Chapter 11

Homes for Life— The Outside Universe

We have seen that the planets, both those known in our solar system and hypothetical ones that may exist in other solar systems, offer a rich variety of homes for chemical life. Planets, however, comprise only an insignificant portion of the matter in the Universe. In most of the Universe, the conditions of temperature, pressure, and energy flow are such that chemical life, based on molecular combinations and recombinations, cannot exist. For example, in the deep interior of stars, molecules and atoms are broken into ions and electrons. Are such environments necessarily barren of any kind of life? We think that this view is quite parochial. There are various alternatives to chemistry that a life-style could be based upon, both for the storage of order and the source of energy to generate it. The most significant unanswered question about the possibility of such exotic bases for life is whether they can evolve sufficient complexity that we could apply the word life to them. If we did not *know* that Earthlife could have arisen from combinations of carbon, hydrogen, oxygen, and nitrogen atoms, it would be difficult to predict the existence of such an intricate phenomenon. After we have identified some possible homes for life, we will discuss alternative ways in which complexity might evolve.

In searching for life forms that may evolve elsewhere than

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on planets, we must first identify other locales which can supply suitable combinations of matter and energy. Our search for possible homes for life will cover the whole Universe. We will again call on COSMEL, so that objects which differ immensely in true size will be viewed on a scale which is convenient to us. We step into the elevator and notice that the largest numbered button is +25. At this level our size will be about one-tenth that of the entire Universe. No +26 level exists in our model. It would be of little use to us to enter a space that we fill almost entirely.

In starting our survey, we will be bold and go to the highest level available. We press the +25 button and step out. For the most part, we see nothing. There is empty space, weakly illuminated by the three-degree microwave radiation that fills the Universe. On looking carefully, however, we see small glows filling space uniformly in all directions, at least to a distance ten times our size. These glows are each about the size of our fingernail, but shine brightly, like a swarm of fireflies lighting the eternal darkness (Plate 18).

The glows are moving like real fireflies, but at speeds comparable to that of light. If we let time pass at its ordinary rate, the speed would seem imperceptibly slow to us at the +25 level, as it would take millions of years for one of the objects to cover the average distance separating it from one of its neighbors. This distance is about three times the size of each object.

The glows are clusters of galaxies. No larger units of matter appear to exist in our Universe. Yet together they all contain only about half the matter that does exist. The remainder is present mostly in the form of isolated hydrogen atoms, spread very thinly in the space between the clusters. To observe one we will aim the COSMEL screen to point into this space, and push the button marked −8. As you will recall, a hydrogen atom on this level is the size of a marble. We are quite lucky and find one hanging in the void of black space immediately outside our elevator door. If we wished to find its nearest neighbor at the −8 level, we

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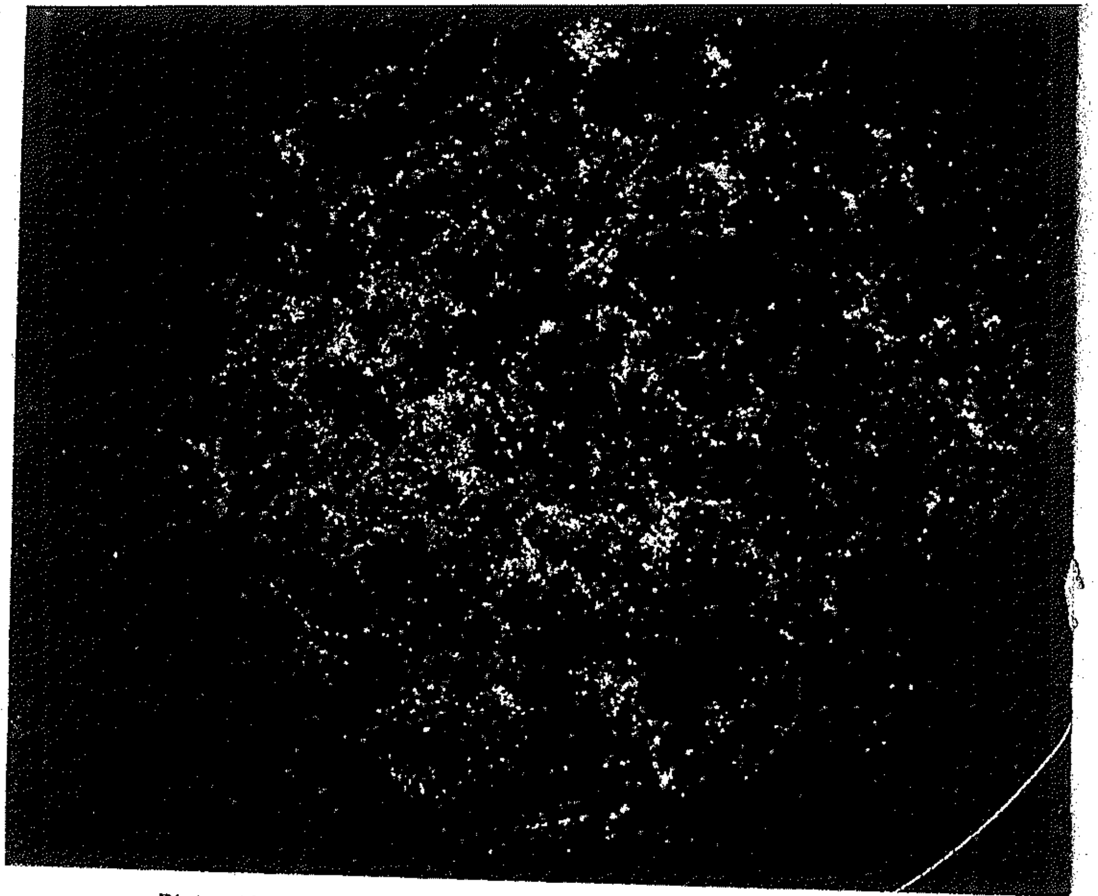

Plate 18. A composite map of the million brightest galaxies visible in the northern sky of Earth. The Universe might appear like this when viewed from the highest levels of COSMEL.

would have to walk a distance equal to that from the Earth to Moon!

There are an enormous number of such isolated hydrogen atoms because space is very large. But there is hardly any way in which they can influence one another, and little energy to help them. Therefore, it is unlikely that the intergalactic hydrogen can play a significant role in the story of life. We will concentrate instead on the clusters of galaxies.

We return to COSMEL and push the +23 button. At this level we are about the size of a cluster and can observe its

parts. As the name suggests, it is made up of individual objects, the galaxies themselves. The cluster is a roughly spherical object, which may contain up to a few hundred galaxies. So the largest object in the Universe, a cluster of galaxies, is about thirty-eight orders of magnitude greater in diameter than the smallest ones, the subatomic particles. Stars lie about halfway between the largest and smallest objects, on the COSMEL levels, while human beings are closer to the very small than to the very large.

At this level the galaxies themselves are mostly oval discs, with the average one similar to a fingernail in size and shape. Their sizes vary within a range of ten, and they also differ in their brightness and form. Some appear as long, wispy spirals, rather than ovals. They all generally have dense centers, diffuse borders, and "haloes" coming out of the plane of the disc (Plate 19). Some galaxies also contain bizarre structures such as long "jets," which may have been ejected by cosmic explosions from the main body. A typical galaxy contains one hundred billion stars, about as many as the atoms contained in a bacterium.

These descriptions may make a galaxy sound disturbingly like some of the living things that we met earlier twenty-five levels down the cosmic elevator shaft, and indeed the structural parallels are eerie. Very probably these resemblances are coincidental, but—? At any event we are not out to bag such big game at this stage, and we will focus our hunt on objects of more familiar size.

COSMIC CLOUDS

We return to COSMEL and descend to level +16 in the outer region of a typical galaxy. Upon emerging we see a large number of wispy clouds of gas and dust, glowing brightly by emitting many forms of radiation. The typical cloud is somewhat larger than we are, and they are spaced a bit farther apart than their individual sizes, giving the appearance of light clouds on a partly overcast night on

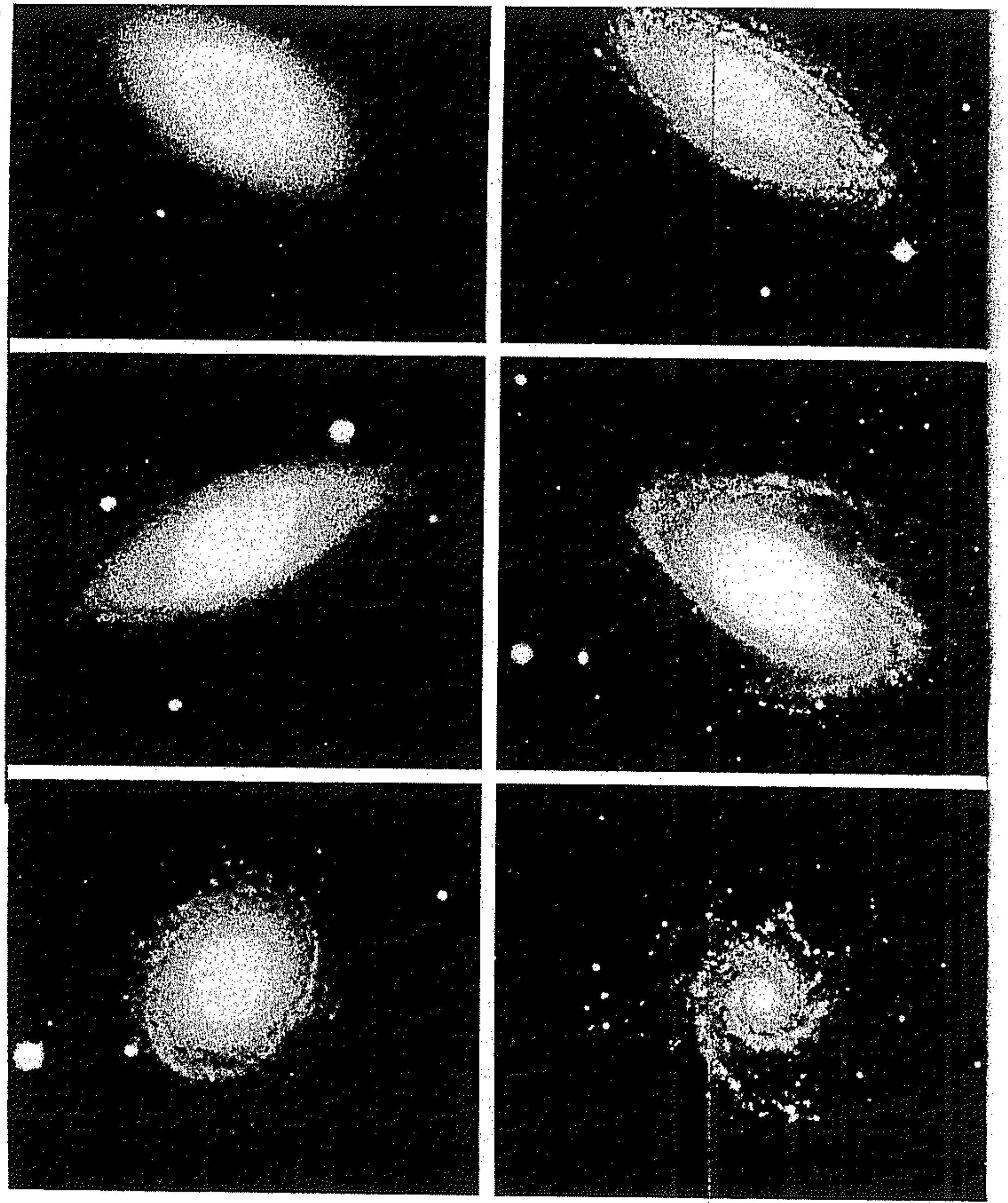

Plate 19. Some typical spiral galaxies, as they would appear on the +22 level of COSMEL.

Earth. Between the galactic clouds is a more rarefied gas, out of which they have condensed because of the mutual gravitational attraction of their components. Both the gas between the clouds and the clouds themselves are mainly composed of hydrogen and helium, the two simplest of the chemical elements. But there are small amounts of other elements, such as carbon, oxygen, and nitrogen, which have been and are so important in Earthlife.

We can use COSMEL again on its lower levels to examine the composition of a cloud. There are occasional stars within a cloud, produced by a process we will discuss below. These stars play an important role, providing much of the radiant energy that drives physical and chemical processes within the cloud. Especially, the ultraviolet light produced by hot young stars can break atoms up into ions and electrons, which seems to be an essential step in determining how chemical reactions occur.

In order to view the next smallest objects known to exist within the cloud at their own size, we must reduce ourselves to the size of a bacterium at COSMEL level −6. We see solid chunks, called dust grains, of unknown composition. They may be similar to the grains of sand found on a beach. They are widely spaced, and the nearest neighbor to the one we are observing may be thousands of kilometers away at this level. Atoms and molecules also exist within the clouds in the space between the dust grains, and they are also kilometers apart, on the average. This is a very rare collection of matter by Earth standards, but its density is still a million times greater than that of the matter in the space between galaxies. Furthermore, the density varies greatly from place to place in the clouds. In some locations it is as high as that in Earth's atmosphere. But the regions of such high density do not last long. Gravity usually forces them to contract to higher and higher densities, heating up as they contract until they begin to emit radiation because of their high temperatures. It is this radiation that illuminates the cloud, rather than the feeble light emitted by the bulk of the clouds themselves. This process culminates in the formation of stars, which we will soon discuss.

We will pause now to take inventory of the atoms and molecules present in such a dense cloud, conveniently using COSMEL at the −8 level. Helium atoms and hydrogen atoms and molecules, the most common ones in the Universe, predominate here also. We find lesser amounts of heavier atoms such as carbon and, somewhat surprisingly, small organic molecules. We have already discussed the somewhat un-Earthlike nature of these molecules in Chapter 5. It is not at all clear how they were formed, and once formed, how they survive the radiation that tends to break them up. At the densities of atoms in most places in the gas clouds, collisions are very infrequent. It is possible that the interstellar molecules are formed on the dust grains. Atoms may collide with the grains and stick to them as flies stick to flypaper. If many atoms are on the same grain at once, they have a much greater chance of forming a molecule than if the same atoms collide in space. Some surfaces show similar catalytic effects on Earth.

A number of writers feel that the presence of organic molecules in interstellar space is of great significance for the origin of life on Earth. We have discussed this predestinist viewpoint in earlier chapters and have explained why we disagree with it. The gas clouds, with their interplay of radiant energy and dispersed molecules, may have a fascinating story of their own to tell once we overcome our egocentric tendencies. In particular, the clouds may furnish the basis for the existence of a totally different form of life—radiant life. We will note that there is a possible biosphere here, and reserve this topic as worthy of treatment in greater depth in the next chapter.

STARS

We next want to study in detail the major components of galaxies, the stars. Stars contain about half the mass of galaxies, and produce most of the radiation by which we see galaxies. Stars are the most characteristic bodies of the present Universe, although this was not true long ago and will not be true in the far future, billions of years from now. In order to appreciate the true glory of the stars, we will first study them where they congregate, in the center of galaxies, rather than in the galactic fringes where our Sun is found.

We will use COSMEL to transport us to a galactic center and then drop to level +13. When we emerge, the first impression is of light everywhere. We find ourselves surrounded by stars, many of which shine as bright as the full Moon does on Earth. Within a distance of a hundred meters, we can count thousands of stars of various color and size. If we were at the same level in a part of a galaxy close to Earth, the nearest star would probably be five kilometers away and the total brightness would be that of the Earth sky at night, millions of times less than at the galactic center. Even at the density in the galactic center, the individual stars are too small to see at this level except as points of light. The nearest star, some ten meters away, is relatively as small as a human cell compared with the whole person.

But while the individual stars are too small to see as discs, their total output of radiation is formidable. Although conditions near the galactic center are not very well understood by astronomers, from the estimated density of stars we can guess that the total intensity of radiation at an average place not especially close to any star will be as bright as a cloudy day on Earth. The radiation comes from all directions rather than from one source, so that the general impression would be like the bright sky on Earth (although not blue!). Starlight is a very significant factor in the conditions that exist in the galactic nucleus, whether or not a star is nearby. The suns truly never set at the center of the galaxy, as there are always enough of them visible to provide almost as much light as we have by day on Earth.

Stars contain a large part of the matter in the Universe, especially that part which is at high density and subjected

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to large flows of energy, both of which are beneficial to the emergence of order. We therefore expect that stars may be one of the main environments where life is to be found. For this reason we will carefully examine some of the important features that may be relevant to the life that inhabits the stars.

In order to begin, we must again decrease our size so that we can examine individual stars more carefully. At COSMEL level +9, we are about the size of an average star. Because the stars are far apart compared with their size, even near the galactic center, we must make sure that we emerge from COSMEL near enough to one to avoid a long walk. To do this we use a locating device in COSMEL to fix on a specific star. We choose as our target our own Sun, whose position is well known. Also, since scientists know the Sun best, what we will describe has the most reliability, although not as much as we would like. Later we will visit other stars that differ from the Sun.

We emerge from COSMEL on level +9 in a region and at a level that we have already explored. It is our own solar system, and we have landed directly in front of the yellow, glowing globe of the Sun. Although when viewed from the distance of Earth or the other planets, it seems solid enough, from close up the Sun is more diffuse, like a meter-wide ball of cotton candy that grows denser as its center is approached. Let us examine it more closely.

THE SUN

We have constructed our model of the Sun in transparent layers so that we can observe the interior readily. This gives us an advantage over experimental scientists, who are limited to direct observation of radiation coming from the Sun's outer layer. Our knowledge of the insides of the Sun and other stars comes from theoretical analysis, and this is somewhat less certain than those scientists responsible for the analysis believe. Nevertheless, it is the best information

available, and we have made liberal use of it in constructing our model. This model shows a visible surface, surrounded by a very wispy but hot outer region. This hot region can normally be seen only during a total solar eclipse, when the Sun's visible surface, called the photosphere, is obscured by Moon. The photosphere is by no means solid. It only appears so because all the visible light from the Sun originates from a thin sphere, which our eyes interpret as a solid body. We have seen the same is true for Jupiter and some of the other planets. There is no sharp change in density at the photosphere corresponding to the difference in density between the atmosphere and the surface of a solid planet like Earth. The density of matter increases slowly inward from the photosphere and decreases slowly outward. The density of the part of the Sun which is above the photosphere is about a thousand times less than that of the atmosphere near the surface of the Earth. The temperature at this point in the Sun is about 4000° C. We can be grateful again that we are only dealing with a model. About halfway down through the photosphere the temperature is 5700° C, which is usually taken as the temperature of the Sun's surface. As we go up outside the photosphere, the density drops but the temperature rises up to a million degrees or more. However, so few atoms are present at these high temperatures that this region is essentially a hot vacuum.

The atoms present in the photosphere, and presumably the interior of the Sun as well, are mostly hydrogen and helium in a ratio of about ten to one. This is approximately the same as that found in the gas between the stars, and represents the average situation in the Universe. In addition, the Sun contains about 2 percent, by mass, of heavier atoms such as carbon, magnesium, iron, and silicon.

As we proceed inward from the photosphere of the Sun, there is a gradual increase in pressure, temperature, and density. The rate of increase with depth is not so different from that in the interior of the Earth or in a planetary atmosphere, but the distances are so much vaster that the values of pressure and temperature eventually reached are immensely greater than anything possible in a planet. Because of the gradualness of the change, there is no solid surface anyplace. The Sun is basically one large atmosphere, in spite of its solid appearance. To emphasize our search for habitats for life we have divided the Sun into three zones. We will visit each zone (using the —12 level of COSMEL) to examine the conditions and state of the matter there. (See Fig. 27.)

Our first zone is quite narrow, no more than the thickness of an apple's skin compared with the apple itself. The site we visit is about one millimeter into the interior of our 1.2-meter globe. The temperature is 30,000° C. At this temperature the atoms have lost some of their electrons, which wander about freely like small children that have temporarily escaped from the clutches of their overfond parents. The overall density is still low here, no greater than that of the air at the surface of the Earth. But because of the high temperature, the pressure this gas exerts is very high, equal to that deep under one of our oceans.

The next site we visit is halfway toward the center of the Sun. Here the temperature is several million degrees, and the gas has been compressed to the density of water. Matter here does not, however, behave like any of our familiar substances on Earth. The electrons have been more completely detached from their atoms and wander about freely, leaving the nuclei behind as positively charged ions. The separated positive and negative electric charges move independently of each other. This state of matter is called a plasma. We consider this zone to be a very promising one for the development of life. We will mark it as a possible biosphere, and reserve it for a more complete discussion in the next chapter.

Our last stop is at the very center of the Sun. The temperature here reaches ten million degrees, and the density is five times greater than that of solid gold, greater than any material known on Earth. The matter does not behave

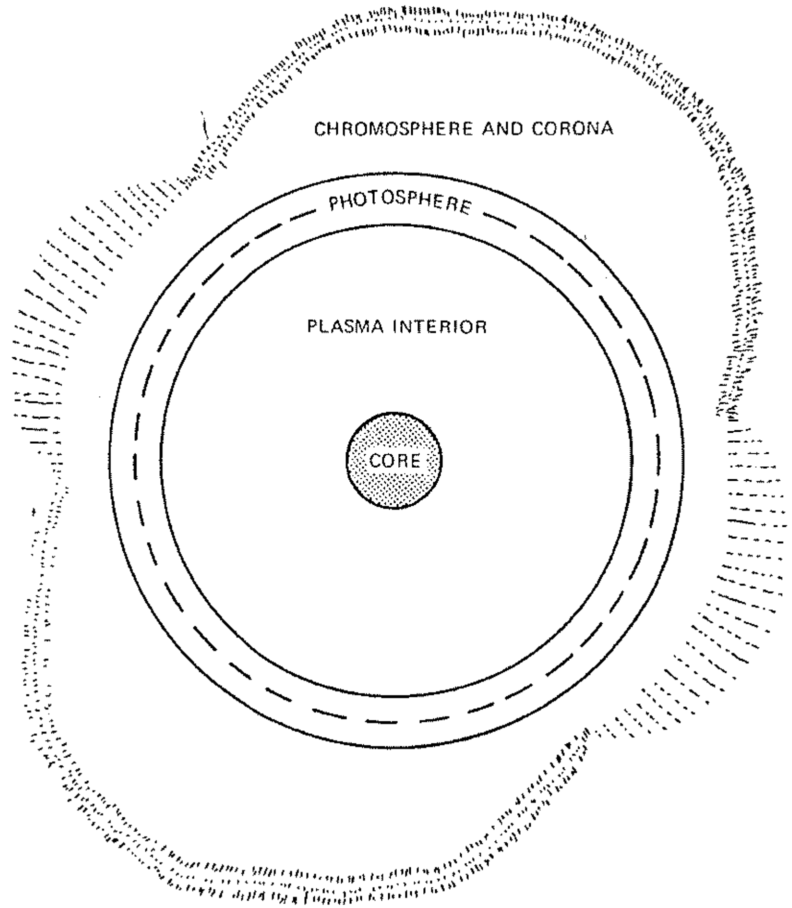

Figure 27. The interior of the Sun shows a gradual change in conditions with distance from the center, rather than abrupt transitions. The central core, in which nuclear-fusion reactions occur, has the highest temperatures and densities. A large region containing plasma surrounds this core. The most readily visible part of the Sun, the photosphere, lies outside of the plasma region. Still farther out from the center is the extremely tenuous corona.

at all like a solid, however, but is again in plasma form, in which separated positive and negative charges move independently of each other.

The high temperature and density near the center of a star allow the star to produce the energy that eventually escapes the surface as radiation. The heat in the center of the Sun originally came from the potential energy that was lost when the Sun was formed from a dense gas by the gravitational attraction of the matter in the gas on itself. This process is similar to the one which takes place when the water in a waterfall hits the bottom and becomes warmer. A star becomes much hotter than a waterfall because the matter in it has so much farther to "fall." Few stars are being formed by this process at any time compared with the total number visible. The birth and growth to maturity of a star like the Sun takes only a few million years, compared with the billions of years of its lifetime. Most stars, including the Sun, are adults, and there are very few stellar "children" to be seen.

The amount of energy that the Sun obtained by "falling together" at its birth was sufficient only to keep it shining for about thirty million years, not nearly enough time for the known origin and evolution of Earthlife to have taken place. The Sun and other stars have kept shining for billions of years only because they found a new energy source, nuclear fusion. The nuclei of hydrogen atoms combine to produce helium together with radiant energy, and the outward pressures of the hot gas and radiation balance the inward force of gravity and keep the Sun from contracting further. This fusion process thereafter provides a reliable energy source for the Sun.

SOME OTHER STARS

Now that we have some idea of what one star looks like close up, we can take a trip to some other stars in our galaxy to see what similarities and differences they show. In order to make this voyage, we must return to some of the higher levels of COSMEL, since the +9 level at which we examined the Sun, the distance to the nearest star is equivalent to walking around the Earth on level 0. A convenient level

for traveling between stars in the galactic boondocks where the Sun exists is +16. We emerge from COSMEL and see the familiar night sky of Earth, except that both the stars of the northern and southern skies of our planet are visible. However, these individual stars can be seen only as minute points of light at the +16 level. Each has been reduced to the approximate size of a virus on Earth. The orbit of Pluto around our own Sun is about as large as a dot that is barely visible.

We find that there are about twenty stars within ten meters of our Sun, and that each star is approximately ten meters from its neighbors (one meter now corresponds to one light year, the distance that light travels in one Earth year). We will approach a number of these neighbors of our Sun on level +16, then return to the +9 level (the size of our own Sun) and inspect each in turn.

A list of the twenty stars nearest to the Sun, with a few of their properties, is given in Table 11-1. Of these stars only two are larger than our Sun, the bright stars visible in our winter skies as Sirius and Procyon. A third star visible only in the southern hemisphere, known as Alpha Centauri, is about the same size as the Sun, while all the other nearby stars are smaller than the Sun, both in radius and in the amount of matter they contain.

Most of the stars in the vicinity of the Sun are similar in composition; that is, they contain mostly hydrogen and helium. They also contain small amounts of the nuclei of heavier atoms, such as carbon, oxygen, and iron.

Like human beings, stars may be found that "live" alone or with one or more companions. Sirius, for example, has a small companion star which we will inspect closely in a little while. Half of the one hundred stars nearest to Earth are members of such multiple star systems, and a similar proportion is believed to hold elsewhere. The distances between the stars in a "family" may vary from values barely greater than their diameters to much greater separations. Where the stars are very close, their shapes may be distorted

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Table 11-1

THE NEAREST STARS TO THE SUN

Star	Distance (light years)	Surface Temperature (degrees K)	Mass of Star Divided by Mass of Sun	Special Features
Proxima Centauri	4.2	2600	.1	Triple Star System
Alpha Centauri A	4.3	5700	1.09	
Alpha Centauri B	4.3	4100	.88	
Barnard's Star	6.0	2600	~1	
Wolf 359	7.7	2500	~1	
Lalande 21185	8.2	3000	.35	
Sirius A	8.7	9400	2.31	Double star
Sirius B	8.7	8000	.98	White dwarf
Luyten 726-8A	8.7	2600	.044	Double star
Luyten 726-8B	8.7	?	.035	
Ross 154	9.3	2600	<1	
Ross 248	10.3	2400	<1	
Epsilon Eridani	10.9	4500	~1	
Ross 128	10.9	2600	<1	
Luyten 789.6	11.0	2500	<1	
61 Cygni A	11.2	4000	.59	Double star
61 Cygni B	11.2	3700	.50	
Procyon A	11.4	6500	1.75	Double star
Procyon B	11.4	6000	.64	White dwarf
Epsilon Indi	11.4	4000	~1	

The names of all the stars depend on the catalog in which they are listed. Note the predominance of small, relatively cool stars.

because of gravity, and there may be a flow of material from one to the other.

Let us now wander a bit farther afield into the galaxy and describe the interesting types of stars we encounter. We certainly have enough room in which to roam. The galaxy is one hundred kilometers in diameter at the +16 level! As we examine a wide range of stars, we find that our Sun is larger than average. As a class, stars vary in mass by a factor of one thousand, from one-tenth that of the Sun to one hundred times greater. This is a wider size range than that of adult human beings, but a much smaller one than that of mammals, which vary from shrew to whale by a factor of one hundred million. Smaller stars than the ones noted above may also exist, unobserved by us because they emit too little radiation.

Apart from their size, stars differ in their color and brightness. When we observe one, we find that there is a fairly simple relation between its color, surface temperature, and the amount and type of radiation that it emits. A yellowish star like our Sun has a surface temperature of about 6000° C, hot enough to boil all substances. Such stars mainly emit the radiation we call visible light and much smaller amounts of infrared and ultraviolet radiation. A star that is bluer or whiter than our Sun is also hotter, perhaps up to 30,000° C. These stars emit much more radiation per unit of surface area than the Sun. Furthermore, one type of white star is much larger than the Sun, so that the total radiation emitted may be as much as a million times greater. Also, this star emits proportionately more ultraviolet radiation and less infrared and visible light. These prodigal suns tend to have short lives because the radiation they emit so copiously derives from a profligate use of nuclear fuel. This fuel is used up in a few million years, a short time compared with the many billion years that our Sun will be able to shine. One consequence of this state of affairs is that such bright stars are rare in the present Universe, and the ones we see have all been made in the comparatively recent past. Some have even been formed after human beings already roamed the African plains. The ultimate fate of these and other stars after they have used up their nuclear fuel will be discussed shortly.

Much more common than the brightest stars are small reddish stars whose temperature may be as low (!) as 2500° C, at which value some metals remain solid. Going closer to such a star, we find that it emits less than 1 percent as much radiation as the Sun, and that radiation is mainly infrared, with very little visible light. These stars are very common and constitute perhaps 90 percent of all stars at present. They are also incredibly long-lived because they emit so little radiation. In the words of astronomer J. L. Greenstein, "In a hundred billion years, the Sun will have faded into a dead, small, infrared, degenerate star probably invisible from the Earth." Most presently existing stars will have burnt out. But a red dwarf star "will still have its full youthful vigor with ninety-five percent of its long life ahead." Truly, the meek shall inherit the Universe. Perhaps someday if we have not found a better solution in the interim, human society will transplant itself to the vicinity of a red dwarf star, extending our future for billions of years.

If life in the vicinity of these stars develops at anything like the same rate it has near the Sun, it will have a very long and probably glorious future ahead of it. However, planets circling such stars at a distance may have temperatures lower than those encountered on planets in our own solar system, with seas of liquid hydrogen covering them. Such an environment would preclude any chemical basis for life, but would open other opportunities for it.

If we are willing to take a longer walk on level +16, we can visit a rather different type of star than the ones in the vicinity of our Sun. A hike of four hundred meters (four hundred light years at ground level) brings us to the star Antares, visible from Earth only as a red point of light. It is still a point of light when viewed on level +16, but if we went down to level +9, where the Sun was about a meter

in diameter, Antares would be a giant ball, some five hundred meters across. At this size, the orbits of all the planets of our solar system out to Mars would fit inside Antares. Some even larger stars have been discovered, and very recently, by using subtle computer methods for reconstructing images, it has actually been possible to photograph one red star (Betelgeuse) as a disc rather than as a point of light (Plate 20). Stars of this type are known as red supergiants, for obvious reasons.

The outermost layers of the atmosphere of such stars are no denser than what we would consider to be a good vacuum on Earth, although they are still much denser than the interstellar space material. Even deep inside the atmosphere, 90 percent of the way toward the center of Antares, the density is perhaps only 1 percent that of the atmosphere at Earth's surface. The temperature at this point is several thousand degrees centigrade. Some molecules can exist under these conditions, and indeed have been identified by the characteristic radiation they emit. The numbers of molecules present are immense by Earth standards. The number of water molecules in the atmosphere of Antares, for example, might be a million times greater than the amount present in Earth's oceans. Furthermore, the densities and temperatures in these stellar atmospheres are high enough that collisions between molecules are much more frequent than among the molecules of interstellar space, even in the dense clouds. It is possible that a rich, high-temperature chemistry could develop in the atmospheres of supergiant stars and serve as the basis for a form of life.

When we proceed to the innermost core of Antares, a region whose size is not much larger than the Earth's, we encounter much denser material. In fact, its density is greater than that of any known solid and up to a million times as much as that of water. If we use COSMEL at its atomic level (—8) to look into the core of a supergiant such as Antares, we find that many of the elements heavier than helium that are found in the Universe are being made there by nuclear

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Plate 20. The disc of the red supergiant star Betelgeuse, as it might appear on COSMEL level +13. The photograph was taken at the Kitt Peak Observatory, using a technique known as speckle interferometry. The origin of the structure shown on the star's surface in the photograph is unknown.

fusion reactions. As we will see, some of these stars later explode, spewing their heavy-element contents into interstellar space, where they mix with hydrogen and helium. An enriched gas of this type was involved in the creation of our own solar system. Since Earthlife depends on substantial amounts of heavier nuclei such as carbon being present, we owe our existence to the processes in these dense, hot cores.

Clearly something strange has happened to convert a normal star to a supergiant like Antares. What has happened is not completely understood, but it is believed that very massive stars become supergiants at a certain stage in their lives. When most of the hydrogen that provides the nuclear fuel for the star has been used up, the central core of the star is no longer supported by the pressure of its energy release against the tendency to contract under its own gravity. The core therefore does contract to a high density and temperature until at a temperature of one hundred million degrees, the helium in the core begins to undergo nuclear fusion to produce still heavier elements and more energy. This new release of energy in the form of radiation "blows out" the outer regions of the star into a thin atmosphere, and the supergiant is formed. Woe to any planets that happen to be within the region into which the star's atmosphere expands in this process. They become heated to the temperature of the stellar atmosphere, which may be 3000° C. However, the process takes a long time, perhaps thousands of years, since the gas in the atmosphere is so thin.

STAR'S END

All sources of free energy must come to an end, including the nuclear fuel in stars. When all the light elements like hydrogen and helium are converted into heavy elements like iron, no more nuclear energy can be extracted. The stellar core has been kept from collapsing only by this energy generation, somewhat as a balloon does not collapse as long as air is blown into it. But now the gravitational force seeking to pull the core together reasserts itself, and the central core contracts still further. There are several possible end results to this process, depending on the mass of the star.

The most common result, which happens to most stars less massive than the Sun, is the formation of a starlike object called a white dwarf. It is estimated that there are some ten billion such stars in our galaxy. We can visit this type of star by retracing our steps and returning to the vicinity of our Sun. When we revisit the bright star Sirius, we recall that it has a nearby companion star (Sirius B), which is a white dwarf. On descending to the +9 level and approaching it, we find that Sirius B is very small, only about 50 percent larger in radius than the Earth, but that small package contains as much mass as our Sun. Sirius B has a high surface temperature, but emits much less radiation than the Sun because it is so small. Entering it, we find that while there is more hydrogen and helium in the outer layers, the inner regions comprise mostly heavier elements like carbon, oxygen, and iron. Furthermore, there are no atoms inside the white dwarf. The electrons are separated from the nuclei by the high pressure and roam freely. In fact, this allows the white-dwarf core to resist the tendency of gravity to contract it still further. Electrons do not like being compressed into a small volume of space, and this reluctance, known to physicists as Pauli's exclusion principle, produces a counterpressure to gravity which stabilizes the star at a radius about that of the Earth. The nuclei in the white dwarf, being much heavier than the electrons, form a solid or liquid similar to those familiar to us but a million times denser. The arrangement of nuclei in the solid will be complex if many different types of nuclei are present inside the star.

Because most stars are low in mass, they will become white dwarfs. Eventually, they will radiate away all their internal energy and end up as "black dwarfs." However, this process will take billions of years because in the late stages the star is cool and radiates very little energy. So a white dwarf lasts

a very long time and has a complex inner structure, immense density, and after a while, rather low temperatures measured in hundreds or thousands of degrees. For much of its lifetime, there will be sizable energy flows from the interior of the star to the outside. All these assumptions point to the possible development of complex forms of life within the star. An ordering of the positions of the nuclei in the solid parts of the interior is an obvious possibility for the basis of one form of life. But in view of the uncertainty among scientists about the detailed conditions inside white dwarfs, we shall not speculate further here about what life may have developed there. There may be some white dwarfs that have already cooled down to a temperature so low that they have become almost invisible "black dwarfs." The surface temperature might then be similar to that of the Earth, at least for many millions of years. Since the object is fairly rich in heavier elements, it will eventually be a planetary body with a mass like that of a star. Such bodies may be fairly common in the Universe, and will become more common in the future as more white dwarfs cool toward oblivion. There might be a flow of energy from the warmer interior of the star, and possibly hot spots would develop because of an uneven distribution of matter inside the star. Under these conditions, the development of chemical life is not hard to imagine. One significant difference from planets would be the immense gravity, almost a million times greater than that at Earth's surface. This would tend to make life and all other phenomena on the stellar surfaces very two-dimensional. Things that are typically kilometers high or deep on Earth would tend to be millimeters on these stars. But this in itself does not preclude the existence of life related to that on Earth with a somewhat different geometrical arrangement. Also, floating objects of bacterial size would be shielded from the effects of gravity. If there are numbers of black dwarfs in the Universe, yet another possible home for rather familiar life may exist.

If a star is somewhat heavier than the Sun but not more than about twice as heavy, even the resistance of electrons to being squeezed together is not enough to keep gravity from compressing the star even more. The electrons are jammed into the positive nuclei, and the two combine, transforming the protons in the nuclei into chargeless neutrons. This process does not leave the star unscathed. A huge burst of energy is released, much of it in the form of peculiar subatomic particles called neutrinos. This burst of neutrinos, accompanied by some electromagnetic radiation that we can easily detect, is observed as a rare type of stellar explosion known as a supernova.

What is left behind after the supernova is most of the star's mass, now converted to neutrons and held together by gravity. The neutrons also resist further compression to some extent, and if the remaining star is not too heavy, a stable object results known as a neutron star. We can visit a neutron star by taking a trip with COSMEL to a diffuse object visible from Earth called the Crab nebula (Plate 21). It is about five thousand light years away, or about a five-kilometer trip on level +16. The stars are beautiful, and it is a lovely night for a stroll, so we hike over to it. A supernova at the position of the Crab was visible to Chinese astronomers in 1054 A.D. Many years later it was found that a faint star within the Crab nebula was emitting regular radiation pulses of various wavelengths, radio waves, light, and X-rays. This "pulsar" was eventually understood to be a rotating neutron star, the remnant of the supernova. There may be millions of such neutron stars within our galaxy.

When we attempt to view the neutron star in the Crab nebula from close up by descending to level +9 as we usually do, we are in for a surprise. While our own Sun was a four-foot globe at that level, the neutron star remains a point of light. We have to retreat all the way down to level +4 to make it readily visible. It is a metallic sphere whose diameter is the size of a human being. It appears to have a crust no thicker than our small finger and a much denser interior. In our normal world it is only about twenty kilome-

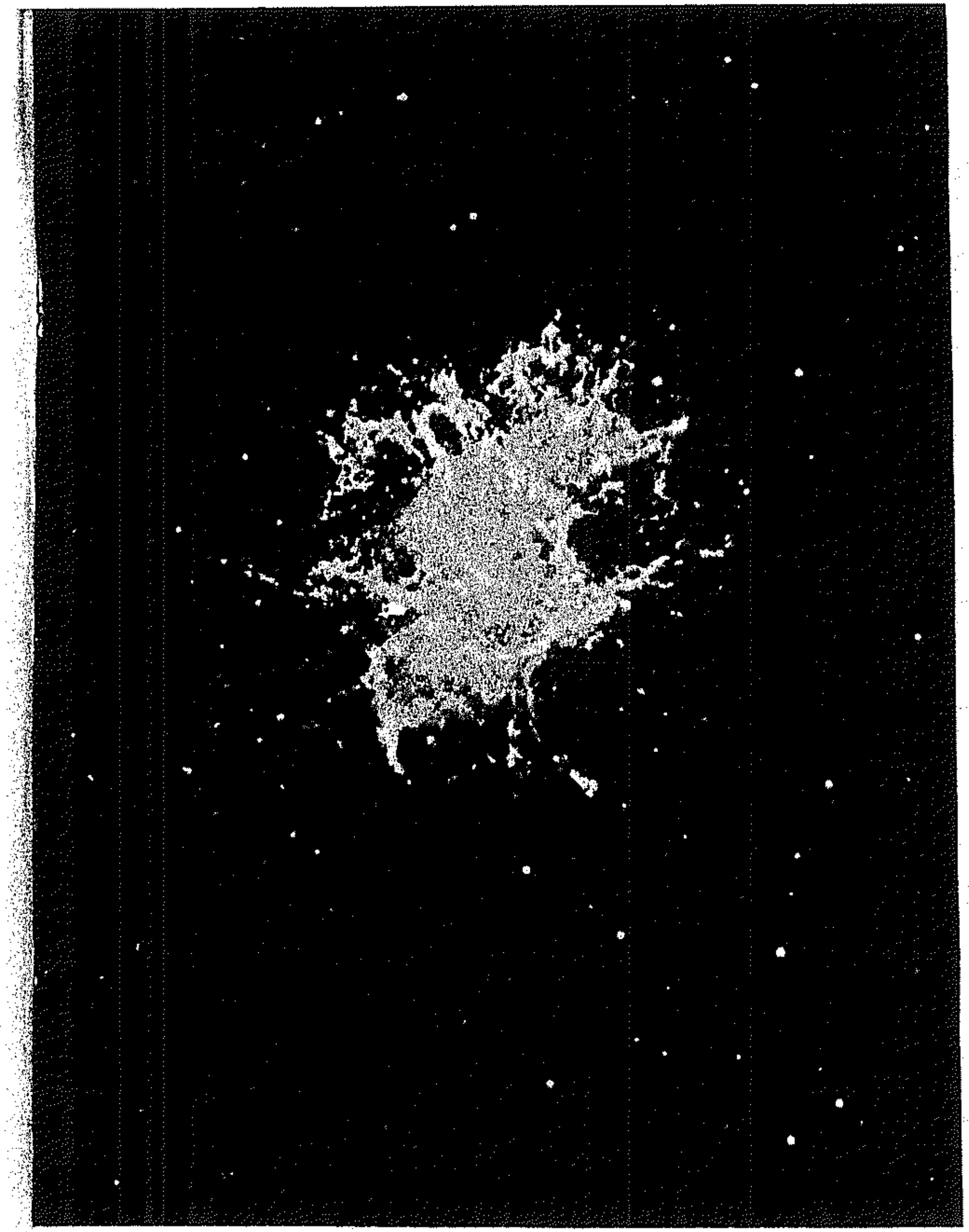

Plate 21. The Crab Nebula, as it might appear on the +18 level of COSMEL. A faint object within the nebula is the neutron star remnant of a supernova explosion that was visible on Earth in 1054.

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ters across, incredibly tiny for a star. Its size relationship to a supergiant is roughly that of a bacterium to a whale. In order to push all a star's mass into a sphere that size, the density must be a hundred trillion times greater than that of water, or a hundred million times greater even than white-dwarf matter. An object the size of a bacterium made of material this dense would weigh about a kilogram. Basically, a neutron star is like a giant nucleus of an atom, held together by gravity and extending over a distance immensely greater than the size of an ordinary nucleus.

Because of the very high density, the gravity outside a neutron star is very high, billions of times stronger than that on Earth's surface. This gravity would tend to squash any ordinary object flat against the surface of the star, down to a layer only a few atoms thick. But this will not bother us on our imaginary journey.

As we enter the neutron star, we find that its outer layer has an intricate physical structure. In this outer layer the pressures are not great enough to force the electrons into the nuclei; instead there is matter similar to that in a white-dwarf star, with separate electrons and nuclei. In all of this region, except for a surface layer that is only a few meters thick in actual size, the nuclei form a solid network and the electrons form a gas that flows between the spaces of the solid. This crust is a kilometer or so deep in actual size. Although a million times denser than water, it is so much less so than the inner star that it is really more of an atmosphere than a crust. This part of the star contains a variety of types of nuclei, typically those with intermediate atomic weights such as iron. The matter is not homogeneous in the crust, and it is even possible that "chemical compounds," in the form of solids containing several nuclei in a regular structure, occur.

There are other effects on the matter in the thin surface layer of the neutron star that drastically alter its properties. These are magnetic forces in and outside the neutron star that are much stronger than any that exist or have been

produced on Earth. Under the influence of such strong magnetic forces, atoms are distorted from their normal shapes into weird configurations (Fig. 28). These "magnetic atoms,"

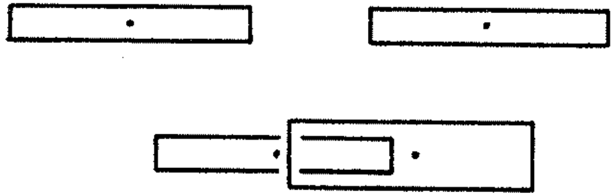

Figure 28. Magnetic atoms. Under the action of the immense magnetic forces present on the surface of a neutron star, the shapes of atoms become distorted into long, thin forms such as the hydrogen atoms pictured here. Such atoms can also fit into one another to give analogues to molecules.

whose existence was proposed by the physicist Malvin Ruderman in 1970, can be much more tightly bound than normal atoms. Also, they bind with each other to form molecules in a very different way. The typical form of such molecules is a long polymer-like chain of atoms, in which the atomic nuclei line up along the direction of the magnetic force and the electrons form a kind of sheath surrounding the line of nuclei (Fig. 29). Two such chains will be attracted to each other by electrical forces (Fig. 30). They are also quite strong, much more so than steel or any ordinary materials. They are even strong enough to stand perpendicular to the surface of the neutron star and can resist its immense gravitational pull, whereas ordinary materials would crumble into rubble a few atoms thick.

It is not well understood to what extent the properties of the chains, or the interactions between chains, depend on the nuclei present in them. But there seem to be ample possibilities for the creation and storage of order in the arrangement of atoms along the chain. There is also a possibility of a replication of order by the formation of new chains in paral-

(*a*)

(*b*)

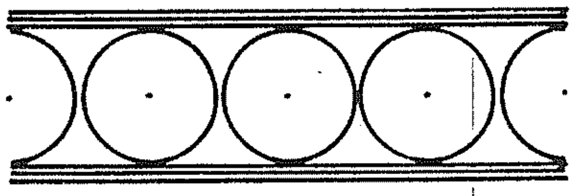

Figure 29. Magnetic atom polymers. An array of magnetic hydrogen atoms can fit together into a long polymerlike chain, in which the nuclei lie along a central line and the electrons surround this line as pictured in (*a*). For heavy atoms such as iron, some of the inner electrons will remain in roughly circular orbits, while the outer electrons will be distorted into long, thin shapes, and the polymer will appear as in (*b*).

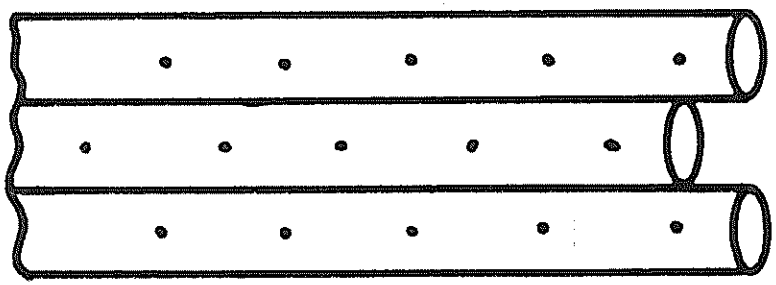

Figure 30. Binding of magnetic atom polymers. Nearby polymers will attract one another, and will bind together into a pattern in which the nuclei of adjacent polymers are displaced laterally, as shown in the figure.

lel with existing chains. This requires a source of free energy to break apart old chains, or a supply of new atoms coming off the surface. Both of these are available from outside the neutron star. A rain of energetic ions and electrons should constantly be hitting parts of the surface because of the influence of the same magnetic forces that bind Ruderman's magnetic chains. These forces can trap charged particles into orbits near the star and cause many of the particles to collide with the surface. The energy flow onto the surface of the neutron star can be larger than the energy flow out of a star like the Sun, and it is concentrated onto a very small space so that it is quite intense. These energetic charged particles can easily eject a nucleus from a chain if they hit one. This should happen about once per second for a typical nucleus on the surface of the star. Therefore, an ample supply of the building blocks for new chains should be available. As long as strong magnetic forces are associated with neutron stars, the surfaces will contain large amounts of exotic, dense forms of matter. With an energy flow available from outside, complex forms and structures may arise. Once again, we have a possible home for life.

Under the crust of the neutron star, the matter is almost pure neutrons with a 1 percent mixture of protons and electrons. It is thought that these objects form a kind of fluid, with no rigid structure extending over large distances. The fluid may have remarkable properties similar to those of liquid helium at very low temperatures. Such a "superfluid" extending over many kilometers can have a variety of types of internal motion with a potential for becoming orderly. In this case the rotational energy of the whole neutron star would provide a source of free energy to help the ordering process. Physicists are just beginning to understand some of the phenomena going on inside of a neutron star, and we may expect that as soon as these are understood, some suggestions will emerge as to the types of complex order that can be present. At that time the question of life at the highest densities we know of can be examined in some detail.

Table 11-2

SOME ENVIRONMENTS OF POSSIBLE INTEREST FOR LIFE

Environment	*How Common It Is*	*What Is Found There*	*Types of Energy Flow*
Interstellar clouds	Thousands in each galaxy. One cloud may contain a mass of a billion Earths	Hydrogen, helium, and some heavier atoms; many types of molecules; and dust grains. All are present at very low densities	Visible and ultraviolet light. Cosmic radiation
Atmospheres of giant stars	Billions in each galaxy. Each atmosphere contains more material than the whole Earth	Hydrogen, helium, and some heavy atoms. Some types of molecules. Densities are similar to Earth's atmosphere	Intense radiation from star's interior. The temperature is several thousand degrees centigrade
Solid interiors of planets	Perhaps 10^{12} in each galaxy	Heavy atoms and molecules in liquid or solid form. The density is slightly greater than Earth-surface matter	Heat from radioactive decays
Interiors of white-dwarf stars	Billions in each galaxy. Each white dwarf contains as much material as 100,000 Earths	Heavy nuclei such as carbon in a liquid or solid arrangement. Electrons float in the liquid. Densities are millions of times greater than Earth matter	Some radiation and heat flow from star's center
Solid neutron star crust	Perhaps 100 million in each galaxy. Each crust contains as much mass as the Earth	Heavy nuclei and electrons. Very intense magnetic fields. Atoms may polymerize in intense fields. Densities are like the interior of white-dwarf stars	High-energy particles from outside. Radiation from interior
Liquid interior of neutron star	Perhaps 100 million in each galaxy. Each star contains as much mass as the Sun	Neutrons, some protons, and electrons. Densities are trillions of times greater than matter at Earth's surface	Some radiation from inside. High stored rotational kinetic energy

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In our survey of the end results of stellar evolution, we have not yet discussed what happens to a star much more massive than the Sun after it uses up its supply of fusible nuclei. As far as we know now, such a star will continue to contract indefinitely even after it is composed of all neutrons, and will approach closer and closer to being a black hole. This is not the place to give a description of the properties of black holes. The most relevant one for our purposes is that no information about what happens inside a black hole can be obtained except by someone prepared to take a one-way trip inside to see. In this respect the outside and inside of a black hole are related as are the present and future. Because of this restriction, it appears idle to discuss life inside a black hole originating from stellar collapse, as we are unlikely to learn anything about it without a price that we are unwilling to pay. Enough environments which may be hospitable to life exist in the accessible parts of the Universe that we need not greatly lament omitting one from our further consideration.

It is time to return home from our tour of the Universe. We will also return in our minds to the vicinity of our own Sun, then to our own planet, to our living rooms, and the level with which we are quite familiar. We have seen a number of habitats that may be homes for more exotic and strange life forms than the betentacled monsters constantly offered us in science fiction. We will discuss some of the more exciting of these forms in the next chapter. Meanwhile, we have summarized a few of the likely environments for life in the Universe in Tables 11-2 and 11-3, just as we did in Table 10-3 in Chapter 10 for life in the solar system.

Table 11-3

A TOURIST GUIDE TO LIFE BEYOND THE SOLAR SYSTEM

Rating	Location	Possible Form of Life
★★★★		
	High interiors of ordinary stars	Plasma life
	Interiors of white-dwarf stars	High-density life
★★★		
	Interstellar gas clouds	Radiant life
	Atmospheres of giant stars	High-temperature chemical life
★★		
	Neutron star surfaces	Magnetic-atom polymer life
	Very cold planet surfaces	Solid-hydrogen life
	Black-dwarf surfaces	Chemical life
★		
	Core of ordinary stars	?
	Typical interstellar space	?

The ratings are on the same scale as in Table 10-3. Plasma life, radiant life, and solid-hydrogen life are discussed in greater detail in Chapter 12.

Physical Life

We have seen that in many of the environments found in the Universe, conditions are so different from those we know on Earth that even the forms of matter present there are unfamiliar. Yet the matter in these environments may meet the requirements necessary for life. In Chapter 11 we identified a number of locations where life based on other physical effects than molecular combinations may have developed. We will now explore in more detail the features of three possible forms of such physical life. The habitats of these speculative physical life forms vary enormously in their properties, yet they are all fairly common in the Universe. Our knowledge of these environments is almost entirely theoretical at present, so that in trying to imagine how they could evolve the complexity necessary for life, we are really extrapolating far beyond our basis in observation. Scientists have been able to do this successfully in some cases, such as understanding the very early history of the Universe, but it is never easy and always uncertain. These limitations should be kept in mind as we continue our discussions.

Our descriptions of physical life will emphasize the alternate methods by which order is stored, since this will be the greatest difference from Earthlife. The sources of free energy already cover a wide range in the forms of life we know, so variations here are less surprising, even though the range

will be much greater in extraterrestrial life. We will also make some very speculative remarks about the directions in which various types of physical life might develop and the types of organisms that might result.

LIFE IN THE SUN

So strong has been the belief that the Sun cannot be a habitable world that a scientific gentleman was pronounced by his medical attendant to be insane, because he had sent a paper to the Royal Society in which he maintained "that the light of the Sun proceeds from a dense and universal aurora which may afford ample light to the inhabitants of the surface beneath, and yet be at such a distance aloft, as not to annoy them."

Thus wrote Sir David Brewster in 1854 in describing the fate of a certain Dr. Elliot in 1787. Sir David, of course, did not agree with the diagnosis. He was engaged in a debate on the question of extraterrestrial life with Dr. William Whewell, and he was advocating the extreme case—that every globe that had been created was inhabited. To most observers at that time, a world needed to be like the Earth to be habitable. Dr. Elliot had affirmed that "vegetation may be obtained there as well as with us"; that "there may be water and dry land there, hills and dales, rain and fair weather," and that "as the light and the seasons must be eternal, the Sun may easily be conceived to be by far the most blissful habitation of the whole system."

It has been recognized, of course, since ancient times that the Sun, as the source of light and warmth for the Earth, was indispensable for life on this planet. Such diverse peoples as the ancient Greeks and Egyptians and Amerindian tribes considered it to be alive in itself and gave it divine status. As scientific knowledge increased about the nature and temperature of the Sun, these views became uncommon. Thoughts of the type voiced by Dr. Elliot represented a last-ditch attempt to rescue at least some area of the Sun as a possible home for life. These ideas were given much greater respectability when they were advocated by the celebrated astronomer Sir William Herschel. He had devised improved telescopes, made fundamental discoveries about the nature of stars, and discovered the planet Uranus.

Alas, even so noted an astronomer can be wrong. We have described the modern view of the Sun in the previous chapter. An environment with a temperature of from thousands to millions of degrees, in which matter has been converted to plasma form, would hardly be considered to be blissful for Earthlife. A modern scientist who advocated life within the Sun would be looked on as eccentric by his colleagues. And yet Sir William Herschel may, in part, have the last word. Let us quote Sir David Brewster again: "Sir William has never asserted and never did believe that the children of the Sun were to be human beings, but, on the contrary, 'creatures fitted to their condition as well as we on this globe are to ours.' "

In an earlier chapter we marked a portion of the interior of the Sun as a biosphere of promise. What type of creature would be able to dwell in this particular condition?

PLASMA LIFE

Our solar biosphere is an area below the photosphere, yet somewhat removed from the center. This is the home of the "plasmobes." It may be difficult to visualize these beings and the realm they inhabit—Plasmaland. There are no permanent spatial structures there, nor even any molecules present. Matter is in the form of a plasma and consists of positively charged ions and detached electrons, both acted on by intense magnetic forces. (Such forces have been detected on the surfaces of stars; for example, in what we know as sunspots. They probably also exist within the Sun with much greater intensity, although we cannot observe them directly.) While such an environment may seem a strange habitat, we think that it can nevertheless serve as a suitable arena

for the evolution of ordered structures, of life, and even of individual living creatures. The plasmobes are composed of patterns of magnetic force, together with groups of moving charges, in a kind of symbiosis. The possibility of living patterns of magnetic force within stars was suggested some time ago by the physicist A. D. Maude, who proposed a method by which certain patterns that occur by chance replicate themselves. In Maude's model the star gradually accumulates a large number of copies of a few such replicated patterns. This scenario is somewhat similar to the one in which Earthlife evolved after the chance production of a replicating molecule. The plausibility of this type of replication happening inside a star would depend on how complex a magnetic pattern would have to be, in order to replicate. If this can occur for very simple patterns, as Maude suggests, then life in a star might indeed arise without any need for a long period of prebiotic evolution.

The hypothetical inhabitants of Plasmaland have a more complex basis for their life, involving charges as well as magnetic forces. Their negative electrons and positive ions interact through collisions as they do in some liquids under Earth conditions. In addition, they respond to the presence of magnetic forces by modifying the way that they move, sometimes by forming arrangements of moving charges that are stable against disturbances from the outside. It is through the use of magnetic forces to produce such stable patterns of motion that Earth scientists are attempting to harness nuclear fusion for the production of useful power.

The effect of magnetic forces on charges is reciprocal, in that moving charges also influence the pattern of magnetic forces, which in turn further influences the motion of the charges. This situation, vaguely analogous to the reciprocal influence of proteins and nucleic acids in Earthlife, can lead to a more rapid growth of order than a situation in which an unvarying quality affects a mutable one.

The development of life in Plasmaland may have started with random motion patterns of the charges. Some of these patterns proved fruitful. The magnetic forces they produced in turn stabilized the patterns of motion that created them. It was a "you scratch my back and I'll scratch yours" situation. It has been found both in experiments on Earth and in calculations that such self-stabilizing arrangements of plasma can occur. Other random patterns produced magnetic forces that dissipated the charges. The frutiful arrangements persisted and, by a kind of natural selection, eventually became the dominant type. Part of the inside of the star became orderly, in the sense that only a few of the patterns of moving charges that were possible did occur, in obvious analogy to the occurrence of only a few of the many possible carbon compounds on Earth. These favored arrangements of charge, through their magnetic forces, acted on other random arrangements to convert them to the favored form. Since this represented an increase in order, a supply of free energy was needed.

The most likely source of free energy for a solar biosphere is the flow of radiation within the Sun. Since this energy originates in the center and flows outward, its intensity gradually diminishes at higher and higher levels inside the Sun. It is this difference between the intensity of radiation at different levels that would be available as free energy. The difference between the intensity at two levels one hundred meters apart deep within the Sun is greater than the flow of sunlight at Earth's surface. Also, the average energy of packets of solar energy is about the same as the energy of each charge within the plasma. This would make it convenient for plasma life to use radiant energy in its vital processes.

A real problem for plasma life is the absence of a solid surface in the Sun. Plasmobes would be vulnerable to being transported from regions where conditions were clement to other locations, such as the center, which are hazardous for them. We have already encountered this problem in connection with life in the clouds of Jupiter and Venus.

There are, however, several ways in principle of dealing with this problem inside the Sun. An object can avoid fall-

ing due to gravity by having the same average density as the surrounding material, thus achieving buoyancy. Having the same average density does not mean being identical to the surroundings, as can be seen from the case of a man floating in a swimming pool. For example, an object could have a more rarefied center and a denser outside than the surroundings and still have the same average density.

A second possibility is to utilize other forces to keep an object suspended. There are flows of material outward from the center of the Sun, somewhat like updrafts on Earth, and these can balance the gravitational pull on a dense object and keep it suspended like a glider. Alternatively, the strong magnetic forces acting within the Sun may be able to suspend some objects, particularly if they are electrically charged.

Finally, it should be recognized that some forms of life may not mind being tossed up and down inside the Sun because they may function equally well within very wide limits of environmental conditions. In fact, there may be advantages to the absence of a surface, in that this would allow free motion between widely different environments, making it possible for an organism to invent its own disequilibrium by moving from one condition to another.

How might plasma life develop if it gets started? Could the individual units, the plasmobes, speciate and become complex as has happened with Earthlife? This depends on what aspects of the system of charges and magnetic forces become ordered. The most direct way for life to become more complex is to increase its number of ordered units. In some sense, the reason that human beings are more complex than bacteria is that the DNA in a human cell contains a thousand times more bases than the DNA in a bacterium. Analogously, a larger collection of charge moving in some orderly fashion would be able to display more complex behavior than a small collection of charge. For example, the larger collection might be able to produce a greater variety of magnetic forces to influence its environment than the smaller collection, just as human DNA can produce more types of protein enzymes than bacterial DNA. Some of these magnetic forces might be arranged to repel other collections of charge, thus "defending" the organisms that produce them. Other magnetic forces might be able to attract passing charges to "feed" the present organism. These magnetic forces could be used to manipulate the environment and increase the supply of free energy by one of the methods discussed above.

The size of a plasmobe would be influenced by several factors, including the maximum amount of charge that can be effectively confined by magnetic forces, and the minimum amount of charge that can function as an ordered collection. Both these factors are difficult to estimate accurately. In a plasma like a star interior, it is possible for a magnetic force to act over very large distances so that even in a very large object, the different parts can exert an influence over each other. This suggests the possibility of plasmobes that are astronomical in size. However, it may be that a large plasmobe will tend to divide into many smaller ones because the magnetic forces are more intense over small regions than over large ones. The minimum size for a plasmobe, in terms of the number of particles needed to exert some self-stabilizing force, could be quite small, no more than a few thousand ions. But larger numbers might be needed to ensure that the configuration is stable against a wide variety of outside disturbances. The time scale for the life processes of plasmobes should be much shorter than for Earthlife of similar size because the physical processes in the plasmobes involve the motion of high-speed particles. Even though the particles do not move freely but are influenced by mutual collisions and magnetic forces, the time interval required for parts of a plasmobe to affect each other should be much less than for familiar organisms. Furthermore, the greater amounts of free energy available would have the same effect of speeding up the plasmobes' "metabolism," unless it contained many more particles than do Earth organisms. Consequently,

plasma life could either develop in the direction of much more rapid evolution and metabolism than Earthlife, or in the direction of organisms that are much more massive than those on Earth. Perhaps both these directions have been chosen.

Plasmaland itself could include a large part of the interior of the Sun, but not the deep interior. In that area the forces associated with radiation flows and high temperatures are probably much greater than the magnetic forces. The presence of such large disruptive forces would make the region hazardous for plasma life. While one tends to think of the inside of a star as homogeneous, conditions in the deep interior actually differ more from those in the outer regions than those at the center of the Earth do from those at its surface. Life that is suitable for some regions of a star might find other regions as inhospitable as humans would find the center of the Earth. However, on Earth, evolution has produced advanced life forms that were able to colonize some areas which were previously uninhabitable. It is possible that evolutionary developments within the Sun have worked similarly to produce beings capable of penetrating the central region. If so, these beings might be able to tap an additional source of energy—nuclear fusion.

It is only in the deep interior of the Sun and of other stars that the temperatures are high enough for fusion reactions to occur. The rate of such reactions can be increased by raising the temperature of the appropriate region, by concentrating the matter there through magnetic forces, or by increasing the concentration of the specific nuclei that serve as fuel. The type of plasma life we have been discussing should be capable of controlling all these factors. The energy from the fusion process would appear in the form of subatomic particles of the same type that are in the Sun already. This would pose a technical problem for any life there. The energy released in an individual fusion reaction would be much greater than the average energy of the particles inside the Sun, so it might be difficult to couple this energy to the internal order of plasma life. The problem would be analogous to the difficulty of Earthlife using an intense flow of X-rays as a source of free energy. If such problems could be overcome, then nuclear fusion could be a useful supplement to the radiant-energy flow available to sustain plasma life. Fusion energy might serve as the "food" for specialized organisms, which might then become part of an integrated biosphere, as has happened for some energy sources on Earth.

If we disregard the possibility of colonization of the center, and Plasmaland is restricted to the outer regions of the Sun, it would still constitute a biosphere immensely larger than that of Earth or any planet. The region involved is three-dimensional rather than two-dimensional, and contains a thousand times as much material as the whole solid Earth, let alone the thin surface layers that comprise the Earth's biosphere. There are of course many other stars like the Sun in the Universe. If the matter in many of them has in fact developed into life, then the scope of such life will be immensely greater than anything that can be achieved by chemical life confined to planet surfaces.

Despite this potential significance of plasma life in the Universe, it will be quite difficult for us even to learn of its existence, let alone the details of family life among the plasmobes. In Chapter 14 we will discuss possible strategies to tackle this problem in the future. Right now we want to shift our location dramatically from a very hot to a very cold spot.

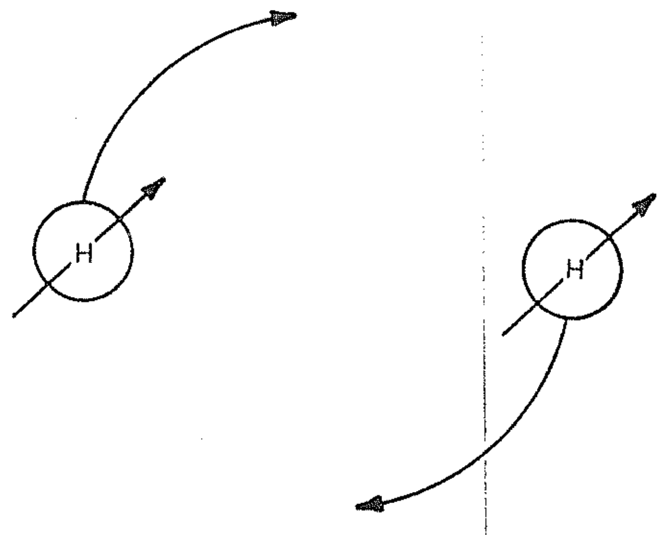
LIFE IN THE COLD AND DARK— THE CRYO-BIOSPHERE

The sun that shines on the hypothetical planet Cryobus is far less robust than ours. It is one of the cool stars that are quite numerous in our galaxy and emits only a feeble reddish glow. Cryobus itself is somewhat like our own Neptune, but is several times further removed from its faint source of warmth than is Neptune from the Sun. As a result, an un-

imaginable chill pervades the surface of Cryobus, on which the temperature is only tens of degrees above absolute zero. Most substances, even the familiar gases of our air such as oxygen and nitrogen, exist as frosty solids. Only the lightest elements, hydrogen and helium, have resisted this fate. As these are the two most common elements in the Universe, Cryobus contains a giant sea of liquid hydrogen molecules (each containing two atoms of hydrogen) under an atmosphere of helium and hydrogen. A few impurities have dissolved in the frigid hydrogen sea, but no other chemical variety exists. In fact, no chemical reactions at all take place, since molecules have too little energy to break bonds during collisions. The chemical composition of the planet and its sea is fixed.

Despite this state of affairs, small bits of living matter float in the sea. Some absorb the weak solar radiation directly, while others feed on nutrients in the solution. From time to time they reproduce themselves. They are made of almost pure solid hydrogen, with some internal trapped helium to keep them afloat (solid hydrogen sinks in liquid hydrogen), and an occasional impurity is present, such as oxygen. With apologies to the readers of J. R. R. Tolkien, we will call these beings H-bits.

Clearly, the life-styles of these organisms, their metabolism, and reproduction are not expressed in terms of our familiar chemical reactions. Fortunately, there are other internal properties which can be influenced both by collisions and by the long wavelength radiation that reaches Cryobus. Atoms in molecules can revolve and rotate in various ways, similar to dancers in a discotheque (Fig. 31). Like the dancers, the molecules will have more or less energy, depending on the amount of rotation. Cryobus is so cold that collisions between the cold hydrogen molecules will usually not suffice to start even the slowest rotation. This task can be performed, however, by the weak infrared and microwave radiation that reaches Cryobus from its sun, just as the ultraviolet radiation absorbed by molecules on Earth serves to break bonds not



(*a*) An *o*-hydrogen molecule

(*b*) A *p*-hydrogen molecule

Figure 31. The two forms of hydrogen molecules are *o*-hydrogen and *p*-hydrogen. In the *o* form, pictured in (*a*), the two hydrogen atoms revolve about a common center, while at the same time their nuclei rotate about their own axes, in the same direction as one another. In the simplest version of the *p* form, pictured in (*b*), the atoms do not revolve, and the nuclei rotate in opposite directions.

normally broken in collisions. On Cryobus, hydrogen molecules will continually absorb energy, start to rotate, and then return to rest after emitting the energy or colliding with other molecules. The different forms of rotating molecules are chemically very similar in their properties. It is not chemistry that is involved in the life on Cryobus.

Rotating hydrogen molecules come in two types known as o-hydrogen and p-hydrogen. These molecules can be compared to pairs of dancers in which each partner spins around either in the same direction or in opposite directions, as well as revolving during the dance. (See Fig. 31.) Within each type there are other minor differences that are less important than the principal one which distinguishes the types. The o-hydrogen molecules rarely convert into p-hydrogen, though the various subclasses of each type can interconvert readily. In liquid hydrogen the less stable o-form will very gradually, over many hours, convert to the p-form, though the process can be speeded if certain substances (atoms or molecules that produce magnetic forces) are present. Unconverted o-hydrogen molecules comprise a reservoir of energy which is quite large (one hundred seventy calories per gram, about as much as cabbage) compared with the heat energies of the molecules on Cryobus.

Let us imagine bits of solid hydrogen floating in the sea of liquid hydrogen. Each hydrogen molecule in the solid lattice may be either in o-form or p-form. At equilibrium, almost all the hydrogens would be in the p-form, but an inflow of energy of the right type in the presence of other molecules as catalysts can convert many of the molecules to the o-form. Since the rate of conversion of o-hydrogen back to p-hydrogen is slow and is affected by the presence of impurities, there would be many opportunities for locally ordered regions of solid to develop which would be rich in one or the other type. This process would be analogous to the chemical specificity that developed among organic compounds in the early stages of Earthlife. While in Earthlife the order is described by the relative amounts of various organic molecules in the biosphere, and by the precise arrangement of these molecules in large polymers, on Cryobus the order is described instead by the precise arrangement of o-hydrogen and p-hydrogen in three-dimensional solid lattices. If such lattices occur repeatedly on Cryobus, with o-hydrogens always in certain positions and p-hydrogens always in other positions, the situation can be as orderly as that on Earth resulting from the repeated occurrence of nucleic acid strands with a specific arrangement of bases. The immobility of the atoms in solid hydrogen does not prevent order from developing through absorption of radiation, and may in fact help preserve order by suppressing collisions that could interconvert the two forms. Situations which are a disadvantage for one mechanism in ordering matter may be a benefit for a different mechanism.

A collection of ordered hydrogen molecules and impurities could form a primitive biosphere at low temperatures, the cryo-biosphere. Such biospheres may be quite common in the Universe, since cool stars are much more numerous than any other kind, and most planets of these stars may be as cold as Cryobus. A similar locale would exist on a planet orbiting a white-dwarf star at the distance that Jupiter is from our Sun, or on a planet in an immense orbit (a light year in radius) around a cool supergiant. In order for life to develop in the cryo-biosphere, it would be necessary for specific properties of the molecules involved to act to increase the initial local concentrations of order. One suitable property is the ability of o-hydrogen molecules to convert to p-hydrogen molecules through the magnetic forces they exert on each other. It is also possible for a rapidly rotating p-hydrogen to convert to the o-form upon collision with another p-hydrogen. Thus, molecules of the two types can catalyze their own formation and destruction.

An H-bit, a more evolved bit of solid hydrogen, would contain relatively stable arrangements of o- and p-hydrogen. Thus, the outside molecules in the solid might all be stable p-hydrogen with little rotation, which would not be likely

to convert to the o-form by collision. Such p-hydrogens could be formed by allowing solid o-hydrogens on the surface to collide with o-hydrogens in the liquid, with both converting. An H-bit could obtain o-hydrogens by allowing rotating p-hydrogens to collide with its magnetic-impurity molecules (such as oxygen). These processes are analogous to the enzymatic process of Earthlife.

As H-bits have a simpler "metabolism" than Earthlife, involving only a few types of molecules in a small number of configurations, they may be able to function with a smaller amount of order than living things on Earth. They may be no more complex than our viruses, or even smaller. A requirement for a specific shape and a minimum size comes from the need to shield those parts containing the less stable o-hydrogen from the environment (except when they are needed to catalyze a process on the surface). These internal o-hydrogens must also be kept apart from one another lest they catalyze their own destruction. The o-hydrogens would best be located midway between the center and surface of the H-bit, and not densely clustered (Fig. 32). This implies a

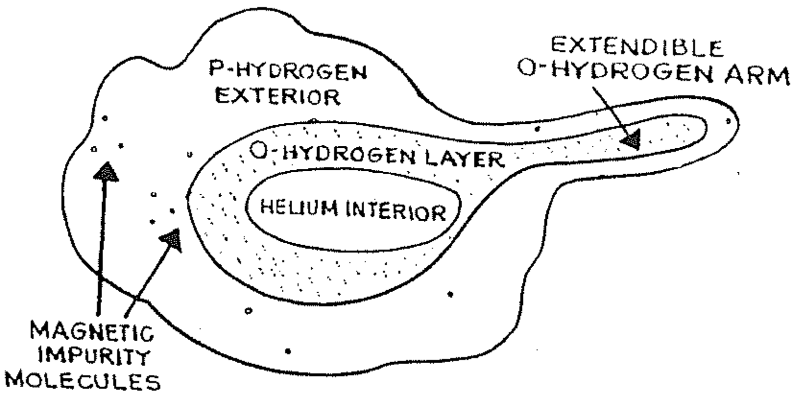


Figure 32. What an H-bit might look like. The hydrogen is in solid form, while the helium in the center is a liquid or gas. The extensible arm is used to catalyze the formation of *p*-hydrogen from *o*-hydrogen in the environment. With the addition of some magnetic impurity molecules, it can also catalyze the opposite process.

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minimum size of at least several times the spacing of molecules in solid hydrogen. The minimal H-bit would contain about a thousand molecules and be about the size of a large protein (10^{-8} meters, or about half our height when we were on the −8 level of COSMEL). The mass of this H-bit would be much less than that of the protein, since hydrogen is the lightest element.

Mechanisms for growth and replication would be useful to help us further in recognizing the H-bits as a type of life. One such process would involve the crystallization of additional hydrogen molecules onto the surface of the H-bit. If the H-bit were arranged so that some parts of it were magnetically active and some inactive, it could control the pattern in the newly formed solid, arranging directly for the production of a duplicate of itself. An alternative process could take place when an H-bit encountered an existing but disordered piece of solid hydrogen. By positioning parts of itself near the solid, it could induce order into it. The new H-bit would not necessarily be a duplicate of the original one, but might itself have catalytic activity. These active H-bits would continue to induce order in random H-bits, while the inactive ones would remain inert until they were converted to active form. In this way the catalytically active H-bits would come to dominate the cryo-biosphere.

Of course, all these processes would require free energy. Those H-bits that lie on the planetary surface or float in the ocean could use solar radiation directly. Others, in the depths of the ocean, might survive on a surplus of o-hydrogen molecules formed by the radiation and stored in the cryo-biosphere. The amounts of energy necessary to sustain H-bit life are probably significantly less than for our own. The processes involved in H-bit metabolism involve intrinsically smaller energy changes. Less energy is also needed to maintain order at the low temperatures present on Cryobus. Furthermore, the properties of liquid hydrogen would make it substantially easier for a bacterium-sized object to move about in it than in water. In all, despite the low-energy con-

tent of the radiation from the sun of Cryobus, free energy should not be a serious problem for H-bit life.

What course would evolution take on Cryobus? A multicellular structure, analogous to that on Earth, would provide similar advantages to those we enjoy. Differentiation into organs that specialize in radiation absorption, o-hydrogen capture, hydrogen-molecule conversion, acquisition of helium for flotation, and so forth would be possible. Some of the gross features of Earthlife might thus be duplicated by a cold life form based on a completely different physical basis. Other facets, of course, would be very different. As the structures involved in life on Cryobus will be based on differences in the rotation of atomic hydrogen, small H-bits and inanimate bits of solid hydrogen will look alike under visible light. An intelligent H-bit would also have a problem in deciding that an Earth bacterium was alive, given the absence of any order in the rotation of the atoms in the bacterium's molecules, just as we would have trouble in detecting life in the H-bit. In either case only by an analysis of behavior, or of the exact arrangement of the molecules within the solid, could one type of life recognize the existence of life in the other type.

RADIANT LIFE IN (ALMOST) EMPTY SPACE

In our last stop, we will revisit the interstellar clouds of gas and dust encountered in our tour of the galaxy. For purposes of contrast we will consider two such clouds. One, which we will name Chaotica, is a typical cloud of average density, remote from the center of the galaxy. Its properties are similar to the clouds described in Chapter 11. The other cloud, Radia, is denser and closer to the galactic center. Most notably, it has been transformed by the presence of a life form—radiant life.

Even in a relatively dense interstellar cloud such as Radia, the atoms and molecules comprising it are quite distant from one another, so that collisions between these particles are very rare. The density is as if a large grain of sand were in front of us and its nearest neighbor were as far away as Moon. While the atoms in the cloud do not interact easily through collisions, they can influence one another by exchanging radiation. Consequently, the process of life that takes place in Radia is profoundly different from anything in our experience with Earthlife, or even contemplated in most fantasies. It is based on the properties of ordered radiation, using matter as a necessary intermediary.

We can best appreciate the properties of radiant life if we first consider how radiation behaves in the lifeless cloud Chaotica. Radiation of various types is emitted by nearby stars and absorbed by the atoms and molecules in the cloud. Different atoms and molecules emit and absorb specific wavelengths. As we have seen, interstellar clouds contain a variety of atoms and molecules, each of which may respond to different wavelengths.

One effect of radiation on atoms is to cause them to lose electrons and become charged ions. It is another process, however, that is most relevant to radiant life. Atoms and molecules can exist in various energy levels. The presence of radiation will influence the number of atoms in each of the levels. This is a more specific effect than ionization because there is a close relationship between the type of atom or molecule and the type of radiation that can influence the population of all its energy levels. The radiation that is emitted and can be absorbed by an atom or molecule is as characteristic of that object as the types of chemical reactions it can undergo.

In Chaotica the atoms and molecules present are distributed randomly among their various possible energy levels in a pattern close to what we have called equilibrium. This random distribution of atoms will emit and absorb radiation in a wide variety of wavelengths, so that little order is present either in the atoms or in the radiation.

A very different situation prevails in Radia, which contains a large organized region, the "radiobiosphere." The

location of Radia near the center of the galaxy is advantageous for life, as it ensures that a plentiful supply of stellar radiation is available as "food" for the radiobiosphere. While other energy sources could conceivably be used by radiant life, this one is obvious and convenient. Because of its density, Radia is quite effective in trapping the photons that hit it. If we assume that hydrogen atoms are the main absorbing species, then for any cloud we can estimate the minimum size it would need to ensure that every photon is absorbed. The answer also depends on the wavelength of the incident photons. At the ordinary interstellar density of hydrogen atoms, a region about one light year in diameter would be needed to absorb each photon of ultraviolet light. On the other hand, in a relatively dense cloud with almost a hundred million hydrogen atoms per cubic centimeter, a region with the radius of Jupiter, about 10^8 meters, would suffice. It is interesting that in a dense cloud, a smaller total number of atoms is needed than in a diffuse one. The cloud with interstellar densities would contain about as many atoms as the Earth, while the denser cloud, such as Radia, would contain only about one hundred million tons of material, about the total weight of the whole human race. It is possible that a minor component of the cloud, rather than hydrogen, could be the principal absorber of external radiation for the radiobiosphere. In that event the size of the cloud would necessarily increase to compensate for the diminished concentration of the absorber.

Within the radiobiosphere of Radia, a much more ordered situation exists than inside Chaotica. Fewer types of atoms and molecules are present, and these absorb and emit radiation more selectively. Furthermore, the atoms and molecules are distributed in a more concentrated way among their many possible energy levels than in Chaotica. This results in a pattern of emitted radiation that is also concentrated in a few of its many possible wavelengths. It now resembles the radiation produced by a laser, rather than the broad spectrum present in sunlight (Fig. 15). These laser-

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like emissions are in turn reabsorbed by other objects within the radiobiosphere. A complex ordered pattern of radiation within Radia results. Furthermore, because the wavelength of this radiation also depends on how the objects emitting it are moving through space, order has developed in the motion of the atoms and molecules of the radiobiosphere.

Precisely which wavelengths are used by the life in Radia depends on the matter present and on the external energy source available to it. The photons emitted by radiating atoms can be much more energetic than those emitted by molecules. It is most convenient for the operation of the radiobiosphere that the photons of its external energy source contain more energy than those used in the transactions of radiant life, because it is usually easier to divide a high-energy photon into several lower-energy ones than to do the opposite. So a radiobiosphere such as that in Radia, based primarily on atoms, would need a source of external energy which comes in large packets, such as ultraviolet light or X-rays. In another cloud where molecules are the dominant form of matter, external sources such as visible, infrared, or microwave radiation could be used.

Although it is possible that a radiobiosphere could exist as a single integrated unit, within Radia a subdivision into smaller, independent units has taken place. Each unit is self-contained, in that it reabsorbs most of the ordered radiation emitted within it. Eventually, of course, a radiobiosphere and each of its units will emit as much energy as it absorbs, but the emitted radiation will be in a less available form, allowing order to increase within the system. If we assume that the radiation involved is visible light, we can calculate the minimum size needed to constitute such a self-contained unit. In a dense cloud like Radia, it measures only one centimeter and contains only one million atoms. On the other hand, if radiant life were to develop in Chaotica with its much lower density, the minimum size for self-containment would be about a thousand kilometers, a tenth as big as Earth.

Such subdivisions are the individual beings of radiant life. They are small enough that radiation emitted anywhere within them can reach any other point in a short time, less than one second for the largest of them. We will call them "radiobes." We can imagine a life cycle for a radiobe. It is "born" as a collection of atoms or molecules in a specific pattern of excitation. These excited atoms, under the influence of extra radiation from outside, gradually emit their own radiation in an orderly pattern. This radiation, interacting with the same group of atoms, reexcites some of them into yet another organized pattern, and this cycle of exchange of order between radiation and atoms continues, perhaps at some point pausing to emit a beam of radiation which can begin the ordering process in a nearby lifeless collection of atoms. If this process appears too physical to be considered a type of life, readers are invited to consult a similar description of the information transfer between nucleic acid and protein in Earthlife and decide whether that process is any less physical.

It is interesting to estimate how much radiation is contained in a radiobiosphere and individual radiobes. One measure of this is the number of photons in a cubic centimeter of biosphere. This depends somewhat on the details of how the photons are emitted and absorbed; but in highly evolved radiobes the photon density should approach 10^8 per cubic centimeter, similar to the density of atoms in a thick cloud. This is about the same as the photon density in the sunlight near Earth. However, that light is diffused over a wide spectrum of wavelengths, while in a radiobe the photons would be concentrated at a few specific wavelengths, which accounts for the much greater amount of order present.

A feature of the interaction between radiation and matter which aids in establishing order in the radiobiosphere is stimulated emission. Suppose an atom is in an excited condition from which it can emit a specific wavelength of radiation. If there is already some radiation of the same wavelength present nearby, the atom is more likely to emit its radiation than if it were isolated. It is somewhat like the human tendency to start yawning when those around us yawn. We have mentioned this effect in connection with lasers, as a way in which the diffuse energy input to the laser becomes concentrated into the narrow band of wavelengths the laser emits. This is a primitive form of the ordering process we are imagining for the radiobiosphere. It is also possible for the opposite effect to occur. Atoms whose arrangement is especially orderly can decline to emit as much radiation as the individual atoms would, thus prolonging the existence of the atoms in an excited condition.

How would a radiobiosphere evolve? It might start from an unordered distribution of atoms in space, together with the radiation they emit and that impinging on them from elsewhere. If the atoms and molecules present, the energy supply, and available time were all suitable, an ordered state could arise and influence the further development of order. The general principles involved would be those that influence the evolution of all life forms.

As the radiobiosphere continued its evolution, it could increase the number of ways in which it influenced its environment, just as Earthlife has. Radiation patterns could possibly influence not only the excitation of atoms and molecules but even what molecules exist. Interfering molecules, ones that absorb radiation essential to the operation of a radiobe, could be destroyed by using the proper radiation. The gravitational contraction of interstellar clouds, which ultimately leads to star formation, could threaten the existence of the radiobiosphere. Part of the cloud could be stabilized against such collapse by the outward pressure of the radiation emitted by the radiobiosphere. Such properties might be useful in helping us detect the existence of radiant life.

Some readers may have difficulty in considering that a collection of isolated atoms and molecules in space, which absorbs and emits complex patterns of radiation, is a life

form at all. We have indicated that it has the same constraints and meets the same requirements as other life forms we have discussed. It requires an energy flow from outside. Given this, it can increase in complexity and store its order. It may even form individual organisms. The difficulty in recognizing it as life would be due to our own psychological limitations, rather than to the principles that are involved.

The living beings of Earthlife function primarily through the interactions of matter with other matter. Some processes of Earthlife, such as photosynthesis, involve the influence of radiation on matter, but this influence is one-sided, in that the living matter does not affect the radiation except to absorb some of it. Matter is the major component of the life we know and of any life forms that have usually been imagined. It would be quite fitting however that electromagnetic radiation is the basis of a form of life. It is in many respects as significant a component of the Universe as what we know as matter. It is more widely distributed than matter, and in some circumstances in the center of hot stars, radiation can even be as densely packed as matter is on Earth.

In radiant life, radiation acts on matter in a way that causes it to emit related radiation. In other words, matter is a tool used by radiation to produce order in itself, in the same sense that proteins are a tool used by nucleic acid in Earthlife to replicate itself. It is probably more correct in either case to consider both components as an essential part of the life process, but we have used the term "radiant life" to emphasize the novelty of ordered radiation within the life form.

It appears less likely that radiant life, completely free of matter, could exist. Radiation, unlike matter, is for the most part indifferent to itself. While two chunks of matter that are near one another can affect each other's behavior through collisions, two independent flows of radiation will usually pass through each other without having any sig-

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nificant effects. The role of the lonely atoms and molecules in Radia appears vital.

On the other hand, when there are substantial amounts of matter in a locality, the interactions of the matter with itself would obscure the effects of the radiation. Interstellar space, where radiation is plentiful and matter is sparse, is the ideal setting for radiant life.

In our comparison of Radia and Chaotica, we have suggested two factors, energy supply and density of matter, that might lead to the evolution of a radiobiosphere in one locality and not in the other. Other factors such as time may also play a vital role in determining whether such life develops.

We do not know how long it would take to evolve radiant life in a suitable region of interstellar space, or whether any radiobiospheres exist at present. Radiation processes are usually thought of as extremely rapid, but that is because we generally observe them in a small region of space. Even light takes years to travel over the astronomical regions that comprise early radiobiospheres. Other slow physical processes, which we have not considered, may hinder their development.

For these reasons we cannot be certain that radiant life exists in the Universe. The same is true for the other forms of physical life that we have discussed. Such definite predictions would go far beyond the current abilities of theoretical science. The examples we have given were meant to demonstrate that life forms based on physical, rather than chemical, processes are possible. If we are correct in thinking this, then it is likely that such life does exist and makes its home in such common environments of the Universe as stars and dust clouds. It is less important whether such life is precisely of the types we have discussed than whether some does exist. We can only learn this by further observation, exploration, and deduction.

Chapter 13

The Creatures of Elsewhere

In this book we have concentrated on the underlying principles and mechanisms by which life in other places than Earth might function. We have also considered the types of biosphere that could develop in these places. The first topic is equivalent to the subject matter that molecular biology deals with in studies of Earthlife, while the second is related to ecology. Most past speculations and fictional accounts of extraterrestrial life, on the other hand, have emphasized a question that falls between these two; that is, one that lies within the scope of zoology and botany: What creatures do other worlds have to offer compared with the ants and elephants, humans and Sequoias of Earth?

One of the remarkable things about Earthlife is the tremendous variety of creatures that have evolved, all sharing the same underlying mode of chemical storage of order. On Earth superficial differences in appearance or behavior mask this underlying similarity. When the basic living process is very different, we might expect great variations in appearance and gross behavior from the creatures of Earthlife. But eerie parallels between Earthlife and other forms may exist in spite of great differences in their bases of life. An analogy to this exists on Earth also. While mammals, birds, and reptiles differ significantly in their physiology,

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