1-1-1968

The Origin, Structure, and Evolution of the Stars

D. H. McNamara

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A glance at the stars on a dark, moonless night away from the lights and other distractions of the city is one of nature's most rewarding scenes. Although the number of stars in the dark vault of the heavens appears to the eye to be incredibly large, only three thousand are visible at any one time. But with the aid of even small telescopes it is possible to observe a million stars, and we are able to photograph well over a hundred million stars with a 200-inch telescope at Mount Palomar. All these stars belong to a unit in space that we commonly call the galaxy, although our galaxy is only one among millions of other galaxies that are found in the universe.

Even to the eye the stars are not uniformly distributed over the sky. They appear to be strongly concentrated to a faint diffuse band of light that we call the Milky Way. The stars tend to concentrate to the Milky Way because the galaxy is a flattened disk, as illustrated in Figure 1. As we look along the plane of the disk, we observe the largest number of stars (corresponding to the Milky Way). At right angles to this plane, the stars thin out rapidly and we see only the stars that might happen to be relatively close to us. As illustrated in Figure 1, the sun lies near the central plane of our galaxy about 27,000 light-years (one light-year equals 6 trillion miles) from the galactic center. The sun is one of approximately 200 billion stars found in our galaxy and revolves in an orbit around the galactic center in a period of approximately 200 million years. Although the total number of stars in the galaxy is very large, the average distance between them (4 light-years) is very great. Let us assume for a moment that we can
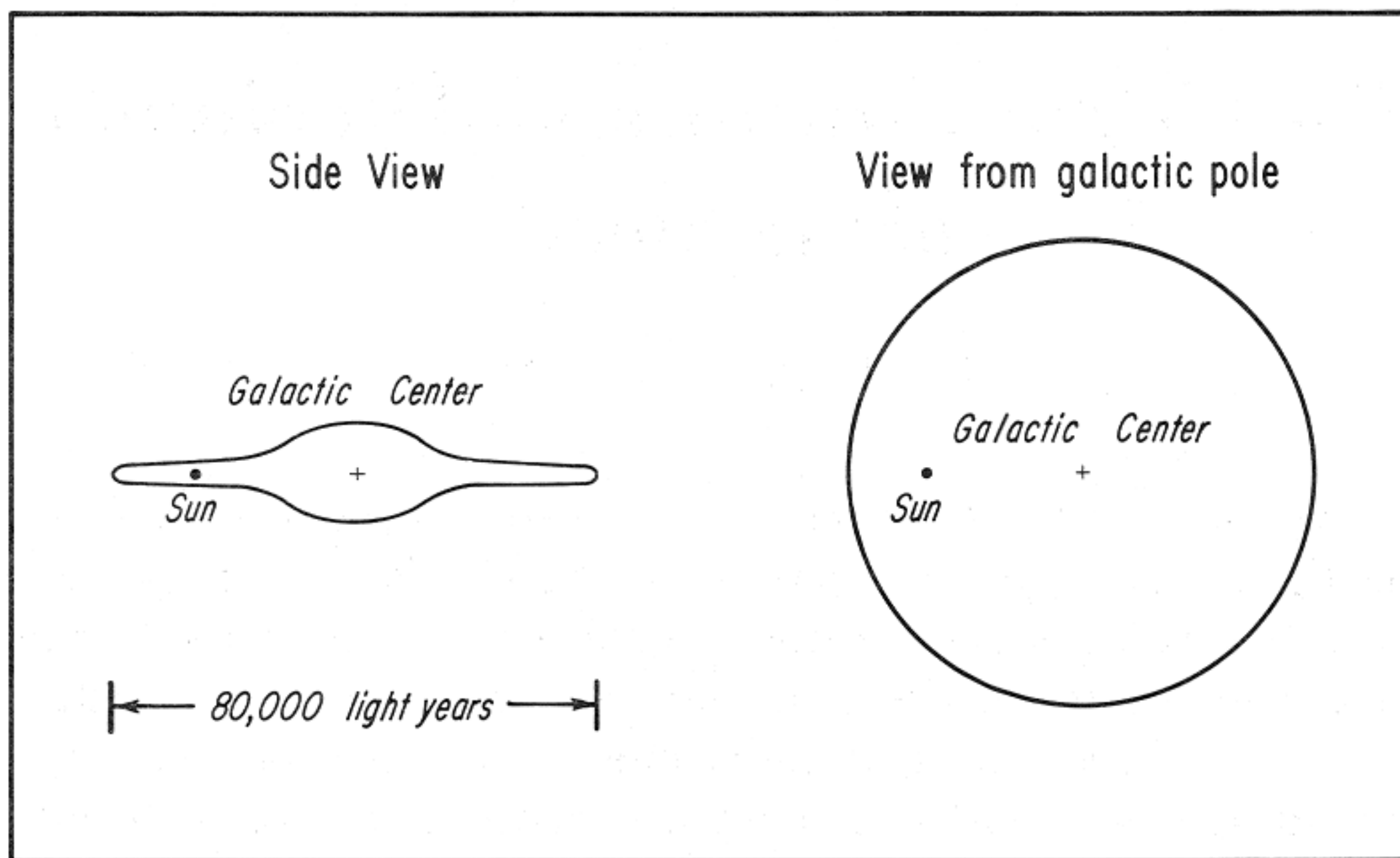

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Figure 1. A model of our galaxy. The solid lines define the region within which the majority of stars are found. The sun is located approximately 27,000 light-years from the galactic center.

shrink the stars down to the size of marbles. On this scale the average distance between the stars would be about fifty miles.

THE STRUCTURE OF STARS

Stars, like people, show a great diversity in their physical characteristics. We find, for example, considerable differences in size, temperature, color, mass, luminosity, and other properties. One of the most fruitful ways of investigating the physical properties of the stars is to plot their colors against their luminosities. This type of plot is known as a color-magnitude or Hertzsprung-Russell diagram (H-R diagram for short). This diagram is based on brightness measurements of stars corrected for distance and accurate measurements of colors or surface temperatures. The vertical scale is the intrinsic brightness (luminosity) expressed in terms of the sun's brightness. This is identical to the ratio of the energy radiated by the star to the energy radiated by the sun. The color or temperature is plotted along the horizontal scale with the blue or high temperature stars on the left and the red or low temperature stars on the right. Figure 2 illustrates the positions occupied in the H-R diagram by the stars found in the neighborhood of the sun. The shaded areas indicate a strong concentration of stars;
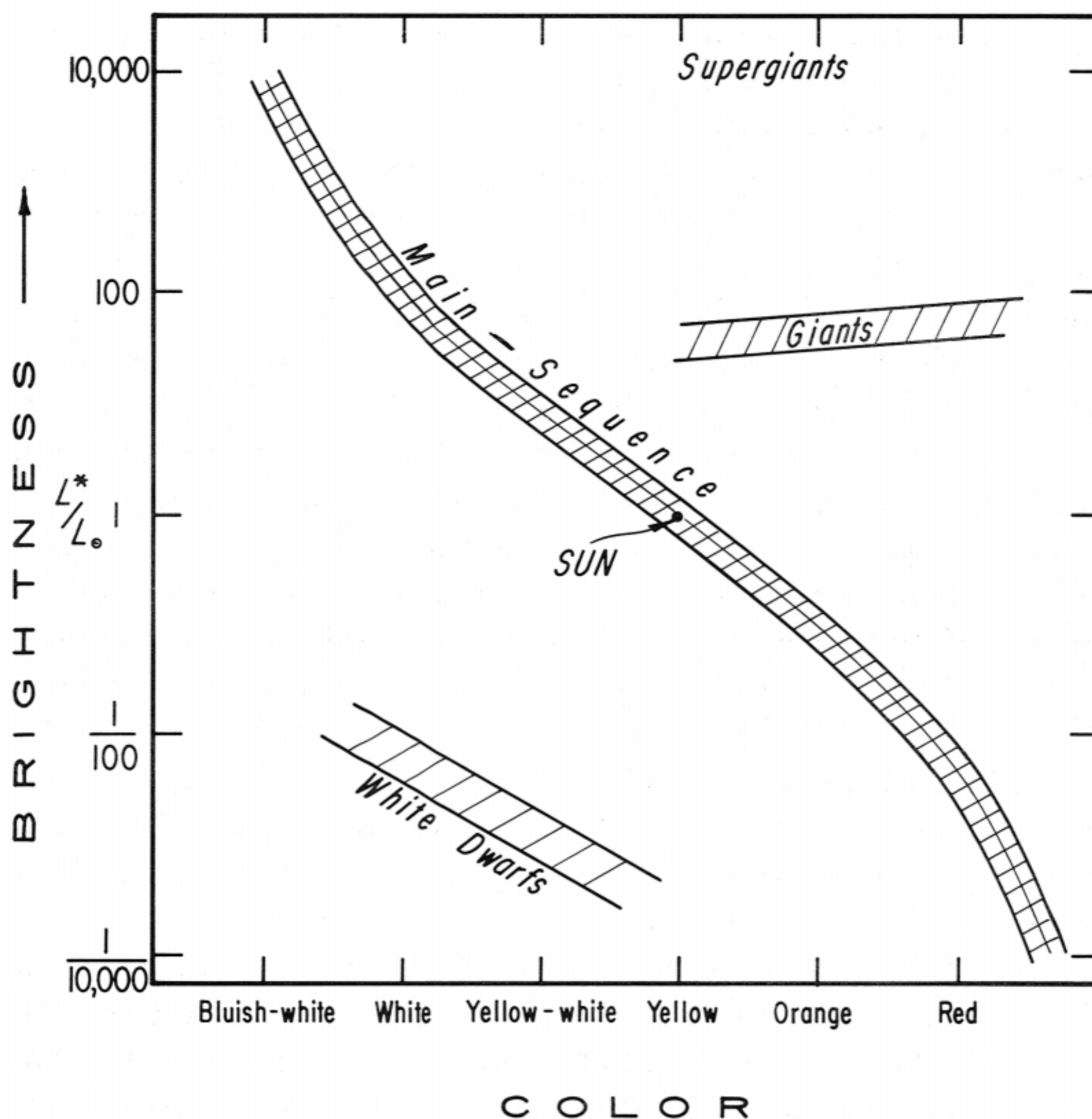
Figure 2. A schematic H-R diagram of stars found in the neighborhood of the sun. The horizontal coordinate is the star's color and the vertical coordinate is the brightness where the star's brightness, L*, is expressed in terms of the sun's (L.) brightness. The majority of stars fall along the main-sequence. The other stars fall principally in the giant or white-dwarf regions.

few stars are found outside these areas. Most of the stars in the solar neighborhood fall on a diagonal line called the main-sequence. The sun itself is a yellow main-sequence star with a surface temperature of 10,000° F. The blue-white stars at the upper end of the main-sequence with surface temperatures of about 50,000° F radiate ten thousand times as much energy as the sun, while the red main-sequence stars with surface temperatures of 5,000° F radiate only one ten-thousandth as much energy as the sun. In a sample volume of space, the lower main-sequence stars far outnumber the upper main-sequence stars.

Although the majority of stars lie on the main-sequence, we do find stars that populate other well-defined regions of the diagram—for instance, the yellow, orange, and red giants that are about 100 times brighter than the sun lying above and to the right of the main-sequence. A few stars are found in the supergiant region at the upper edge of the diagram; and another group of white and yellow stars, hundreds of times less luminous than the sun, called white dwarfs, is found in the lower left region of this diagram. Since a yellow super-giant star at the same temperature as the sun radiates the same amount of energy per square inch of the surface, it must have a surface area 10,000 times greater than the sun or a radius 100 times greater (since surface area is proportional to the square of the radius) to radiate 10,000 times as much energy per second. By a similar argument we can show that a typical white dwarf star must have a radius about 1/100th that of the sun or about the size of the earth itself. By studying the positions of stars in the H-R diagram, we have discovered that stars differ enormously in their sizes and also in the amount of energy they radiate.

A significant question of physical makeup of stars arises: What is the most fundamental physical difference between the low-luminosity red stars of the main-sequence and the high-luminosity blue stars of the upper main-sequence? The answer to this question can fortunately be given because many main-sequence stars are double stars. As a matter of fact, as many as one-half of the stars that appear single to the eye are actually binary systems. These stars move in orbits around their common center of gravity, indicating they attract each other. Since the force of attraction between them depends on their masses, the measurement of this force allows us to "weigh" them—that is, to find their masses. The data available from double stars indicate that the low-luminosity red stars have masses about one-fifth the solar mass. The yellow stars that lie near the sun in the H-R diagram have just one solar mass, and the upper blue-white main-sequence stars are as much as twenty times as massive as the sun. These results lead us to an important discovery: the mass-luminosity relation, which indicates that the more massive stars are the more lumi-nous and thus expend their fuel at a much faster rate than low mass stars. The luminosity depends very critically upon the

mass. If the mass is doubled, the luminosity is increased by twelve. Evidently the most fundamental physical characteristic of a main-sequence star is its mass. The mass determines the luminosities and surface temperatures.

THE ORIGIN OF STARS

Now that we have considered some of the basic physical properties of the stars, I want to raise some issues that perhaps you have never thought about before: How and when were the stars born? Are stars being formed at the present time? What is their ultimate fate?

To make a beginning with the first question, we must realize that the space between the stars (interstellar space) is not entirely empty. Scattered throughout the galaxy is a diffuse gas, consisting primarily of hydrogen atoms, that is concentrated frequently in clouds. The interstellar gas is so rarefied that a volume element of one cubic inch in interstellar space would contain only one or two atoms. Some of the cloud complexes, however, would contain a thousand times as many atoms. In addition to the gas, we find tiny dust particles about the size of the wavelength of visible light (0.00001 inches) that are very effective in scattering the light of distant stars—acting like a smog to hinder our view.

Although the interstellar gas and dust are a very low density medium, the galaxy is so huge that the total mass of this material accounts for about one-tenth the mass of the galaxy—quite enough to provide material for the formation of new stars. Astronomers believe that initially the galaxy was an ellipsoid of gas that tended to flatten to its present form because of its rotation. The physical processes by which the first stars were formed are not well understood, but local condensations of gas may have cooled and the hotter surrounding gas caused the cooler gas to begin to contract under compression. We have already pointed out that at the present time the interstellar medium is tied up primarily in cloud complexes. A typical cloud may be thirty light-years in diameter and contain enough material to produce a hundred stars. Figure 3 is a photograph of such a cloud or nebula in the constellation of Monoceros. The cloud shines by virtue of the high-luminosity stars embedded in the nebula, and some dark foreground

clouds are seen projected on the nebula. Once the clouds begin to condense, they continue to contract under their gravitation. Many astronomers believe that some of the small dark globules found throughout the bright nebulous regions (as can be seen in Figure 3) are the initial phases of star formation. As the protostar continues to contract, one-half of the potential energy stored up in the gravitational field is converted to heat and
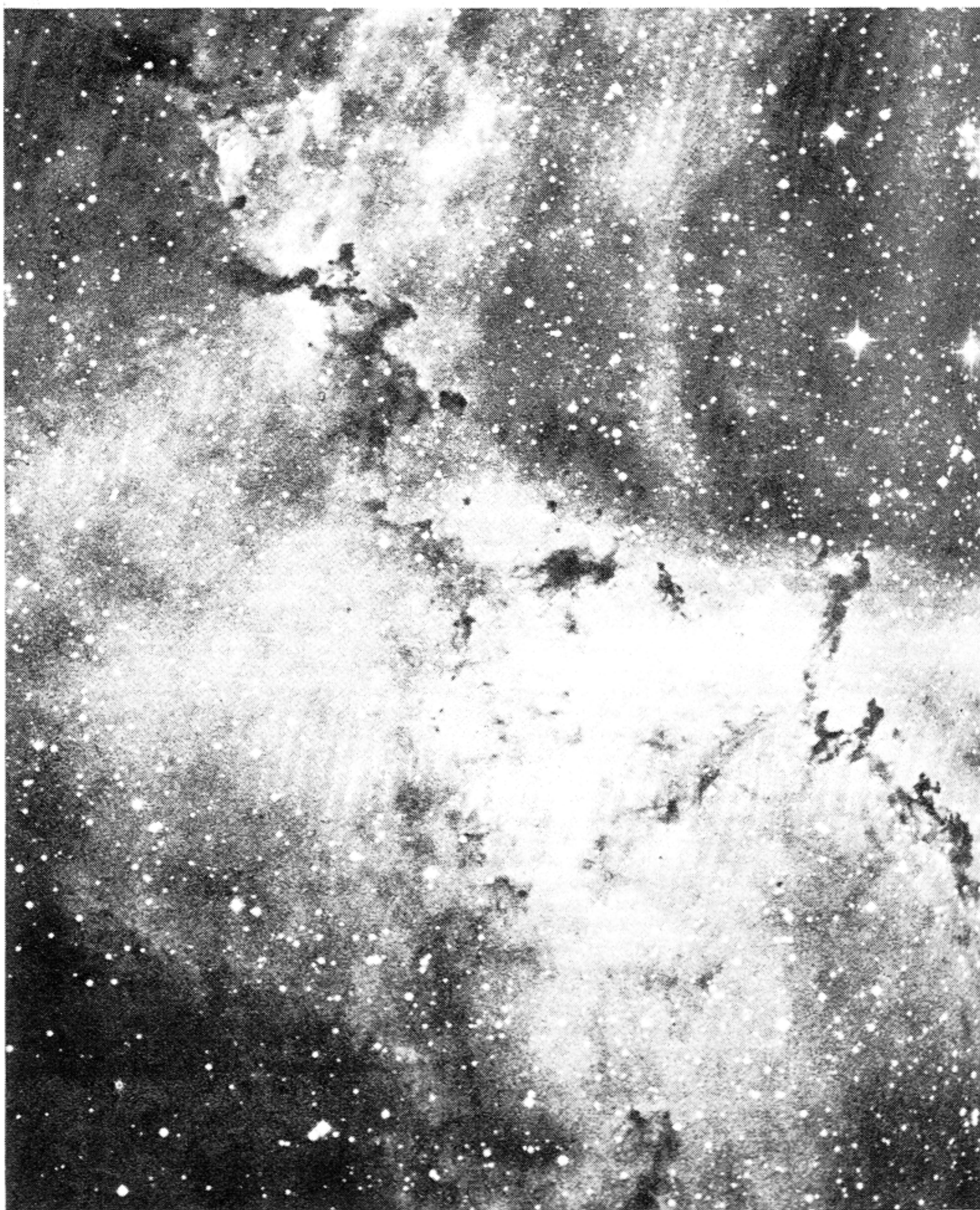

Figure 3. Nebula in the constellation of Monoceros photographed in red light with the 48-inch Schmidt telescope. This nebula is particularly rich in dark globules (dark clouds seen projected on the bright nebula).

increases the central temperature and the other half is simply radiated away.

Why does the protostar stop contracting? Precisely, as pointed out above, because the internal temperature rises, and when the temperature reaches a certain critical value, energy begins to be generated in the interior. Eventually the energy generated in the interior compensates for the energy radiated away on the surface. Contraction ceases and we end up with an enormous sphere of hot gas, with a central temperature of the order of fifteen million degrees. The star is now in a state of delicate balance—the gas and radiation pressure that tend to force the star to expand are just balanced by the gravitational force that tends to make the star collapse. Sophisticated mathematical calculations on large computers indicate that when the energy produced in the interior compensates for the energy losses at the surface, the star is a typical main-sequence star. If the protostar starts initially with twenty solar masses, it reaches the main-sequence at the upper left of the H-R diagram along the evolutionary track (dashed lines) shown in Figure 4. A protostar with one solar mass will reach the same position in the H-R diagram occupied by the sun; if it has twice the mass of the sun, it will reach the main-sequence with twelve times the sun's luminosity, and so on. Note that the gravitational contraction stage is much shorter for the more massive stars than the less massive stars. For example, the sun requires about fifty million years to pass through the contraction stage, whereas a star with twenty solar masses requires only 300,000 years, as indicated in Figure 4.

Having reached a stage of equilibrium, how long do the stars remain on the main-sequence and what type of stars do they become after leaving the main-sequence? To answer this question we must first identify the source of the star's energy. We have already pointed out that the internal temperatures of main-sequence stars are very high—on the order of 15,000,000° F to 30,000,000° F. Indeed, if we could peel off the outermost layers of the sun and expose the earth directly to the intense radiation of the inner part, the earth would be vaporized within a few minutes. At such high temperatures the electrons are stripped from the nuclei of the atoms, and the nuclei move about at very high velocities. Collisions between the particles are very frequent—most of the time they merely bounce off

$$t_{(life\ time)} = 10^{10} \left(\frac{Mass\ *}{Mass\ ^\circ} \right) \left(\frac{L_\circ}{L\ *} \right) \ (\ years \ )$$

Time Spent as a Main-Sequence Star & Gravitational Contraction Stage
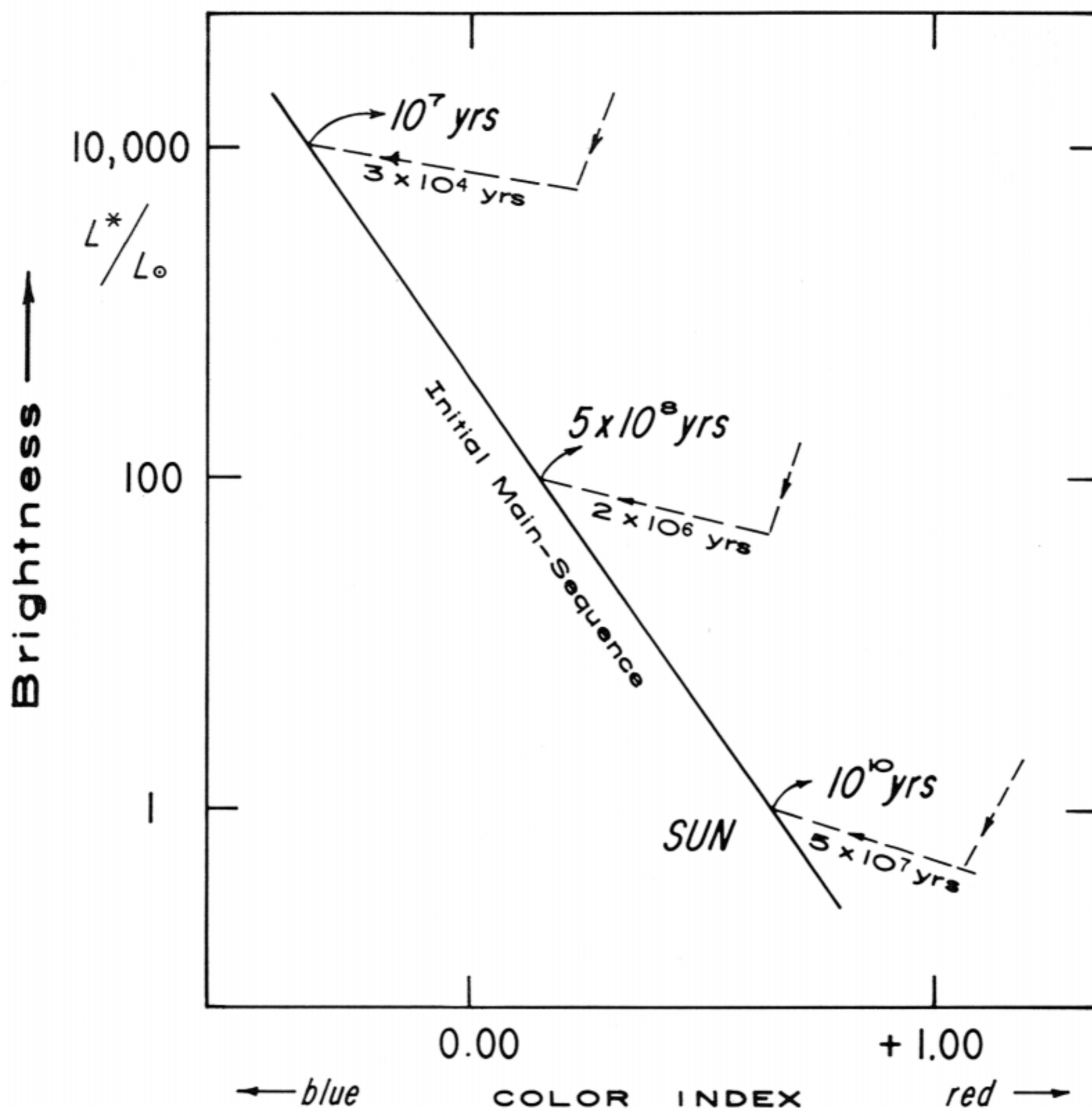

Figure 4. Evolutionary tracks on to (dashed line) and off (solid lines) the main-sequence. The times given are the intervals of time required for a protostar to contract to the main-sequence and the time intervals a star remains on the main-sequence.

each other, but occasionally they will interact in a nuclear reaction to form a heavier nucleus and release energy according to the Einstein equation, $E = mc^2$, where E is the energy released when a mass, m, is transformed into energy. The symbol c is the velocity of light.

There must be an enormous amount of nuclear fuel to have kept the sun shining at about its present rate for the last five billion years (the estimated age of the earth). A study of the possible nuclear processes shows that nuclear reactions involving the most abundant element *hydrogen* can successfully

account for the energy radiated by the sun and stars. There are two series of reactions, which we shall not describe in detail here, that provide the energy at the central temperatures calculated for main-sequence stars. Both of these reactions have the same final result—the conversion of four hydrogen nuclei into one helium nucleus. About seven-tenths of one percent of the mass is converted to energy. Utilizing Einstein's equation it is easy to show that the sun must convert four and a half million tons of matter into energy every second to maintain its present brightness. In the deep interior of the sun this would require more than 500 million tons of hydrogen converted to helium each second.

THE EVOLUTION OF STARS

How long can the sun shine, expending energy at its present rate? The sun has only so much hydrogen; and, when it is used up, the sun must change its structure. Starting with the "cosmic abundance" of hydrogen, it is easy to show that the sun will exhaust twelve percent of its hydrogen supply in about ten billion years. The twelve-percent value has been chosen because calculations with large computers show that a star begins to evolve up and to the right of the main-sequence when about twelve percent of its mass of hydrogen is converted to helium. Ten billion years is the time interval that the sun will remain a main-sequence star. Since the sun is probably about five billion years old at the present time, it is a middle-aged star.

Now the mass-luminosity relation that we have alluded to previously indicates that the more massive a star is, the brighter it is, which implies that it expends its fuel at a greater rate. As we have pointed out previously, if the mass is doubled, the luminosity is not just doubled but increased by a factor of about twelve. The more massive stars are spendthrifts, expending their energy at prodigious rates—so rapidly they cannot last very long. We may calculate the time a star spends on the main-sequence with the aid of the equation

$$\dagger \text{lifetime (years)} = 10^{10} \left(\frac{\text{Mass*}}{\text{Mass}_\odot} \right) \left(\frac{\text{Lum}_\odot}{\text{Lum*}} \right),$$

where $\text{Lum}_\odot$ is the luminosity of the sun and Lum* is the luminosity of the star. For example, a star of ten solar masses radiating 10,000 times as much energy as the sun would remain

a main-sequence star for only ten million years (10^7 yrs.)—a brief moment compared with the sun's age. On the other hand, a main-sequence red star, with a mass of one-half that of the sun, radiating energy at the rate of one one-hundredth that of the sun could remain on the main-sequence for more than a trillion years (10^{12} yrs.); practically indefinitely. The solid curve in Figure 4 illustrates the evolutionary tracks of stars off the main-sequence and also gives the time spent as main-sequence stars for stars in different regions of the H-R diagram. Our calculations indicate that the more massive stars "burn" their fuel so rapidly they cannot last very long. Some of these bright stars must have been formed more recently than the earth, perhaps some even as recently as the appearance of early man. By the same arguments, there must have been stars that were in the sky a billion years ago that exhausted their energy supplies and simply faded away.

It may appear surprising at first that when a star begins to evolve away from the main-sequence it moves to the right in the H-R diagram. When about twelve percent of the hydrogen fuel has been burned, the helium content is built up in the interior—the core consequently contracts, releasing energy that forces the outer layers to swell and become cooler. The energy source is now shifted to an envelope around the core, as illustrated in Figure 5. The increase in the luminosity of the star resulting from increased size more than compensates for the decrease in luminosity caused by the drop in temperature, so the star moves up and to the right in the H-R diagram. This continues until the star becomes a red giant. At this stage the central temperatures may be high enough ($200,000,000°$ F) to ignite helium as a new nuclear fuel. In this new reaction helium nuclei are converted to the nuclei of carbon and other heavier elements. The length of time that a star remains a red giant is not well known, but the observational evidence indicates that it is short compared to the main-sequence phase.

What chance does the astronomer on the earth have of catching a star going through some of the antics that we have described? It is practically impossible because star aging is slow on the timescale of human life. On a relative scale the "lifetime" of a star like the sun is about 10^8 greater than the lifetime of a man.

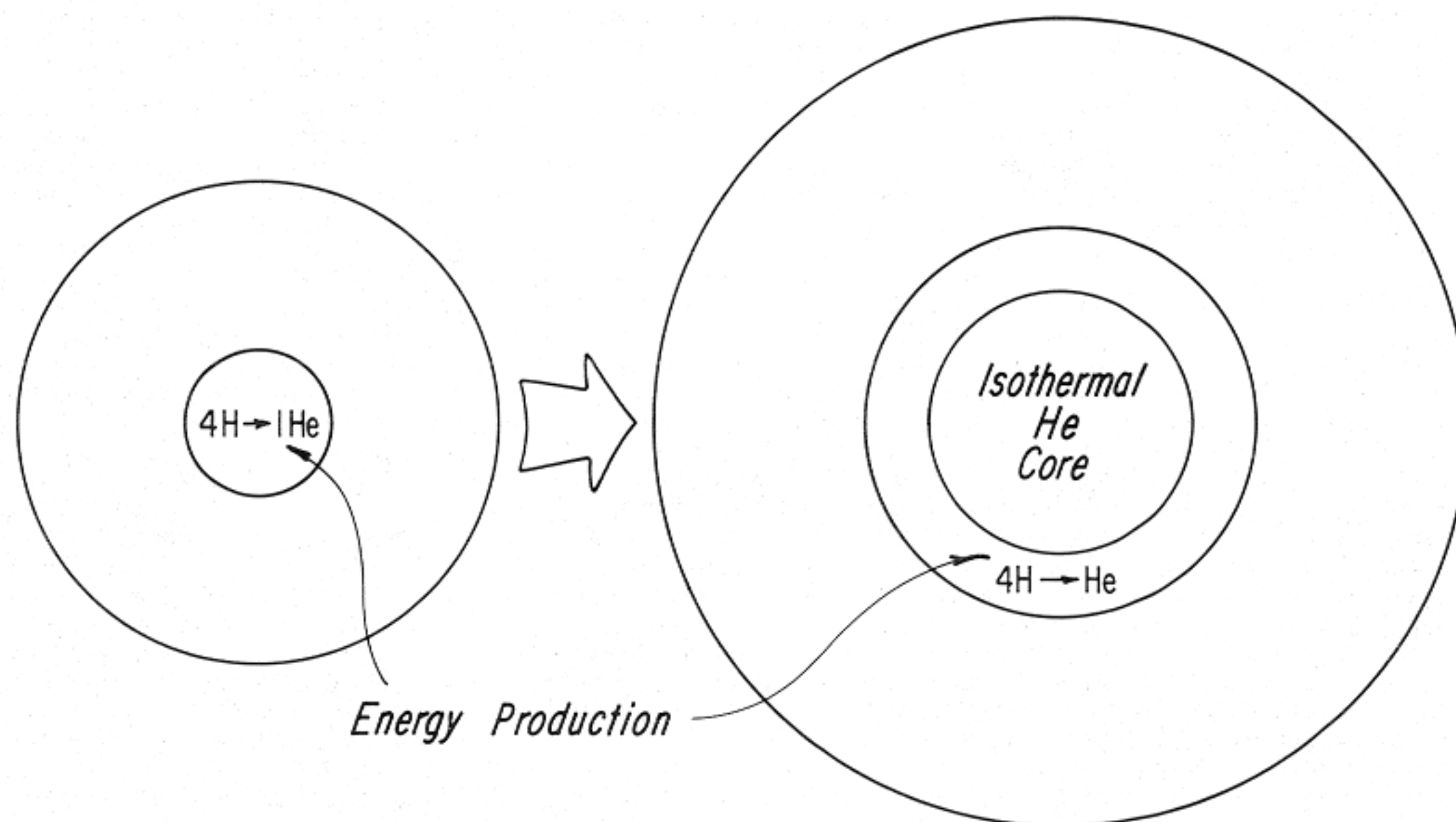## Changes of Internal Structure of Star With Time

Figure 5. A star's expansion as the energy-producing region is shifted from the core to an envelope around the core.

To illustrate our problem let us imagine that a visitor from another planet has arrived here in Provo to observe the birth, growth, and death of human life. To make his observing time commensurate with the astronomer's, we can allow him only five seconds. Humans do not change in this time interval—and neither do the stars in the lifetime of an astronomer. Consequently, indirect methods are required to verify our theories, but we do not have to wait for the changes to occur if we can identify, by observations, which are young stars, which are old stars, and what the course of evolution may be in between.

Fortunately, many stars are frequently found in large groupings called clusters, as illustrated in Figure 6. These stars must have all been formed at approximately the same time in a space roughly the size occupied by the group at the present time. One of the important advantages in studying these clusters is that all the stars are at the same distance so that differences in apparent brightness correspond to differences in their true luminosity. Now even a cursory examination of a cluster such as that shown in Figure 6 indicates that stars differ considerably in brightness and consequently must differ in their masses—because of the mass-luminosity relation. A specific cluster, therefore, affords us an opportunity to study the effects evolutionary changes have on individual stars; and moreover, by

Figure 6. The galactic star cluster NGC 2682 in the constellation Cancer.

comparing one cluster with another, we can anticipate finding differences between them that may reveal the stellar aging process.

We have already pointed out that when a star depletes its hydrogen supply by about twelve percent, it moves to the right in the H-R diagram. According to the equation on page 15, the more massive stars will evolve first because they consume their hydrogen supply faster. Figure 7 shows how we would anticipate individual stars to move away from the main-
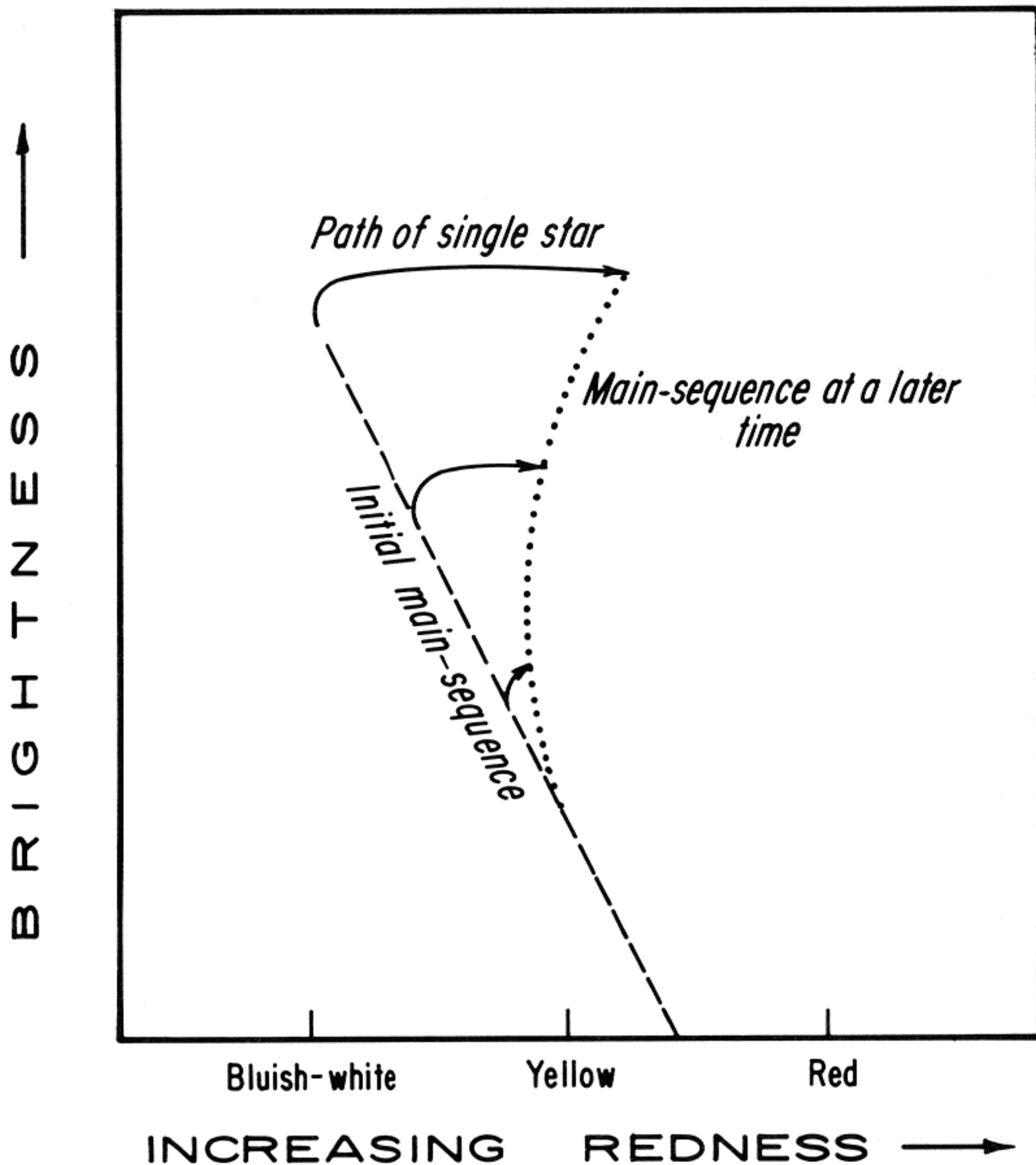
Figure 7. The predicted evolution of stars away from the main-sequence. Note how the more luminous stars change most rapidly and how the main-sequence becomes curved to the right with the elapse of time.

sequence. The brightest and more massive stars have evolved considerably, while the less massive stars on the main-sequence have not yet moved significantly from their positions on the initial main-sequence. This "turn-off" from the main-sequence is actually verified by studies of star clusters. Figure 8 shows the H-R diagrams of several clusters. It is evident that the h and x Persei cluster has upper main-sequence stars well represented as well as a number of supergiant red stars. The Pleiades cluster, on the other hand, shows a "turn-off" from the main-sequence and has no stars brighter than 1,000 times the bright-
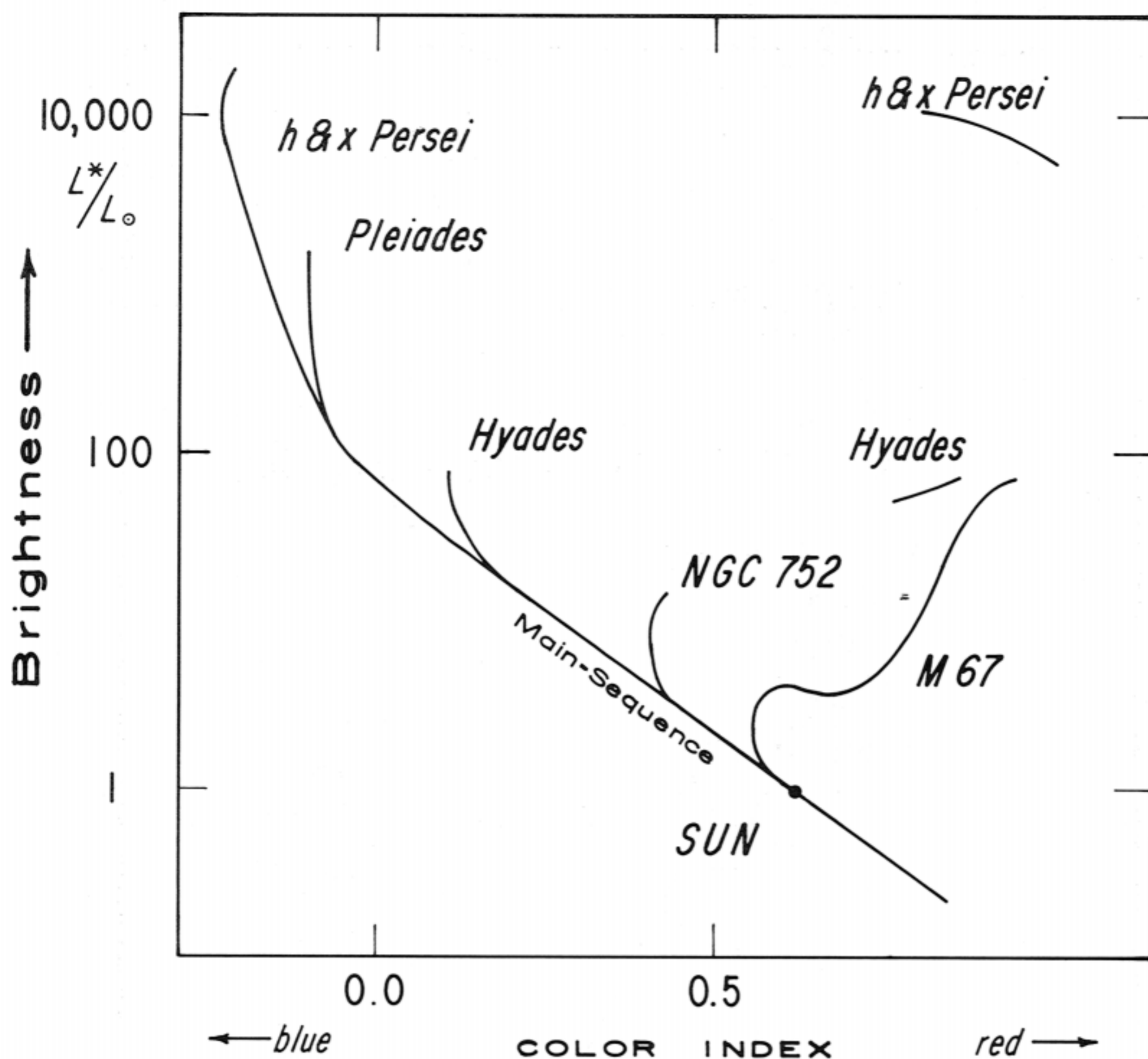
H-R Diagram of Several Star Clusters

Figure 8.   The observed H-R diagrams of five star clusters are shown. Note how the "turn-off" from the main-sequence differs from one cluster to another. According to theoretical calculations h and x Perei is the youngest cluster and M 67 is the oldest.

ness of the sun; while the Hyades cluster has no members brighter than 100 times the brightness of the sun. The M 67 cluster has the lowest "turn-off" point lying just above the sun. Note how the brighter stars of M 67 are red giants lying just below the Hyades red giants.

It is clear that the h and x Persei cluster is the youngest and M 67 must be the oldest. The two youngest clusters, h and x Persei and the Pleiades, are still associated with bright and dark interstellar clouds. In an older cluster like the Hyades or NGC 752, the more massive and luminous stars have depleted their hydrogen fuel and have evolved off the main-sequence through the red giant stage and faded out, possibly passing through the white-dwarf stage (the celestial grave-yard). The only stars now left are the less massive ones, which

expend their fuel less rapidly and consequently have longer lives.

It is of interest that the ages of the clusters can be determined from the "turn-off" points in the H-R diagram. For example, the ages of stars in the h and x Persei cluster are between 5 and 10 million years; in the Pleiades cluster, 100 million years; in the Hyades cluster, 1 billion years; and in the M 67 cluster, about 10 billion years.

It is not entirely clear just what happens to the stars immediately after the red-giant stage, but the observational evidence indicates that they probably move from the right to the left on a roughly horizontal track. After all energy sources have been exhausted, the star must collapse and become a white dwarf. Before a massive star can become a white dwarf—the kind all good stars become when they die—it must eject vast quantities of gas back into the interstellar medium, because white dwarfs cannot have masses exceeding one and two-tenths the solar mass.

SUMMARY

In summary, stars form from contracting gas and dust clouds composed chiefly of hydrogen. They contract in relatively short astronomical time intervals. The contraction is arrested when they begin to convert hydrogen into helium as main-sequence stars. The time spent as a main-sequence star depends upon the mass—the more massive stars departing first from the main-sequence. Stars evolve to the right in the H-R diagram and become giant stars expanding and probably ejecting matter back into space, and then pass rapidly through a number of other stages until they collapse and become white dwarfs when all energy sources have been depleted. The white dwarfs gradually cool and probably end up as cold clinkers in the heavens.

The theory of stellar evolution indicates that the lifetime of a star like the sun is almost staggering, but we are at the same time inescapably faced with the fact that such a star is not a timeless structure. All the available evidence we can muster indicates that some time in the future (perhaps five billion years from now) the sun will evolve rapidly to the red-giant stage. The energy output will increase by 100 times its present value. The surface temperature of the earth will

increase to such a high value that life on the earth will be impossible. After all its nuclear fuel has been used up, the sun will begin to collapse to become a white dwarf, no larger than the earth in size. With further passage of aeons of time, the sun will cool from a white dwarf to a dull red one and finally will fade completely away.

The theory of stellar evolution outlined above meets all the tests of a great scientific theory: relative simplicity, fruitful in its predictions and explanations, and intellectually satisfying. It gives the astronomers a broad framework to view the way we have come during the last fifty years of stellar research and points the direction we must go in the future. Like many scientific theories, part will prove to be wrong, but an appreciable part is almost certainly correct. Only a future generation of astronomers will be able to sift out the errors that are now undetected.

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