

THE FORMATION OF STARS

Evidence for the apparent explosion of the universe some few billion years ago has also blown up some comfortable theories of star development. The author, an astrophysicist who has made major contributions to concepts of stellar evolution, writes of a new theory and current problems.

by *Lyman Spitzer, Jr.*

If research in astronomy had stopped in 1913, our knowledge of stellar evolution today would be in a satisfactory state. At that time astronomers had a plausible theory of a star's life cycle. Einstein's theory of relativity, advanced only a few years before, showed that mass and energy were interchangeable. It was therefore natural for astronomers to assume that stars were formed as large massive bodies which through successive century after century continued to radiate away matter. Ultimately most of the matter in a star, according to this picture, would be radiated away as light and heat. In this way all the stars, despite their large differences in mass, formed part of the same evolutionary sequence.

Unfortunately, this simple, sweeping, and satisfying picture became discredited by additional information, both astronomical and physical. On the astronomical side, evidence began to accumulate that the universe has not lasted long enough for most stars to radiate away much of their matter. The expansion of the universe, the presence of uranium on the earth, the existence of certain relatively transitory clusters of stars, all indicate that something happened about three billion years ago. If the universe was not created then, it was certainly very extensively reorganized; some sort of cosmic explosion apparently took place at that time. Since the sun, a fairly typical star, would require many hundreds of billions of years to radiate an appreciable fraction of its mass, its total mass has ob-

viously not changed appreciably within this last few billion years.

On the physical side, nuclear physicists have learned a great deal about the specific processes by which matter can be converted into energy. The only known process of importance which can liberate energy inside a star is the combination of four hydrogen atoms to form a helium atom. Calculations carried out by the nuclear physicist, Professor Hans Bethe, show that in the stars this process occurs through the catalytic action of carbon and nitrogen nuclei. Since four hydrogen atoms weigh 0.7 percent more than one helium atom, the additional mass is released as energy and can be radiated by the star. Even if a star is originally all hydrogen, the total mass radiated can evidently not exceed a very small fraction of the mass of the star.

As a result of these findings we now know that the universe has apparently not lasted long enough in its present form for stars to radiate much of their mass, and in any case there seems to be no physical process by which a star could radiate away most of its matter even if there were time enough. We are forced to conclude that the present variety of stars in the sky is the result of the original method of star formation rather than of any evolutionary process. And the formation of stars in general is still a closed book, since the explosion of the universe a few billion years ago has so far defied any attempts at detailed analysis. It is even possible that the basic

laws of nature may have been quite different at that time. Thus our research in the direction of general stellar evolution reminds one of Browning's philosopher, who had

"... written three books on the soul,
Proving absurd all written hitherto
And putting us to ignorance again."

Supergiant Stars

While the origin of the universe is still beyond our understanding, some progress has been made in explaining the origin of a certain class of stars, which may have been created relatively recently. A supergiant star is one which radiates light and heat some ten thousand times as strongly as our own sun. There are not many of these stars, but in a galaxy of many billions of lesser stars they stand out in the same way that a searchlight stands out from a swarm of fireflies. These stars are burning their candle at both ends and they cannot last very long, astronomically speaking. Within a mere hundred million years, such a star must burn all its hydrogen into helium. There is no known way in which a star can remain dark for a long period of time and then suddenly start shining. We conclude that these supergiant stars have formed within the last hundred million years—less than a tenth of the age of the universe.

Of course, it is possible that nuclear physicists have overlooked some important process by which a star can radiate a much larger fraction of its mass than the hydrogen-into-helium process liberates. This does not seem very likely, since the energies with which the atoms hit each other inside a star average only a few thousand electron volts—a small fraction of the energies developed in such atom-busting devices as the cyclotron and synchrotron—and since the nuclear reactions produced at low energies have been fairly well explored in the laboratory.

If it is assumed that these stars have in fact been formed within the last hundred million years, the mechanism for this formation is a problem which astronomers may hope to investigate with some hope of success. Within this interval, conditions in the universe have apparently not changed very much and an examination of the universe about us may actually indicate how supergiant stars have formed in the past, and may even be forming at the present time.

Clouds—The Clue

The clouds of matter which float about between the stars are an obvious source of material for star formation. Recent investigations show that these clouds are in fact so closely associated with supergiant stars that a physical connection between them seems very likely.

In brief, the observations indicate that supergiant stars are found only in those aggregations of stars where interstellar clouds of matter are also present. More specifically, observations of stellar galaxies, each one a million or so light years away and each, like our own galaxy, containing many billions of stars, show that supergiant stars are found only in spiral galaxies. These spiral systems, like the huge galaxy in which our sun is located, are flattened, disk-shaped systems some hundred thousand light years in diameter, each one rotating about an axis perpendicular to the plane of its disk. A typical spiral galaxy is shown in the accompanying figure. The characteristic feature of these systems, after which they are named, is the presence of a pair of arms which apparently come out of the central nucleus and wind around the system.

In the elliptical galaxies—which are not rotating so rapidly, are not so flattened, and show no spiral structure—no supergiant stars are found. In fact, long-exposure plates at the Mt. Wilson Observatory have shown that the stars in these systems have a sharp upper limit on their brightness; no star greater

A typical spiral galaxy. Both supergiant stars and interstellar clouds of obscuring matter are found only in these huge, flattened rotating systems. (Yerkes Observatory Photo)



than the critical brightness can be found, while below this critical brightness myriads of stars appear on the photographic plate. This result is in marked contrast to the observed brightness of the stars in spiral galaxies, where there are always one or two brightest supergiant stars, a number of less bright supergiants, and a gradually increasing number of fainter and fainter stars. This sharp upper limit on the brightness of stars in elliptical galaxies is just what one would expect if no new stars had been formed since the beginning of the universe, and if the brightest ones had burned up all their fuel and gone out.

Detailed examination of galaxies also indicates that clouds of matter between the stars are found only in spiral systems. In elliptical galaxies the vast stretches between the stars are very nearly empty, but in flattened spiral galaxies like our own there is about as much matter between the stars as there is inside the stars. This association between obscuring clouds and supergiant stars is strengthened by the fact that in the closest galaxy, the great nebula in Andromeda, supergiant stars are observed to occur in exactly those regions where the obscuring clouds are most prominent. Thus the observational evidence indicating a physical connection between clouds and supergiant stars is very strong.

Before we can accept the hypothesis that supergiant stars have in fact formed from these clouds we must investigate whether or not there is some process which could cause interstellar matter to condense into stars. In this way we are led to consider the physical nature of the stuff between the stars, and the forces which operate on it. Thirty-five years ago the very existence of interstellar matter was not fully realized but recently extensive information on this topic has been obtained.

Atoms in Space

The dominant constituents of interstellar matter are believed to be individual atoms. These atoms absorb or emit light of particular wave-lengths, which can be measured accurately by use of the spectroscope. In some regions, where the gas is at a high temperature, bright emission lines of hydrogen, oxygen, and nitrogen are observed. Measurements of the intensities of these lines show that the density of the interstellar gas is about one hydrogen atom in each cubic centimeter, with other elements pres-

ent as slight impurities. The interstellar medium is a much better vacuum than is ever obtained in a terrestrial laboratory. If a fly were to breathe a single breath into a vacuum chamber as big as the Empire State Building, the resulting density of the air would still be much greater than the density of the interstellar gas.

In other regions of space the interstellar gas is cool, and no emission lines are produced. Instead, the atoms absorb the light from distant stars, producing absorption lines at particular wave-lengths. The absorption lines of the abundant gases, hydrogen, helium, nitrogen, oxygen, etc., when these are cool, lie far out in the ultraviolet where they cannot be detected. Interstellar absorption lines of sodium, calcium, titanium, and iron lie within the observable spectrum and have been observed in the spectra of bright stars a few thousand light years away. These lines are very sharp, and can usually be distinguished from the lines produced by the atoms in a stellar atmosphere, where the high temperature and pressure give wide lines.

Recent work has been concerned with the detailed distribution of interstellar gas. Measurement of the strongest absorption lines, with the most powerful spectrographs available at the 100-inch telescope of the Mt. Wilson Observatory, shows that a single line is frequently made up of several components. Each separate component is produced by absorption in a single cloud of gas, the different components being separated in wave-length by the difference in Doppler effect produced by the different cloud velocities. These clouds, each one about twenty light years across, are moving through space at speeds of some ten to twenty miles a second. A more detailed understanding of the nature of these clouds is desirable before one can discuss in detail how interstellar matter can form new stars. Further work along these lines is now in progress.

Solid Particles

In addition to the separate atoms drifting about in space, small solid particles, or grains, are also present. Each grain is about one hundred-thousandth of an inch in diameter; ten thousand placed end to end would make a line about as long as a period on this page. Since the size of these grains is just about equal to the wave-length of visible light, these particles are of the size which is most effective in

absorbing and scattering light waves. These particles are responsible for the general obscuration produced by the clouds shown in the accompanying figure. Particles of smaller size are presumably also present, but these do not produce such a noticeable effect, and can therefore not be detected.

The properties of these particles have been determined from accurate measurements of the obscuration which they produce in light of different wave-lengths. This obscuration is greater for blue light than for red light, which proves that the particles cannot be much *larger* in size than the wave-length of light. On the other hand, the obscuration varies inversely only as the first power of the wave-length, instead of as the fourth power which is observed for scattering by the molecules of the atmosphere. From this one can conclude that the grains are not very much *smaller* in size than the wave-length of light. In this way a particle size of about the wave-length of light has been determined. From the fact that the grains seem to scatter more than they absorb it seems likely that they are dielectric rather than metallic in composition. If, as seems likely, these grains were produced by the sticking together of individual atoms, the enormous abundance of hydrogen relative to other elements would be expected to produce solid hydrogen compounds, in particular, ordinary ice. However, impurities of all other elements would also be present.

Studies of the distribution of these grains have indicated that the clouds in which these grains are concentrated are apparently identical with the gaseous clouds already described. Thus whatever pushes atoms into clouds also pushes the grains together.

Forces in Interstellar Space

To discuss in detail how stuff in space can condense to form new stars we must determine the physical conditions of matter in space. In particular, we must combine the observational evidence described above with our knowledge of basic physical principles to investigate the different forces that are at work on the different particles. Only in this way can we predict how the interstellar medium will behave under various widely different conditions.

In the immense vacuum between the stars, an interstellar particle spends most of its time moving in a straight line without interruption. Occasionally,

one of two things may happen to it: an encounter with another interstellar particle, or an encounter with a light wave, or photon. The information which physicists have obtained on such processes is not so complete as astronomers would like, but is sufficient for an approximate evaluation of the effects which these various collisions will produce.

The collisions of the interstellar atoms and grains with each other help determine the temperature of matter in space. In most cases, the collisions are elastic and the kinetic energy of the different particles is exchanged back and forth; as a result, the distribution of velocities corresponds to that in thermal equilibrium at some particular temperature. Photoemission of energetic electrons from hydrogen atoms and grains, on absorption of photons, tends to keep the temperature high, but inelastic collisions between atoms and grains tend to give a low temperature. Near a very hot and very bright star the gas will be heated up to about $10,000^{\circ}\text{K}$, but in other regions a temperature of about 100°K seems likely. This difference of temperature between different regions is believed to produce cosmic currents, or winds, in the same way as the winds on earth are produced.

In some cases the interstellar particles stick to each other on collision. Thus atoms stick together to form molecules, molecules stick together to form larger molecules, and grains grow by slow accretion. This process was analyzed during the war by a number of Dutch astronomers, who were able to show that the interstellar grains have probably been formed by this evolutionary process within the last few billion years. More accurate physical information on collisions between particles at low energies is required to make this theory more quantitative.

Collisions between grains and photons are important in star building. It is well known that light exerts pressure. Since starlight in a galaxy comes from all directions in the galactic plane, a single grain will be knocked this way or that by photon collisions, without any net motion resulting. However, when several grains are present, the shadow of each one on the other unbalances the radiative force, and photons striking from the opposite sides push the grains toward each other. As a result, there is an effective force of attraction between grains which is several thousand times as great as the gravitational force between them.

Star Formation

The further we go away from observational data the more uncertain our theories become. The mechanism of star formation, which is the ultimate objective of much of the work described above, is still in a rather speculative state. However, putting all the above information together does provide a reasonable preliminary picture for the process by which stars can be formed from interstellar matter.

The process may be assumed to start with an interstellar gas, formed at the same time as the rest of the universe. The first step in the process is then the slow condensation of interstellar particles from the gas. After these particles have reached a certain size, the radiative attraction between them forces them together and they drift toward each other, forming an obscuring cloud in a time of about ten million years. In a cloud, where the density of grains is high, the temperature tends to be low. In the surrounding region the high temperature produces high pressure, and the low-temperature, low-pressure cloud therefore becomes compressed. In this way the density of gas within a cloud will be increased, corresponding to the observed result that a cloud of grains is also a cloud of gas.

Currents produced by differences of temperature and also by the general rotation of the galaxy will tend to tear some of these clouds to pieces. On the other hand, the forces of condensation will pull them together, and some clouds may be expected to go on contracting. The radiative force becomes ineffective when the clouds become so opaque that light does not penetrate into them very far. At this point gravitation takes over and tends to produce a further contraction. In this stage a cloud has a diameter of a light year or less. Small opaque clouds of this type, called globules, have been known for some time, and are shown in the accompanying figure.

One of the chief problems concerns the angular momentum of this prestellar globule, or protostar. According to Newton's laws of motion, the angular momentum, which is proportional to the product of the radius and the rotational velocity, remains constant; as the radius decreases the rotational speed increases. Since the radius of a typical cloud is some ten million times the radius of a supergiant star, this increase in rotational speed can be quite impressive. Unless some way can be found to dispose of

the angular momentum, a protostar would hurl itself to pieces by centrifugal force. The possibility that turbulent motions in the gas may carry the angular momentum away has been explored by several German astronomers. However, the turbulent velocities involved would exceed the velocity of sound in the interstellar gas, and physical information about this type of turbulence is virtually nonexistent. In this country the possibility has been advanced that a galactic magnetic field might produce electrical eddy currents in a rotating protostar, which would then damp out the angular momentum.

An interesting variant of this star-building picture has been proposed by Dr. Fred Whipple, one of the astronomers who has contributed most to this theory of star building. He suggests that a condensing cloud may have produced our solar system. In view of the widespread general interest in the formation of the solar system, such a bold extrapolation of these theoretical concepts back to conditions several billion years ago is naturally of much significance.

It is evident that the picture of star formation which has been described here is still in a formative stage. The work in progress is being carried out co-operatively by a number of astronomers all over the world. Perhaps when the 200-inch telescope probes further into the secrets of space, and when further progress in experimental and theoretical physics increases our understanding of the processes at work between the stars, we may then outline with more assurance the detailed steps by which supergiant stars may be forming almost before our very eyes.



The compact opaque globule may be a protostar, contracting to form a new star.