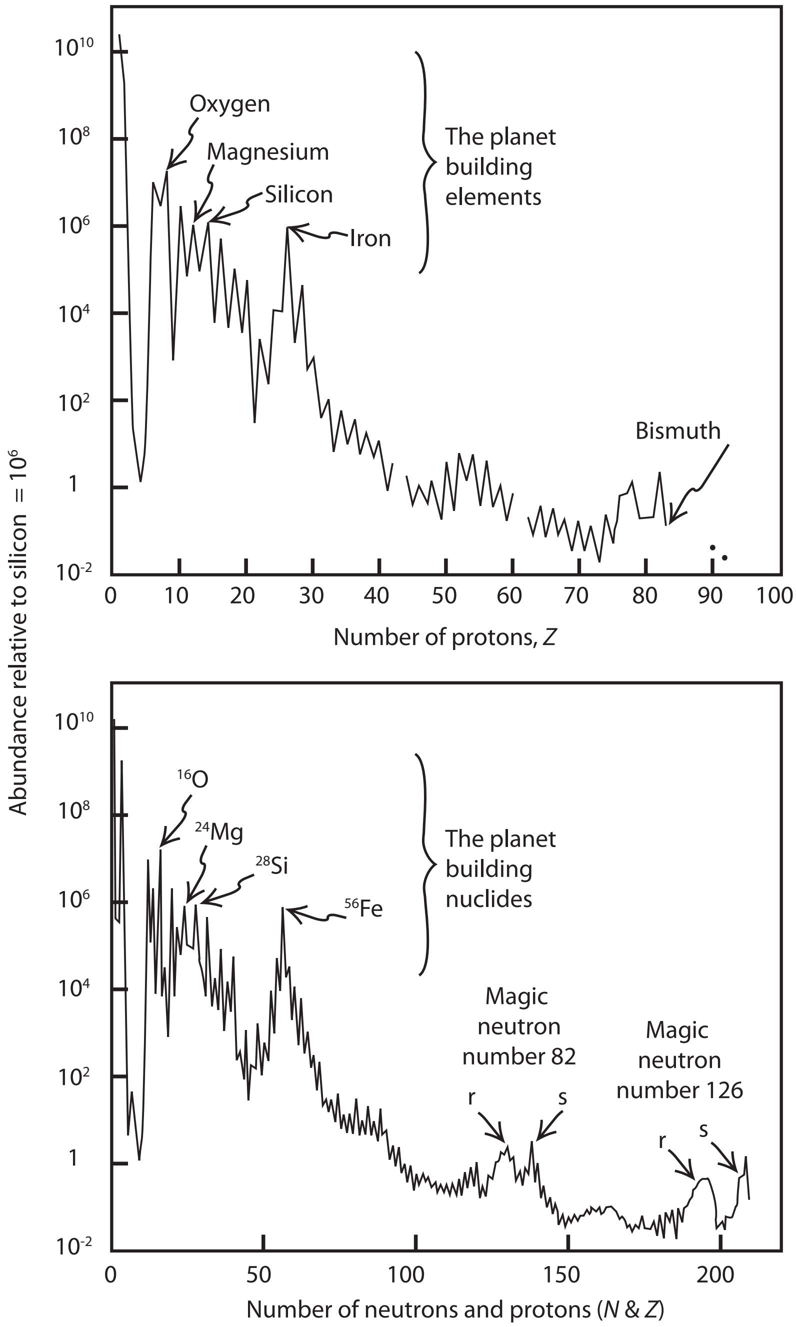


Fig. 3-11: Top panel: Abundances of elements produced during nucleosynthesis in stars. The trough for Li, Be, and B exists because these elements were produced in small amounts during the Big Bang and then partially consumed in stellar interiors. The "sawtooth" is the result of nature's preference for even-numbered elements. The highest peaks are the alpha particle nuclides that will become the raw materials for planets and life. Slight peaks at high mass number reflect the preference for nuclei with 82 or 126 neutrons. *Bottom panel:* The relative abundance of the isobars (i.e., some isobars have more than one element). Only two isobars of nuclear number less than 208 are not represented in nature, those of mass 5 and mass 8. The double peaks for magic neutron numbers are evidence for s-process and r-process operating during element formation.

numbered neighbors. This pattern reflects a preference in nuclear architecture for even numbers. Nuclides with both an even number of neutrons and an even number of protons are strongly favored. Except for ^{2}H (1p, 1n), ^{6}Li (3p, 3n), ^{10}B (5p, 5n), and ^{14}N (7p, 7n), no stable nuclide with both an odd number of neutrons and an odd number of protons exists in nature. Other odd-odd nuclides formed in stars subsequently undergo radio decay to form the preferred even-even nuclides (by converting a neutron to a proton).

Summary

After the Big Bang made hydrogen and helium, nucleosynthesis in stars produced the remaining elements. Particularities of nuclear stability had far-reaching consequences for the universe. The lack of stability of masses 5 and 8 prevented production of heavy elements during the Big Bang, creating the possibility for later development of stars and stellar evolution. The enhanced stability of alpha-particle nuclides during nuclear fusion led to the formation of certain elements in great abundance. These elements then became the raw material for planets and life later in the history of the Universe. The fact that ^{56}Fe is the most stable nucleus and that nuclear fusion cannot occur beyond that point is what leads to instability of massive stars, the formation of heavier elements and the distribution of all the elements through the galaxies. All of these consequences that are central to the operation of the universe and its ultimate habitability are the result of the detailed laws of relative stabilities of atomic nuclei.

The size of stars is central to their role in the overall evolution of galaxies. Large stars have massive gravitational forces leading to intense nuclear fires and very bright, short lifetimes. These stars produce all the elements and distribute them through supernova explosions. Such stars provide the elements required for planets and life, but would not themselves form habitable solar systems because of their short lifetimes and expolosive deaths. Smaller stars like the sun, with their lesser gravitational contraction, are rendered stable with lower-temperature nuclear fires produced by fusion of hydrogen to form helium, and can have lifetimes of billions of years. This leads to long-lived solar systems where