THE BIRTH AND DEATH OF A STAR

Astronomical studies of the life histories of the stars lead to some interesting speculations about our own future

by ALLAN SANDAGE

THE MASTER PROBLEM in the field of stellar evolution is to describe, explain, and understand the life histories of the stars, from the time they were created and began to shine, until the time they exhaust their fuel supply and become dark clinkers on the stellar ash heap.

It was not so many years ago that the topic of stellar evolution was considered to be nothing but speculation—a fit subject of conversation on those dark and stormy nights when observational astronomers have leisure. But today, stellar evolution is a rapidly developing field of astronomical research, touching almost every branch of astrophysics. The genesis of this change occurred in 1938 when the physicist Hans Bethe found that the source of stellar energy is atomic. Reasoning from general principles of nuclear physics, Bethe outlined the now famous set of catalytic nuclear reactions called the carbon cycle, which operates in the stars and which converts four hydrogen atoms into one helium nucleus with a subsequent release of energy. This discovery opened the door to detailed studies, both by the theoretical astrophysicists and the observational astronomers, of the way in which the structures of the stars change as they age.

The problem of tracing the life history of a single star like the sun is most difficult because the time scale for stellar evolution is enormous. Put in familiar terms, the astronomical problem is similar to the dilemma of a biologist if he were required to describe the aging process in human beings by observing the human scene for half a minute. We shall later see that the life-span of the sun is about 12 billion years. Because the human span is short, any particular astronomer can observe the sun for less than one part in a hundred million of the total solar lifetime.

Now, obviously, the biologist cannot direct his attention to a single individual and expect to find evidence of aging in 30 seconds. He must rather devise some indirect method to solve his problem, such as surveying a large sample of the human population and noting age parameters among this sample. Variations in the size of individuals could be one difference which depends upon age. The degree of wrinkling of the face or the baldness of the human head would be others. A careful study of such differences would permit our biologist to construct a reasonable picture of human development. This snapshot method of solution is the only one available to the astronomer, and by its use a theory of stellar development has emerged.

Inspection of the stars in our immediate neighborhood gives evidence of a large diversity of age. Unmistakable signs of extreme youth are found side by side with extreme old age. The oldest stars date to nearly the beginning of the universe, while the youngest are less than a million years old. Astronomers determine stellar ages the same way that a heat engineer finds the burning time of a coal furnace, when he knows the amount of coal

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Messier 16, a region in the Milky Way Galaxy, is one of the many places where stars are being born today. The bright areas are large clouds of gas and dust illuminated by nearby stars.

contained within his furnace and knows the rate at which his fuel is being consumed.

As we have seen, the source of stellar energy is atomic, obtained from the conversion of hydrogen into helium. We know from nuclear physics how much energy is released per nuclear conversion. We also know how many hydrogen atoms are available in a given star (that is to say, we know the star's mass). We therefore know the total potential energy content of the stars. For any particular star, observational astronomy gives the *rate* at which this available energy is being used up and radiated into space. Ipso facto, the age of that star is determined.

Direct measurements of stellar distances and light intensities show that some stars are spendthrift of their fuel supply. They release into space over one-millionth of their energy store every year. At this rate, their entire available energy supply will be exhausted in a million years and they will die of fuel starvation. Because such stars are visible in our skies today we know they must have been created less than a million years ago.

A million years is an extremely short time in terms of the total age of the universe. It is about equal to the time that has elapsed since some rudimentary form of man first emerged upon earth. We therefore have good evidence for the creation of stars within very recent geological times. It is indirect evidence to be sure, because a star has never actually been seen in the process of creation, but something almost as convincing is observed.

It is a remarkable fact that these very young and highly luminous stars are found in and *only* in regions of our galaxy containing large amounts of free cosmic gas and dust. This strongly suggests that the birthplace of new stars is in the dust clouds between the older stars, and that this dust is the material out of which stars condense.

These observations are so suggestive that astronomers now believe (perhaps somewhat optimistically) that they know what physical processes must take place in the creation of new stars. Presumably, when the density of a cloud of gas and dust becomes large enough, a sizable segment of the cloud becomes gravitationally unstable and begins to collapse under its own weight. The packing of matter into a smaller and smaller space due to slow collapse releases energy from the gravitational field and the gas and dust becomes hot. And as this pre-star condenses more and more, the central temperature within the globule goes higher and higher until, at the stage where the volume has shrunk a billion, billion times, the temperature and density are large enough for collisions between the hydrogen atoms to begin. These collisions lead to nuclear reactions of the same type as in a hydrogen bomb. At this stage an explosion does *not* occur, however, because a new star has the unfailing ability to adjust itself to release this energy gradually, contrary to the conditions inside a bomb. When nuclear reactions begin, the contraction of our protostar stops and a stable star is born.

Stable stars

A stable star is one of nature's most magnificent inventions. The large amount of matter within a star is in equilibrium at every point; that is to say, it neither collapses nor expands. This means that a star arranges itself so that the forces acting on every small element of volume in the interior just balance. These forces are the gravitational force tending to pull the material toward the center, and the pressure of the gas tending to push the material outward. From the laws of physics we know that the pressure of the gas is determined by the temperature, and the gravitational pull by the total mass. The higher the mass of the star, the higher the central temperature must be to overcome the increased gravitational force.

But this is not the whole story, because the rate of nuclear reactions also depends critically on temperature. At high temperatures the hydrogen atoms are speeding about at breakneck speeds and collisions are frequent. High temperature therefore means high energy production and a very luminous star is the result. From similar arguments it can be shown that the final radius of our stable star depends upon the distribution of pressure, which is also given once the mass is known. Hence all the conditions of a stable star—i.e., its radius, its luminosity, and, as a direct consequence, its surface temperature—are determined by the total mass.

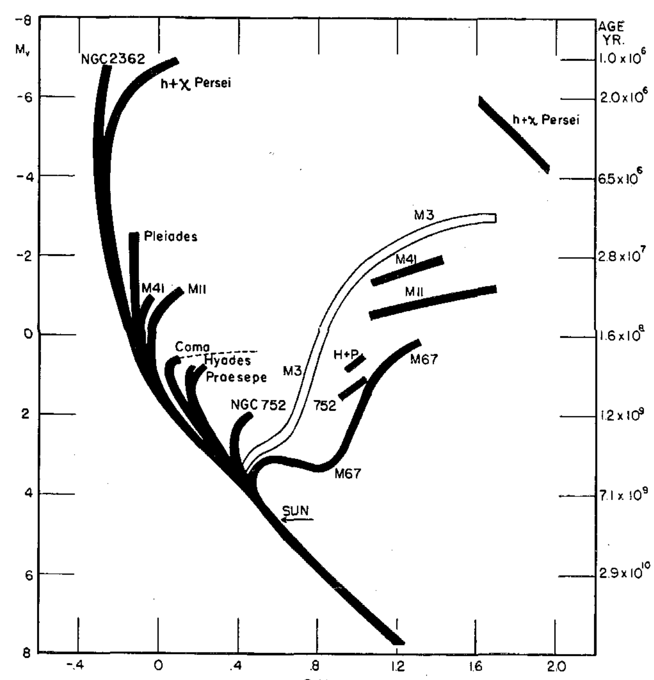
This means that there is a unique relation between surface temperature and the luminosity of the stars, and these are quantities which can be found directly by observation. The astronomer summarizes this information in the so-called color magnitude diagram (right), where the observed data are plotted for all stars. New stars which are just at the beginning of their evolutionary life lie on a line in this diagram which is called the main sequence.

It is now of interest to follow the history of a star as time goes on. By fairly easy calculation it can be shown from the theory of stable gas masses that the internal conditions of an aging star must change with time because of the presence of the waste products of the nuclear burning—namely the created helium atoms. These helium atoms are the ashes of the nuclear flame and remain deep in the stellar interior, close to their place of formation.

At first glance it would seem that helium atoms replacing the original hydrogen would not make much difference to the balance of forces within the star but this is not correct. Atom for atom, helium weighs four times as much as hydrogen and this weight difference per particle means that, for the same temperature, there is a difference in pressure of hydrogen and helium gas.

Detailed consideration of the relevant physical processes shows that the star compensates for the change in its internal chemical composition by increasing in radius and luminosity. It must brighten and expand to remain stable as the helium content increases. This change occurs quite gradually until 12 percent of the original hydrogen supply has been transferred into helium. During this period of gradual change, the star remains close to the main sequence. The sun is now in this stage of its evolution, because it has converted only 6 percent of its available hydrogen supply into helium.

Theory tells us that when 12 percent of the fuel has been exhausted, the star can no longer compensate for its increased helium content by small changes, but must drastically increase in radius and move rapidly



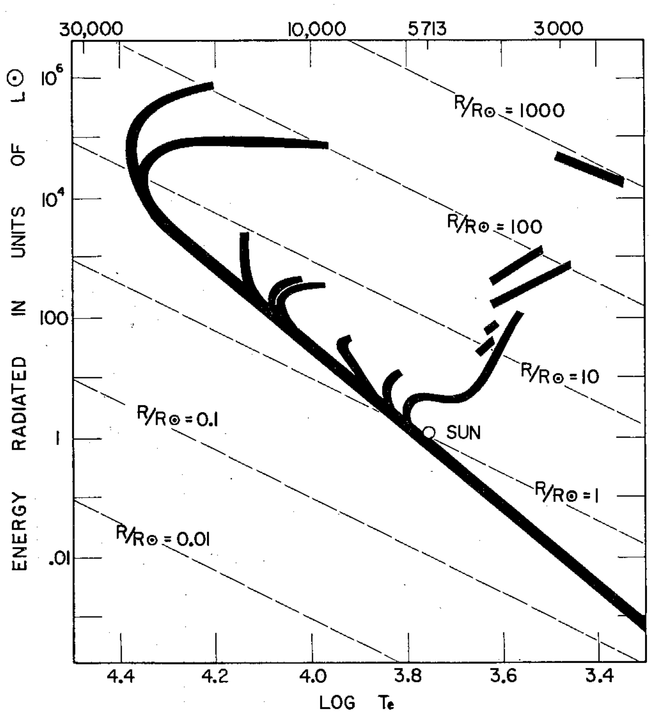
Color-magnitude diagram for stars in the individual clusters named above. The horizontal scale (B-V) is a measure of color or surface temperature. Blue stars are to the left, red stars to the right. The vertical scale is a logarithmic measure of the energy output.

from the main sequence. At this point the star is near the end of its life, because it swiftly increases in luminosity, consumes its remaining fuel at a tremendous rate, and finally sinks into obscurity and death as its fuel is depleted.

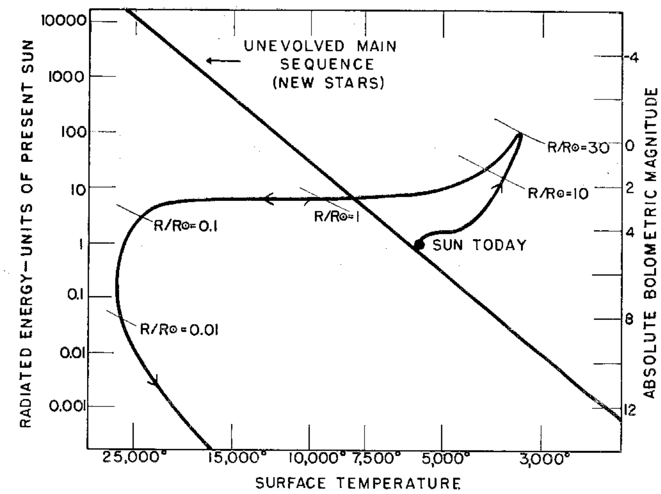
These predictions from the theory of stellar structure are *not* idle speculation. First, they follow from very basic principles of physics, and second, *they are observed to occur* in clusters of stars. We cannot, of course, follow the evolution of a single star for reasons of time scale already explained. However, individual stars in a group are all the same age but have an initial range of mass. They evolve at different rates because the rate of hydrogen consumption increases rapidly with the mass. Hence, in a cluster, we find stars at all different stages in their evolutionary history. We follow the evolution by the snapshot method.

The observational data are shown in the diagram below. The data for a number of different clusters are superimposed on the same diagram. Some stars in this diagram are still near the main sequence, while others have reached the 12 percent limit and have increased rapidly in radius and moved to the right.

From the data in these diagrams we date the stars in the various clusters by the coal furnace method already described. In particular, we can determine the age of the oldest cluster, M 67, to be about 5 billion years. Notice



Temperature (Te)-luminosity (L) diagram showing the position of stars in certain clusters that were shown in the diagram on page 19. The main sequence is the straight line running from the upper left to lower right. New, unevolved stars lie on this sequence; evolved stars lie to the right. The radii of the stars in different parts of the diagram are shown by dotted lines. The unit R⊙ is the present radius of the sun; L⊙ is the luminosity of the present sun.



Temperature-luminosity diagram showing the evolutionary track of the sun. The radius of the sun, in terms of its present value, is shown along the track.

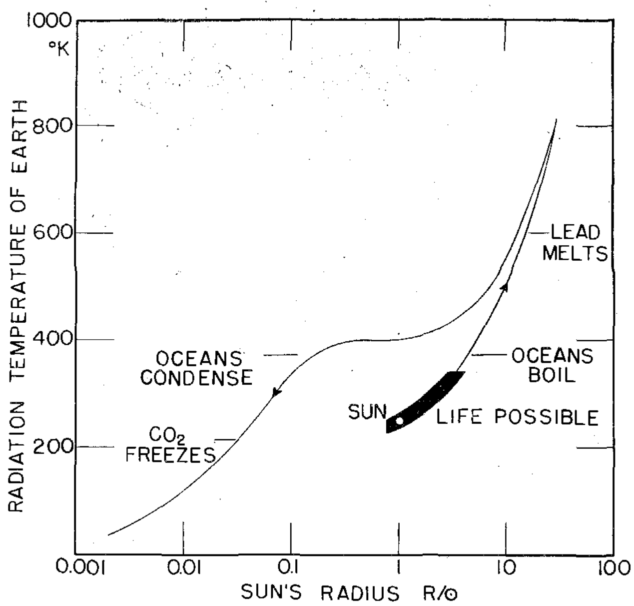
the position of the sun. It has moved slightly from the sequence because it has already consumed part of its fuel and is contaminated with helium. It is still below the 12 percent limit and is comfortably close to the main sequence. The sun has lived perhaps half of its total life span. It is now approaching middle age.

If the theory outlined above is correct, and observation confirms it at every point, we can predict the evolutionary track of the sun for future time and, in particular, determine the effect of such evolution on the conditions of the earth.

There is good reason to believe that the sun's evolutionary track in the color magnitude diagram should be quite similar to the tracks in M 67. From this similarity transformation we construct the predicted track of the sun, which is shown above.

In another 6 billion years the sun will have reached the 12 percent limit and will then begin to expand rapidly in radius, moving to the right in the color magnitude diagram. At its maximum size the aging sun will grow to 30 times its present radius, and will appear in the sky as a dull red globe 15 degrees in diameter, instead of its present ½ degree. In this stage, our sun is burning its fuel at a tremendous rate and will soon after exhaust its hydrogen supply. Now begins the slow decline in brightness along the nearly horizontal track shown in the diagram, until finally the sun must die and most likely will become a white dwarf.

During this interval, conditions on the earth will not remain as they are today but the temperature at the surface must go up. Our state of knowledge of stellar evolution is now advanced to a point where fairly definite predictions of these temperature changes can be made. The diagram at the top of page 21 shows the calculated values of the radiation temperature of the earth plotted against the radius of the sun. There will be a catastrophe to most forms of life when the sun reaches four times its present radius. At this point the earth's temperature will be about 70 degrees centigrade.



How the radiation temperature of the earth will change when the sun alters its radius. Temperature is on the absolute or Kelvin scale, where zero corresponds to minus 273 degrees centigrade.

As the sun continues to expand it will brighten and will drive the temperature first above the boiling point of water and then to the melting point of lead, until finally, at the sun's greatest brightness, the earth's temperature reaches more than 800 degrees centigrade. Life will have ceased, the oceans will have boiled away, and conditions will be miserable.

Under these conditions it would be interesting to compute what the atmosphere of the earth would be like. For one thing the oxygen-carbon equilibrium, which is now in operation due to plant life, will probably be destroyed. For another, the water originally in the oceans will exist as dense clouds high about the earth's surface. These clouds will reflect a large fraction of the sun's rays and the temperatures may be somewhat lower than those shown in the diagram, but not much lower.

From the high of 800 degrees centigrade, the temperature of the earth will decrease as the sun declines in brightness. It will eventually cool until the oceans rain down over the scorched land. This will be a brief period followed by continued cooling until the oceans freeze. And as the sun becomes dimmer and dimmer, the coldness on the earth will be profound.

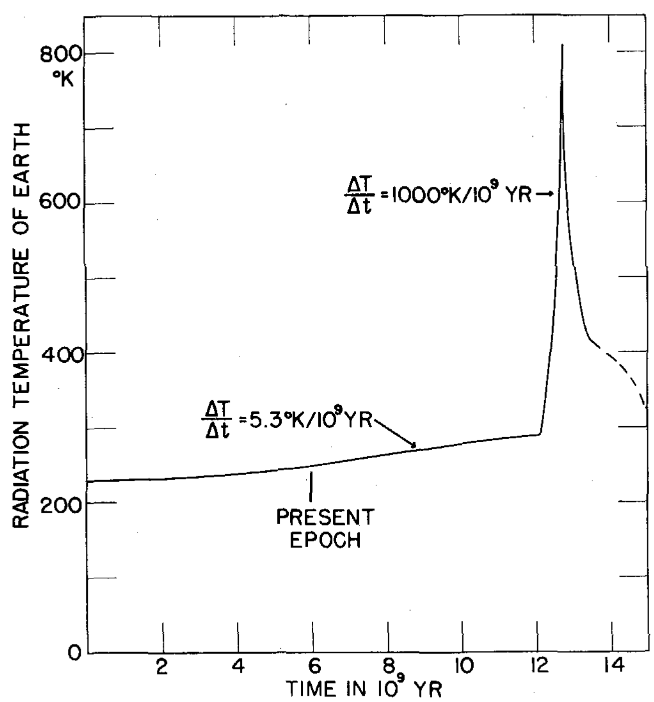
It is of great interest to compute the time scale of these future temperature changes. The diagram at the right shows the variation of the earth's temperature with time. The present age of the sun is taken to be 6 billion years. We see that the rise in the temperature of our planet has been gradual over the past 6 billion years—amounting to less than 20 degrees centigrade. The rise will continue in a gradual way for 6 billion years more and then the catastrophic rise begins which dooms civilization to the final heat death. The end comes rapidly when the temperature goes up 500 degrees in only 500 million years.

In the 6 billion years remaining it is conceivable that biological evolution by adaptive processes can change the human species sufficiently rapidly to compensate for the remaining gradual temperature rise of the earth. Presumably a biologist could in principle predict the course which evolution of the human species must take to meet the changing conditions.

The picture which has just been painted may be one of great terror to sensitive people. From these facts of astrophysics it appears quite likely that human life is doomed by natural processes, if not by man's folly. It is as if the Lord were playing a mad game with things of his creation. After 12 billion years of trial and error, chance mutations and evolution of living matter, the Lord tires of this play and puts his toys away with fire.

But let us not despair of *our* plight. Our sun is only one among millions in our galaxy and our galaxy is but one among millions in the universe. Most astronomers now believe that solar systems like our own are common. If this view holds, then there may be other places much like our own where life exists.

We on this planet are lucky. The rate of aging of our sun is slow. We have another 6 billion years to live. Many stars more massive than the sun exist and here the rate of aging is more rapid. Planets circling these stars go through the same temperature cycles as ours but at a more rapid rate. It follows that there may be people in the universe *this very day* facing the dilemma of the heat death. God made the sun of such a mass that we yet have time ahead. A 10 percent increase of the original solar mass would put us today at the end of life. Is it chance, or does it have some purpose that our sun was not so massive?



How the radiation temperature of the earth will change as time goes on. Average change of temperature per unit time is shown here.