The following article written by George Gamow in 1948 describes his ideas of synthesis of elements in the epoch shortly following the Big Bang. The current understading of this process is somewhat different from what is outlined in this article. Firstly, the distance estimation by Hubble is now known to be wrong by a factor of almost ten. This revision (and the recent discovery of the existence of the cosmological constant; see *Resonance*, p.91, May 2004)) puts the age of the universe at approximately 14 billion years. There is therefore no contradiction with the age of the universe any longer.

Secondly, it is no longer believed that *all* elements are formed in the early universe. Elements heavier than beryllium, whose atomic number is 4, are difficult to fuse as there is no stable isotope with atomic weight 8 which can be formed by two helium nuclei. Heavier elements are therefore produced only in the cores of stars (with the help of a reaction involving three helium nuclei), and not during the 'primordial nucleosynthesis' era of the universe.

*Editors*

# Galaxies in Flight

*George Gamow*

**If the island universes are indeed racing away from one another, the fact may shed light on the primordial formation of nuclei and atoms.**

In the year 1929 the Mount Wilson astronomer Edwin Hubble made a very remarkable discovery. He found that the giant accumulations of stars known as galaxies, which are scattered in great multitude through the vast expanses of the universe as far as the best telescopes can see, seem to be running away from one another at fabulously high speeds. From this observed fact originated the famous theory of the expanding universe. Although the theory is still not finally proved, it seeded a whole generation of fruitful study, not only in astronomy but also in geology, physics and chemistry. It gave us a new start for investigating the age of the universe and the creation of the stuff of which it is made. If our far-flung cosmos came originally from a dense hot core of material concentrated in one place, then we can reasonably assume that this tightly packed core must have consisted in the beginning of elementary building blocks, most of them

Reproduced from *Scientific American*, pp.21-24, July 1948

probably neutrons, out of which all the chemical elements later were made. I shall discuss briefly some recent studies of this phase of the expanding-universe theory which have been made by Ralph Alpher, Hans Bethe and George Gamow. The main subject of this article, however, is the basic theory itself, and how it stands up today, 19 years after Hubble's discovery.

The idea of stellar galaxies is a comparatively recent discovery in astronomy. The celestial shapes that we now recognize as galaxies had been observed for a long time as faint nebulosities of various regular forms, but they were generally believed to be simply luminous clouds of gas floating in the spaces between the stars of the Milky Way. Observations with more powerful telescopes, however, resolved these "nebulosities" and showed that they were not clouds but huge collections of extremely faint stars. These giant stellar aggregates were far beyond the outer limits of our own stellar system, the Milky Way; in fact, it soon became clear that they formed systems very similar in shape and structure to the Milky Way galaxy itself.

The nearest and most familiar external galaxy is the great nebula in Andromeda, which can be seen with the naked eye as a faint, spindle-shaped speck of light in the upper part (from the Northern Hemisphere) of the constellation of Andromeda. Photographs made with large telescopes show that this galaxy has a rather complicated structure consisting of an elliptical center, or "galactic nucleus," and "spiral arms" flung into the surrounding space from the central body. The photographs also show two nearly spherical nebulosities close by, probably satellites of the central system.

Among the myriads of stars in the arms of the Andromeda Nebula are many pulsating ones, of the type called Cepheid variables. They brighten and fade in a regular rhythm, and their pulsation period provides a method of determining their absolute brightness. By comparing their apparent brightness (which depends on their distance from us) with their calculated absolute brightness, Hubble was able to prove that the Andromeda Nebula is some 680,000 light-years from the Milky Way. To a hypothetical observer in the Andromeda galaxy, the Milky Way would look much the same as the Andromeda system looks to us, except that the spiral arms of the Milky Way are somewhat more open. Our sun, with its family of planets, would be seen through a telescope within the Andromeda Nebula as a rather faint star near the end of one of the spiral arms, some 30,000 light-years from the Milky Way center.

The Galaxies generally are shaped like a discus. The Andromeda system looks like an elongated spindle to us because it is tilted to our line of sight, but there are many other galaxies that we see from the top or straight on edge. Most galaxies have the same sort of spiral arms as the Milky Way and Andromeda, but there are also some armless ones. Individual stars are much more difficult to distinguish in armless galaxies and in the nuclei of spiral ones than in the spiral arms. It was only several years ago that Walter Baade of the Mount Wilson Observatory succeeded in resolving these interior stars by using special photographic plates and carrying out the exposures with great care. His pictures revealed an unexpected fact: the stars forming the nuclear regions of spiral galaxies, and all stars of the armless galaxies, have very different physical characteristics from those in the spiral arms. The meaning of this difference in stellar population is not clear, but there is no doubt that it has an extremely important bearing on stellar and galactic evolution.

The galaxies are scattered more or less uniformly through space as far as our telescopes can probe. The average distance between neighboring nebulae is about two million light-years. The limit of our vision with the 100-inch telescope, the largest with which observations have yet been made, is about 500 million light-years. Hence in the observable region of space there are some 100 million galaxies. The new 200-inch telescope on Mount Palomar, which will double the distance we can see into space, may reveal an enormously larger number. Most galaxies are isolationist, dwelling in remote and solitary splendor, but we find a number that group themselves together to form more or less compact clusters. In the constellation of Corona Borealis, for example, there is a cluster containing some 400 galaxies. Our Milky Way is a member of a small cluster which embraces among others, the Andromeda Nebula and the two galaxies known as the Magellanic Clouds, which are of a relatively rare type that has no well-defined shape.

The distances of all but the nearest galaxies are so great that even the most powerful telescopes fail to resolve them into individual stars. Astronomers' calculations of their distances depend entirely on their apparent brightness. Hubble, studying a group of about 100 well-known neighboring galaxies, established the fact that on the average they were of about the same size and the same intrinsic luminosity. Using this standard, we can estimate the distances of remote groups of galaxies by comparing their mean apparent brightness with that of nearby galaxies whose distances are known. Such measurements give the value of 7.5 million light-years for the distance of one of the nearest groups of galaxies in Virgo. Similar galactic groups in the constellations of

Coma Berenices, Corona Borealis and Bootes are respectively 30 million, 100 million and 180 million light-years away.

Now what was it that gave Hubble the notion that the galaxies are running away from one another and that the universe is expanding? His basic discovery was made with that indispensable tool of the astronomer, the spectrograph, which analyzes the color components of the light coming from stars. Studying the spectra of distant galaxies, he noticed a curious fact: all the lines in their spectra, regardless of the wavelength or color of the line, were displaced toward the red end of the spectrum. Furthermore, the amount of this "red shift" was always directly proportional to the distance of the galaxy from us. The most natural explanation source of this shift was that the source of the light was moving away. This is the so-called Doppler effect, of which the classic and most familiar example is the change in pitch of a locomotive whistle as the train approaches us and then speeds away. A light wave, like a sound wave, appears to shift to a longer wavelength when it reaches us from a receding source. And the speed with which the source is moving away is directly proportional to the shift in wavelength. Since the red shift of the galaxies also varied as their distance from us, Hubble concluded that the speed of the receding stars was proportional to their distance; the farther away they moved from one another, the faster they traveled. The red shift of the most distant galaxies that have thus far been observed is 13 per cent, which suggests that they are receding from us at the terrific velocity of 25,000 miles per second.

You must not conclude from this that we stand at the center of the universe and that all the rest of it is running away from us. Picture a slowly inflated rubber balloon with a large number of dots painted on its surface. An observer on one of the spots would be under the impression that the other dots were racing away from him in all directions, and so indeed they would be, but the same thing would be true no matter which dot he was on. In the case of the galaxies, we are dealing with the effect of a uniform expansion throughout all of space.

If you pick an arbitrary point in space, say the earth, and divide the distance of a given galaxy by its recession velocity, you get a figure which represents the length of time that the galaxy has been receding from that point. The strange and wonderful consequence of Hubble's observations is that the figure will be the same no matter what pair of galaxies you pick. Thus it works out that at a fixed, calculable time in the past all the galaxies now so widely scattered were packed tightly together in one place. And the time figure you arrive at is the age of the universe, measured from that instant when the original condensed lump of universal matter was torn apart by the primordial "explosion" that started its headlong expansion.

To get this figure, we must know the exact values for the distances and the recession velocities of distant galaxies. This is less simple than it sounds. The velocities, as we have seen, can be computed from the observed red shift and the distances, presumably, from the galaxies' apparent brightness. But there is a catch: the apparent brightness of the stars is affected not only by their distance but also by the fact that the light coming from them is redder, and therefore carries less energy than if the light source were stationary. To illustrate this, suppose for a moment that you are shot at by a gangster operating a submachine gun from the back window of a speeding car. Since the vehicle is receding, the bullets move more slowly toward you than they would from a stationary gun, and they strike your bullet-proof jacket with less energy. A receding light source produces exactly the same effect; its emitted light quanta strike the eye with less energy and therefore look redder than they should. An astronomer must make the same correction for the weakening of light intensity as a ballistics expert would make in estimating the muzzle speed of the bullets.

There is a further complication. If the submachine gun shoots, say, one bullet per second, its bullets will strike you at longer and longer intervals as the gun recedes, for each successive bullet will have farther to travel. Similarly, light quanta from receding stars enter the observer's eye with less frequency, and this fact calls for another correction of the observed brightness.

Applying both corrections, and taking the most accurate possible observations, Hubble calculated that the universe began to expand less than one billion years ago. This result stands in contradiction to geological evidence, which indicates that the age of the solid earth crust, estimated quite reliably from radioactive decay in the rocks must be at least two billion years. Since numerous pieces of evidence in various sciences support the two billion-year estimate. Hubble was forced to reconsider the expansion theory and consider the possibility that the red shift was due not to the normal Doppler effect but to some unknown physical factor which caused light to lose part of its energy during its long trip through intergalactic space.

Such a conclusion would ruin many beautiful scientific developments that have flowed from the hypothesis of the expanding universe. It would confront physicists with the difficult task of explaining the red shift in non-Dopplerian terms – which would seem to contradict everything we know at present about light. Fortunately there is a simple way out of the dilemma which is usually overlooked by the proponents of the "stop-the-expansion" point of view. The point is that Hubbles method of estimating the distances of faraway galaxies assumes that at the moment when they emitted their light they were just as bright as the galaxies we see closer at hand. It must he remembered, however, that the light we see from the distant galaxies was emitted at a fantastically distant time in the past; the light now coming to us from the Coma Berenices cluster, for example, started on its way some 40 million years ago, and the most distant galaxies used by Hubble in his studies are seen as they were almost half a billion years ago!

Do we have the right to assume that the galaxies, which are evolving like everything else in the universe, have kept their luminosity constant over such long periods of time? In view of the known facts about the evolutionary life of individual stars, which maintain their luminosity by the expenditure of nuclear energy, such an assumption would be very strange indeed. Actually, we can remove the entire difficulty in Hubble's time scale by remembering that the nuclear processes that fuel the stars are not endlessly self-perpetuating but are accompanied by a gradual dissipation of the originally available energy. The assumption that an average galaxy loses a mere five per cent of its luminosity in the course of 500 million years would bring the age of the universe to the two billion-year figure demanded by other astronomical, geological and physical evidence.

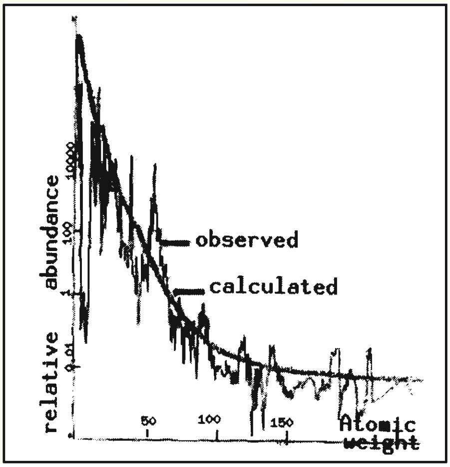
The conclusion finds confirmation in recent work by Joel Stebbins and A E Whitford at the Mount Wilson Observatory, who have studied the apparent luminosities of distant galaxies on special plates sensitive to red light. To everyone's surprise, they found these galaxies much brighter in the red part of the spectrum than they had previously appeared to be on ordinary photographic plates, which are sensitive mostly to the blue rays. It looked at first as if this phenomenon was due to the same kind of optical scattering which makes the sun look red during dust storms; light from the galaxies, it was thought, was reddened by the clouds of fine intergalactic dust through which it passed. Calculations showed, however, that to account for the observed reddening would take a fantastic quantity of dust – 100 times as much as the total amount of matter in the galaxies themselves. Such an assumption would come into serious conflict with many facts and theories about the structure of the universe.

It therefore seems more reasonable to suppose that the distant galaxies look redder simply because they actually were redder when they emitted the light which is now reaching our telescopes. This could be explained if we assumed that young galaxies contain more red stars than more mature ones. Further studies by Stebbins and Whitford should yield important information about the evolutionary life of individual galaxies. Already they have demonstrated quite clearly the danger of building any conclusions on the hypothesis of constancy of galactic brightness.

Having made this fiery defense of the right of our universe to expand, let us consider the physical consequence of the expansion theory suggested at the beginning of this article. What physical process was responsible for the present relative quantities of the various chemical elements that make up the universe? Why, for example are oxygen. iron and silicon so abundant; and gold silver and mercury so rare?

We know that, except for the lightest elements (such as hydrogen, helium, nitrogen and carbon, involved in the sun's nuclear cycle), transformation of one atomic nucleus into another requires tremendous temperatures such as do not exist at the present time even in the hot interiors of the stars. Consequently there can not have been any revolutionary change in the relative abundance of the various elements since the expansion of the universe began. On the other hand there has been some change, for a number of atoms are radioactive and have gradually decayed into more stable elements.

Considering the latter case first, we note, for example, that the lighter isotope of uranium, U-235 (atomic bomb stuff) constitutes only .7 per cent of a given amount of uranium found in nature; the rest is the heavier isotope U-238. The half-life of U-235 is only .7 billion years while that of U-238 is 4.5 billion years. If we make the reasonable assumption that at the original formation of the universe both isotopes were produced in about equal amounts the age of the universe figures up to about four billion years. Similar calculations based on the naturally radioactive isotope of potassium relative abundance .01 per cent; half-life-billion years) yields the figure of 1.6 billion years. While there is a discrepancy, both figures agree roughly in order of magnitude with the age of the




***Elements are distributed in relative amounts according to the atomic weight. Author's theory coincides with elements observed in stars.***

universe as estimated from the red shift and other evidence. Thus we have fairly good reason to suppose that the radioactive elements were formed at the beginning of the universe.

Actually, the picture presented by the expanding universe theory, which assumes that in its original state all matter was squeezed together in one solid mass of extremely high density and temperature, gives us exactly the right conditions for building up all the known elements in the periodic system. As I have mentioned, Alpher, Bethe and Gamow have attempted to reconstruct in some detail the processes by which the various elements may have been created during the early evolutionary stages of the expanding universe.

Our studies indicate that, under the tremendous temperatures and densities prevailing in the nucleus of the universe during the stage of its maximum contraction, primordial matter must have consisted entirely of free neutrons moving much too fast to stick together and form stable nuclei. As the universe started to expand, this primordial gas began to cool. When its temperature dropped to about one billion degrees, neutron condensation began. The neutrons collected in aggregates of varying numbers of articles. It is known that neutron aggregates are intrinsically unstable unless about half of their particles carry a positive electric charge. Hence they must have emitted electrons until they achieved a state of electrical equilibrium. The electrons fell into orbits around the nuclei and formed electronic envelopes around them; thus atoms were created.

I shall not attempt here to go into a detailed description of the rather involved, mathematical theory of atom-building, but shall simply present a graph which compares the abundance curves of the chemical elements as observed and as calculated by our theory. The theoretical curve corresponds pretty well with the observed values; the fluctuations of the empirical to curve are due to minor periodic variations of nuclear properties and can be explained by a more detailed form of the theory.

According to our calculations, the formation of elements must have started five minutes after the maximum compression of the universe. It was fully accomplished in all essentials, about 10 minutes later. By that time the density of matter had dropped below the minimum necessary for nuclear-building processes. All the elements were created in that critical 10 minutes, and their relative abundance in the universe has remained essentially constant throughout the two or three billion years of subsequent expansion.