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THE TIME-SCALE OF THE UNIVERSE[1]

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It is beyond our power—and may be beyond the bounds of reason—to specify the age of the material universe precisely, like an old epitaph: "Aged 82 years, 6 months and 17 days." But human life has not only an individual duration, but a general time-scale. Only under exceptional circumstances does a man change greatly in thirty days—and rarely does he fail to change greatly in thirty years. There are, therefore, more than astronomical reasons for measuring our ages in years—they afford a scale commensurate with the changes which accompany them.

It is certainly legitimate to inquire, Can we set up a similarly rational time-scale for the description of natural phenomena in the large? Will the units of this scale be thousands of years, or millions, or billions, or greater? and will different scale-units be appropriate for different ranges of phenomena—just as the rapid development of a child in his first year makes it reasonable to give his age in months?

In my student days, at the turn of the century, no definite answer could be given to these questions. We had very strong reasons indeed to believe that millions, rather than thousands, of years formed an appropriate scale for the greater geological processes; but there was no trustworthy evidence concerning how many millions of years were involved.

We realized, too, that, unless wholly unknown forces or influences of some sort were imperceptibly at work, the history of a finite material universe must run its course in a finite interval of time. This conclusion

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[1] The ninth James Arthur Lecture, delivered at New York University, May 14, 1940.

was based upon the one physical principle which has withstood unchallenged the revolutionary changes of the subsequent forty years—the Second Law of Thermodynamics. The energy in such a universe is indestructible—though, as we now know, capable of reversible transformation into mass. But it is steadily becoming less available. Water runs, and stones roll, down-hill, and this tends, in the long run, to flatten out the high spots and fill up the low ones. Heat is carried by conduction or radiation from hotter bodies to colder ones. In a thousand other ways, also, nature tends toward mediocrity—a dead level of uniformity and quiescence. There may be other forces—such as the deep-seated ones which build mountains—which, for a time, apparently arrest or reverse the downward tendency, but these draw on other stores of energy—which must be finite in amount—and diminish their availability, so that at long last mediocrity reigns.

This conclusion is unpleasant to most people; but it is supported by the tremendous weight of the Law of Averages. The argument is really simple enough. Suppose we had 10,000 smooth, spherical grains of white sand—all indistinguishably alike in size, shape and weight—and 10,000 more, exactly like the others except that they were black. Pour the white sand carefully, then the black sand cautiously on top of it, into a glass globe of such a size that it is still only half full. Then shake the globe. After a good shaking we will get a grayish mixture. Keep on shaking. What is the chance that by mere luck the white sand will some time all get on the right hand side of the globe and the black on the left? No elaborate analysis is needed to give the answer: it just naturally won't happen. Of course, if the white grains were lighter than the black, shaking would bring them to the top like cream; but we have expressly assumed that this is not so: the two kinds of grains are indistinguishable except by color, and the color makes no difference to the effects of shaking.

The interesting configurations of the material universe, with mountains and valleys, hot and cold bodies, etc., turn out, upon further analysis, to be comparable to interesting configurations of the sand—say a sand-painting on the gray surface. The fault of the analogy is that "shaking" is a catastrophic process, while conduction, radiation, etc., act gradually. But the conclusion that the interesting configurations tend to run down to undistinguished mediocrity is true for both. Technically, this is called an increase of entropy. We shall not be far wrong if we think of it as an increase of mediocrity or of dullness.[2]

Two conclusions follow. First, as regards the future, the universe bids fair, by an overwhelming probability, to become gradually less and less interesting. The approach to the final state of deadly dullness is likely to be asymptotically slow, but sure.

Second, while we can reason thus about the remote future (on the assumption that known natural laws are alone operative) we can not do the same about the past. A homely illustration of Lord Kelvin's comes to mind. Suppose that, in an open field, I pick up a stone so hot that I drop it instantly. I can figure out how long it will take to cool; but all I can say with certainty about the past is that, not so long ago, it has been in a hot place. I can calculate that if it has been lying in the field an hour it had then a certain surface temperature, if two hours, a much higher temperature, and so on, but I can not find out how or when it was heated without further information.

The stars, unlike the stone, are what an ingenuous student of mine once, on an examination, called "self-heating bodies"; but, with suitable changes, the analogy is still valid. We can carry our analysis of the past—a sort of reversed prediction—back a long way, but not forever. Sooner or later our calculations, based on the assumption that the ordinary, vastly probable, processes of "running down" have been continually at work, reach a limit, and we can go no farther back.

It would be unsound to conclude that there must have been some specific intervention of other influences or forces.

In any statistical system—like the globe full of sand-grains—any possible configuration must occur, again and again, in a sufficiently great number of trials, provided the effects of shaking (or its equivalent) are really at random. The universe is at present in a very interesting and improbable state, but this does not *prove* that it may not have got into this state by mere accident.

In a *very* long time, such as $10^{10^{100}}$ years, almost anything may happen. This argument has been clearly stated by J. B. S. Haldane, who caps it with the epigram: "The correct deduction from the Second Law is not that the present state of the universe could not have happened by chance, but that most of eternity is dull."

This we knew, in a general way, forty years ago; but the evidence that the material universe is in a transitory state is far more impressive now than it was then. From the nuclei of atoms to the remotest galaxies, we find irreversible changes—a one-way progress. In several cases we can measure or estimate

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[2] I have elaborated this illustration to bring out the importance of the *intrinsically indistinguishable* character of the individual grains—an essential element which has been inadequately stressed in some discussions of the subject. If each grain were marked with a number, and we recorded the position of every one in the gray mixture, and then shook it vigorously, the probability that grain 8392, and every other grain, would come back to the same position it had before would be even less than the chance that all the white grains would be found on one side.

the time-rates of these changes; and one of the most remarkable results of modern physics is that these independent paths of approach lead to the same result. The time-scale, from atoms to nebulae, is measured in billions of years[3]—millions are far too small, trillions much too great. Some of this evidence I will try to summarize, necessarily in brief, without entering upon many fascinating by-ways.

RADIOACTIVITY AND THE AGE OF THE EARTH

(1) Among the major modern discoveries is that atoms of many sorts are unstable and subject to spontaneous disintegration. The atomic nucleus (which automatically clothes itself with electrons enough to build up the rest of the structure) may eject a portion of itself, and settle down into one of a new kind, differing in charge, in mass, or in both. More than twenty such unstable atoms occur naturally, and hundreds of others have been made artificially by bombardment with particles of high energy. With the latter we shall deal later; at present we have to do with the former. These fall into three series commonly called after their most prominent members, radium, actinium and thorium. Each series starts with an almost stable atom, so that only a very small fraction of those present disintegrate in a year. By the delicate and precise technique of radioactive measurements—of which there is no time to speak here—these fractions have been determined with considerable accuracy. Heavy uranium (the abundant isotope U_{238}, of atomic weight 238) loses by spontaneous change, during one year, one out of 6,570 millions of the atoms originally present; light uranium, or actino-uranium, U_{235}, one out of 1,030 millions, and thorium, Th_{232}, one out of 20 billions.[4] The transformed atoms are far less stable, and go in each case through a long series of changes, in some of which alpha-particles (helium nuclei) are ejected, and in others electrons. At last each series ends in a stable nucleus—all three of them isotopes of lead, of weights 206, 207 and 208, respectively. Some of the intermediate products have lives of about a million years; others last only a minute fraction of a second. In all cases, the rates of radioactive change can not be altered perceptibly by any external influence that has been brought to bear. High temperatures and pressures are utterly without effect; and even the drastic process of bombardment with high-speed particles—though it may transform the nuclei which are directly hit into something quite different—has no effect on those which are missed.

On the time-scale with which we have to deal these changes may all be regarded as very rapid, and we may forget the intermediate stages, and talk as if each parent element turned directly into lead, without introducing error into our calculations.

If, now, a uranium-containing mineral is left alone in the rock for a billion years, about 15 per cent. of the atoms originally present will have broken down—to be more precise, 14 per cent., since toward the end there are fewer left to disintegrate than at first. Corresponding to these, an equal number of atoms of lead will have been produced. Their weight will be 12 per cent. of that of the uranium originally present, or 14 per cent. of those remaining—the other 2 per cent. representing helium given off during the process. The older the mineral, the more lead there will be, and from its ratio to the uranium we can find how long the crystal has been undisturbed.

Certain obvious corrections are necessary. If thorium is also present, we must allow for the lead which it has produced at the same time. Actino-uranium is always present to the extent of 1/140 of the heavy uranium, and may easily be allowed for. We must be sure that the crystal has not been altered chemically—for example, by the action of percolating water—during its long entombment in the rock. Hence, only the inner portions of clean crystals, showing no visible effects of this sort, are employed. Finally, how can we be sure that there was not some lead in the crystal when it was formed?

Nature is kind to us here. We can measure, with the mass-spectrograph, the relative amounts of lead of atomic weight 206, 207 and 208. "Ordinary" lead contains also a small proportion of another isotope, of weight 204, which does not appear to be produced by radioactive processes. Measuring this, we can determine and allow for the ordinary lead which may have been present at the start.

With these precautions, the radioactive method for determining the age of minerals appears to be thoroughly reliable. It is applicable mainly to igneous rocks, and gives the time since they solidified. The geological age of such rocks can usually be determined by a study of the neighboring strata. In this way many points of the geological sequence can be dated, and the agreement with the order of succession indicated by the stratigraphic and paleontological evidence is admirable.

We are concerned to-night with the greatest ages this revealed, and these run up to 1,500 or even 1,800 million years. The most striking example is a pegmatite in Manitoba, in which have been found crystals of uraninite containing uranium, of monazite containing thorium, and of mica containing rubidium. This is also radioactive, and breaks down very slowly into an isotope of strontium. The ages determined independently from these three minerals and based on different radioactive processes, come to 1,600, 1,900, and about 1,700 million years.

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[3] In the customary American notation, 10^9 years, not 10^6 or 10^{12}.

[4] A. O. Nier, *Phys. Rev.*, 55: 153, 1939; A. F. Kovarik and N. I. Adams, *Phys. Rev.*, 53: 928, 1938.

There seems to be no escape from the conclusion that these minerals had actually been lying undisturbed in the rock for more than a billion and a half years, until the miner blasted them out. The Earth must be at least as old as this.

The same radioactive processes may be used to find an upper limit to the age of the Earth, or at least of its crust. Radioactive tests are so delicate that we can find, with considerable accuracy, the amounts of uranium and thorium which are present per ton of rock, and hence, taking an average of rock-types, for the upper crust of our planet. The amount of lead must be found by ordinary chemical methods, but is fairly well estimable. Now, so long as the Earth's crust *as a whole* has not been mixed with other matter, the lead produced by the decay of the uranium and thorium must still be in it. A simple calculation shows that all the existing lead would have been produced radioactively in between three and four billion years. This figure is considerably less accurate than the last; but it should represent a true upper limit, as there was very probably "ordinary" lead present. Provided that the amounts of uranium, thorium and lead are well determined, this calculation holds, no matter how many times the material of the crust may have been melted or re-worked, so long as no process selectively removed the uranium or the lead into the inaccessible interior of the earth. It appears, then, that the earth's crust is more than 1¾ and less than 3½ billions of years old.

That so great a time-interval can be determined within a factor of two is remarkable.

If all the helium which is produced by radioactive changes within a mineral remained in it, measurement of its amount would serve to determine its age. If some of the gas escapes—as it is likely to do except from dense crystals or fine-grained rocks—the calculated age will be too low. This method, applied to terrestrial minerals, gives ages comparable with the lead-ratio methods, or lower.

Paneth has employed it upon meteorites, finding low values in some cases (as might be expected) and maximum ages up to 2,800 million years for others. The recent researches of Whipple at Harvard show that several bright meteors which have been accurately observed by photography were moving around the sun in asteroid-like orbits before they hit the earth. These meteorites may then be regarded as members of the solar system—though there is a chance that a small percentage were visitors from interstellar space.

The age of the earth appears therefore to be substantially the same as that of the solar system as a whole (so far as we can test it).

At this point we lose the powerful aid of chemical analysis. Theoretically we might hope to detect uranium, thorium and lead spectroscopically in the Sun, or even the stars. Lead has actually been found; but unfortunately the character of the spectra of uranium and thorium, which contain great numbers of rather weak lines, makes the spectroscopic test in the Sun relatively insensitive, and no evidence is available.

(2) A determination of time-scale of a radically different sort may be made from observations of the extra-galactic nebulae (or external galaxies, as some prefer to call them). The brilliant work of Hubble has proved that these objects are enormous clouds of stars, thousands of light-years in diameter, and, except for the very nearest, millions of light-years away. The distances of the nearer ones can be determined satisfactorily, by a study of the brightness of individual stars within them, especially of variable stars of the Cepheid type, and in this way Hubble has found the distribution of size and brightness among the members of the nearest of the great clusters in which these nebulae often congregate. On the reasonable assumption that the average brightness and the range about the average is similar from one cluster to another, the distances of faint clusters can be derived, some of them as great as 300 million light-years.

The spectra of these nebulae are what might be expected from a cloud of stars; but their spectral lines show a "red-shift" which increases steadily with increasing faintness and distance. This shift is of exactly the kind which would be produced by the Doppler effect due to a very rapid recession. The velocities thus derived are far greater than any previously known, and attain the enormous value of 42,000 kilometers per second for members of a cluster in Ursa Major, whose distance is estimated at 240 million light-years. The observations of these spectra, which have been made mainly by Humason, demand the 100-inch telescope, a specially designed spectrograph of very great light-power, and great skill and assiduity. Spectra have been photographed for nebulae too faint to be directly seen even with this greatest of telescopes—the necessary guiding being done with the aid of a nearby star, whose position, relative to the nebula, had been measured on long-exposure photographs and allowed for.

Hubble has shown conclusively that, in general, the velocity of recession of a nebula is proportional to its distance, a nebula one million light-years away having a velocity of 162 km/sec, etc. There are moderate outstanding differences for the separate nebulae, which presumably represent their "peculiar" or individual motions; but these do not at all obscure the general trend.

This proportionality between velocity and distance may be expressed as follows. If the nebulae could all have been collected at one point at a certain time in the remote past, and each one launched into space in its present direction, and with its present speed, they would all, at the present time, have reached their observed positions and distances. We can not, of course, be sure that their actual motions have continued at a uniform rate; but the assumption that they have gives a time-scale appropriate to the description of these motions. Making the simple calculation we find that the hypothetical starting-time comes to 1,840 million years ago.

The agreement of this with the calculated age of the earth or of the solar system is very striking, since it is absolutely unforced. The two calculations have no data whatever in common, and their results might just as well have disagreed by a factor of ten, or even a hundred, as have agreed, as they do, within a factor less than two.

The interpretation of these red-shifts leads us far into the field of general relativity. According to this space itself, if it contains matter, will usually not be in a steady state but may expand or contract—the matter moving, too. The observed red-shifts are explicable if the universe is now expanding. Many different courses of change are mathematically possible: Space may have once been much smaller than at present, with the stars (or whatever they were if they had not yet begun to shine) close together; or it may have expanded, at first slowly, then faster, from a finite original size smaller than at present. In the future it may continue to expand indefinitely, or reach a maximum "size" and then contract again. With our present limited knowledge, we can not rule out any of these possibilities. When certain data regarding the numbers and distribution of nebulae down to the faintest limit observable with the 200-inch telescope become available, it may be practicable to specify which type of solution fits the more accurately known facts.

In the meantime, the most interesting solution is that of Lemaître, according to which the whole universe was once packed into a narrow compass. He goes so far, a little speculatively, as to envisage a state in which all matter formed one gigantic atom, which broke up and threw off the raw materials for millions of galaxies, and millions of billions of stars. The principal attraction of this scheme is that it pictures a short but tumultuous time in the early days of our present universe, during which all sorts of things which never can happen now might have occurred—such as the origin of the planetary system, and—as we shall see later—the formation of the heavy radio-active atoms.

The interval since these "fireworks," as Lemaître once called them, should be of the order of the 1,800 million years already calculated—perhaps shorter. This makes the earth and all parts of the visible universe contemporaries, and less than two billion years of age.

(3) Objections to this "short" time-scale have been raised by various investigators. Some have proved to be unfounded, but one, suggested a dozen years ago by Jeans, deserves our consideration.

The orbits of binary stars of long period (decades or centuries) are usually highly eccentric, while those of close pairs with periods of months or days are usually nearly circular. So long as a double star remains isolated in space, the relative orbit of the components will be unaltered. If another stray star should pass near it, but at ten times the distance of the close pair, its attraction, being somewhat greater on one component than on the other, would alter the orbit, but not seriously. But if the intruder passed nearer to one of the stars than its companion was at the time, the perturbation due to its attraction would be large and might produce great alterations in the orbit. Sometimes the new orbit would be more eccentric than the old, and sometimes less: But Jeans has shown that the net effect of a great number of such encounters would be to make the average orbital eccentricity 0.66, with a wide range in the individual values.

The actual mean eccentricity for pairs whose orbits have been computed, which can usually be done only if their periods are less than three or four hundred years, is about 0.5, but there is evidence that for the wider and slower moving pairs it increases to about Jeans's value.

For short periods of months or less, the intruding star would have to come far closer to alter the orbit to the same degree. Such close approaches will evidently be much less likely than the wider ones which are effective for the slow pairs, hence, given time enough and not too much, the orbits of the wide pairs should be pretty well "knocked about" while the close pairs are still little affected.

With the present density of distribution of the stars in space, and their present velocities, this production of eccentric orbits should be an exceedingly slow process. Jeans estimates that to get it well toward completion would require 5 trillion years (5×10^{12}).[5]

This leads to a time-scale a thousand times as long as the one we have previously met. The argument is based on sound mathematical analysis, but also on an assumption—that the binary orbits got their high eccentricities in this way. It has been completely upset by the application of just the same reasoning to another class of stellar systems, namely, the moving clusters.

The star-group of the Hyades in Taurus—recognized and known by this name since classical antiquity—contains about 300 stars distributed within a region some forty light-years in diameter, which are moving together in space, in the same direction, and at the same rather rapid rate. Such community of motion

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[5] "Astronomy and Cosmogony," p. 322. Cambridge, 1928.

can not possibly be an accident. No one doubts that the cluster stars have a common origin, and that they have been moving together indefinitely long in the past. The attraction of the stars on one another must hold the cluster together, but this is so small that if the cluster were isolated in space its outer stars would take 50 million years or more to revolve around the center.

Expressed otherwise, it is only about a millionth part of the attraction which the components of a wide binary pair (with separation 100 times that of the earth from the sun) exert upon one another. The disturbing force due to a star passing by at a fairly considerable distance, although small compared with the mutual attraction of a binary pair, would often be great enough to set the cluster star (or the binary pair together) in motion at such a rate that it would escape entirely from the attraction of the cluster and be lost to it.

This is effectively an irreversible process. One interloping star *might* meet another interloper under such circumstances that after their encounter one of them was left moving so slowly relative to the cluster's center that it would be "captured"; but the probability of this is infinitesimally small.

All moving clusters must therefore be gradually disintegrating as their members are removed, one by one. The process is slow; but it must be far more rapid than the alteration of the far more firmly bound binary orbits by similar encounters. Hence, if the latter had taken place to any considerable extent, sparse clusters such as the Hyades, and denser ones like the Pleiades, too, would have been completely disrupted into apparently unrelated stars.

The clusters are there in the sky; and some, such as the Hyades, contain typical binary stars with eccentric orbits. The conclusion is unescapable that the double stars have not had enough knocking about to produce the eccentricities of their orbits (which must have originated in some other way not yet understood) and hence that they have not been subject to encounters for anything like the trillions of years which Jeans suggests.

A detailed analysis by Bok[6] shows that there is a second force tending toward the disintegration of a moving cluster, which is usually more effective than the chance encounters already discussed, namely, the tidal effect due to the attraction of the great mass of stars at the center of the galaxy. He calculates that the Hyades will apparently resist this influence, without much change, for two billion years to come, but that, within a billion years more, the cluster will be completely dissipated. A denser and more massive cluster like the Pleiades should last ten times as long.

These numerical calculations are based upon data entirely independent of any which entered into the earlier discussions. The analysis deals this time with the future, not with the past, but once more it leads to a time-scale measured in billions of years.

(4) There is still one more time-scale which we have to consider—that of the life of a star as a luminous body. The main principles of this study were developed by Eddington between fifteen and twenty years ago. A large mass of matter in space—anything more than 100,000 times as massive as the Earth—must have an enormous pressure in its interior, owing to its own gravitation. To withstand this pressure without collapse, the material must be at a very high temperature, millions of degrees, except for a few stars of exceptionally great size. Hence, the matter must be gaseous and highly ionized, with most of the electrons knocked off the atoms. The properties of matter in this state are much simpler than in any other, so that a general theory of the internal constitution of the stars becomes possible.

Since the inside is hotter than the surface, heat must leak out from the interior down the temperature gradient; and it is this which keeps the stars shining. The opacity of the gas can be determined by modern atomic theory, and hence the total energy radiation from the star's surface—its luminosity—may be calculated. It is found that the luminosity increases very rapidly with the star's mass—rather faster than its fourth power, on the average. For the same mass, it changes but slowly with the star's size (inversely as the square root of its radius). Differences in the internal density distribution—the "model"—make surprisingly little difference in the luminosity, hardly more than one stellar magnitude. The chemical composition makes little difference, too, except for the abundance of hydrogen. A mass of almost pure hydrogen is cooler than one composed mainly of heavy atoms, and its luminosity will be less by fully six magnitudes—a factor of 300.

Applying this to the sun, Strömgren finds that the calculated and observed luminosities agree if hydrogen forms 36 per cent. by weight, of the interior mass, the rest being heavy elements.

The principal point of all this for us now is that a large mass, isolated in space, has *got* to shine, to be a star, and to disperse enormous stores of energy into the unknown depths of space.

The only source known to the older physics from which this could be derived is the gravitational energy of the star itself. A steady contraction, too slow to be detectable within the few centuries of exact observation, would draw from this enough to keep the sun shining. But the whole store of energy which could have thus been available to the sun in the past is easily calculable; and it is only enough to supply the present rate of radiation for 15 million years.

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[6] Harvard College Observatory *Circular* No. 384, 1939.

Here is a short time-scale with a vengeance. There must be some way out; and this way, suggested on general principles by various astrophysicists twenty years ago, has just been established on a basis of experimental physics. Relativity predicts that mass and energy should be interconvertible; and many nuclear reactions have been observed in the laboratory in the last few years in which the diminution of the combined masses of the interacting nuclei, and the appearance of the corresponding amount of energy, have been observed. The great energy-liberating process is the building up of hydrogen into heavier elements. The transformation of four atoms of hydrogen into one of helium, for example, diminishes the mass by 1 part in 135.

Now the sun's energy-radiation is known, and it corresponds to a loss of mass of 4,200,000 metric tons per second, corresponding to the transmutation of 570 million tons of hydrogen into helium per second. This is a prodigious amount, but, at 36 per cent. of the whole mass, there is enough hydrogen in the sun to last 40 billion years at this rate—so that we now get a rather long time-scale.

The process by which this transmutation takes place has been identified in detail by the theoretical and experimental work of Bethe. Hydrogen nuclei (protons) colliding with a carbon nucleus, under suitable conditions, build it up into the heavier isotope. Collisions with this again build first the lighter, then the heavier isotope of nitrogen, and collisions with the last split off an alpha particle (helium) and leave a carbon nucleus ready to begin again. Electrons or gamma rays are given off at every stage of the process and carry the released energy into the surrounding gas.

Every stage of this series of atomic events has now been studied in the laboratory, and it is possible to calculate at what rate the cycle would occur in the gas inside the sun for a given temperature, pressure and composition. Assuming 35 per cent. of hydrogen and 1 per cent. of the heavier elements (which accords well with the intensities of lines in stellar spectra) it is found that enough heat to keep the sun going would be liberated if the temperature at its center was 19 million degrees. This is very close to the value of the central temperature which had previously been derived from the sun's observed size and mass, and the assumed hydrogen abundance.

We may therefore fairly claim that we know just why the sun shines, and can be reasonably sure that it will keep on shining for at least 10 billion years in the future (not forty, because it should grow brighter as the hydrogen gets used up). How long it has been shining in the past depends on how much hydrogen was "originally" there when it started as an independent body. If it was almost all hydrogen then, this would have been some 80 billion years ago, but this is an extreme limit.

Bethe's theory accounts not only for the sun, but for the whole great main sequence of stars, which extends from great hot white stars like those in Orion through Sirius and Procyon to the sun and to the faint red dwarf stars.

From the bright end of this sequence to the faint, we come upon stars of smaller and smaller mass, and also smaller diameter. The central temperatures may be as high as 35 million degrees at the upper end, and as low as 12 million at the bottom. The rate at which the transmutation process works increases enormously with the temperature, and the differences just described are very nearly what would be needed to provide the great radiation from the massive stars, and the feeble luminosity of the small ones.

This theory accounts for the present properties of all these stars, and enables us to predict their future; but it tells us little about their past. If, in any way, bodies of composition resembling the sun's, and of all sorts of masses, were scattered here and there through space, each one would settle down into a star. If its central temperature was at first too low to "turn on the heat" from atomic transformation, it would draw on its gravitational energy and contract till the interior became hot enough to make this work. After a few millions of years doing this, it would settle down to a steady life of billions of years, gradually consuming its hydrogen. The gravitational contraction would last longest for the least massive stars, which radiate feebly; but, after a few hundred million years, all trace of this adolescent stage would be lost.

So far, all is well; but there are still a number of acute and unsolved problems. First comes the visible existence of stars of very high luminosity. For example, Y Cygni, near the top of the main sequence, has seventeen times the sun's mass, and about 30,000 times its luminosity. It must therefore be living its life nearly 2,000 times as fast as the sun. For 29 Canis Majoris, at the very top, the mass is 46 and the luminosity is estimated by Chandrasekhar as 700,000, so that it is living more than 10,000 times as fast as the sun. The transformation of its whole mass from hydrogen to helium would supply this rate of shining for only about 10 million years, while Y Cygni might last 60 million.

Many other stars are known which are many thousands of times as luminous as the sun, and must be living their lives hundreds of times faster; and among these are red super-giants of enormous diameter like Zeta Aurigae. If these are built at all like the sun inside, their central temperatures can not be much over a million degrees. The self-regenerating carbon cycle would not work at all at these temperatures—the only hope seems to be in the interaction of deuterons (heavy hydrogen) and protons (or for somewhat higher temperatures, of lithium, etc.). These elements are very rare on earth, and in the sun. We can not prove that they might not have been more abundant in these stars. But all known nuclear reactions which involve them use them up, and, whatever assumptions we choose to make, the difficulty of the short time-scale remains. Milne's suggestion (which can not at present be disproved, though it does not look likely) that these giant stars have small dense hot nuclei in which other nuclear reactions are at work, only reduces the difficulty to the same level as for the hotter stars.

Here we are faced with a difficulty which is not yet resolved. Perhaps these stars began their existence as luminous bodies at a relatively late date in the billion years or more of history which other evidence assigns to the sidereal universe. In that case, it is hard to explain in what physical state the matter which composed them previously was, and what prevented it from starting to condense. Moreover, where are the stars which it is reasonable to suppose started earlier and have exhausted their hydrogen?

Again, it is conceivable that inside these stars the far more drastic hypothetical process of the complete transformation of mass into energy may take place—the annihilation of matter. Since nothing of the sort has been observed in the laboratory (saving the mutual annihilation of positive and negative electrons, which is beside the point) we are here in the realm of the purely speculative.

A second puzzle is raised by the existence of the white dwarfs—stars of low luminosity and enormously high density. More of these are being discovered every year, and it is evident that they form the most numerous of all classes of stars, excepting the red dwarfs, if the count is made, as it should fairly be, in a given volume of space.

Our theoretical understanding of these stars is the most satisfactory that we possess. They represent senility—the approach to the final state in which all the available energy, gravitational, nuclear, or what not, has been exhausted and radiated away into space, and nothing more can happen. Within them, the electrons are degenerate—jammed together as closely as the quantum laws permit, and further contraction is impossible.

Chandrasekhar has shown that the radius and density of a star in this state are determined by its mass (and the amount of hydrogen remaining in it). The greater the mass, the smaller and denser will be the star. For masses less than a certain limit (1.4 times the sun's mass, if no hydrogen is present) the process of contraction will end in a degenerate state. For larger masses the critical conditions will not be reached, and so far as our present knowledge goes, a star may contract indefinitely.

Now to reach the white-dwarf stage, a star like the companion of Sirius, which has nearly the same mass as the sun, must have gotten rid of all its stores of energy. If it started like the sun, it would require many billions of years to do this, while white dwarfs of smaller mass (o^2 Eridani B) which live their lives more slowly, will take still longer. When we find numbers of such stars in an expanding universe which looks as if it were only a billion or two years old, we are moved to drop into the vernacular and ask "How did they get that way?"

A bold answer was given by de Sitter. May it not be that these dense stars *came through* the period when space was last small, so that they are older than the galaxies? They would be tough nuts to crack; everything depends on how great the turmoil was at the critical time.

Finally, one more puzzle is "How did the radioactive elements get there?" These are certainly decaying, and, when bombarded in the laboratory, they break up all the more. To build them up out of lighter atoms would probably demand extreme conditions of temperature and pressure, such as can not be reached in the hotter stellar interiors.

It was supposed, a few years ago, that the liberation of energy by transmutation of hydrogen might result, as a by-product, in the formation of the heavier elements. But a careful investigation by Bethe indicates that this is extremely improbable—at least at such temperatures as exist inside the stars. So long as hydrogen and carbon are both present, this temperature can not rise much above 30 million degrees. Otherwise there would be so rapid an evolution of energy as to force a reversal of the process of gravitational contraction, expanding the star, and making its interior cooler. No way for the formation of sodium and heavier atoms appears to be open. But these elements exist in considerable abundance on the surfaces of the stars, and it is probable that they form a large part of the 64 per cent. of the sun's interior which is not hydrogen.

How they got there we do not know. It is tempting to think that just before the last expansion of the universe started, much, if not all, of its matter was under great pressure and at an exceedingly high temperature; but this is speculative.

The outcome of our discussion is this. A time-scale for the universe measured in billions of years—and in very few of them—is indicated by four independent lines of evidence. The outstanding difficulties are to explain why the giant stars still shine, and why the white dwarfs are already present.

Above all, all the witnesses proclaim with one voice that the present order of things is transitory. As Eddington puts it, "the stars are in their first innings." If things go on as they are, in less than a hundred billion years the spiral nebulae will have receded out of sight, the radioactive atoms will have run down, all but the fainter stars will be going-out—and the universe will be thoroughly uninteresting.

Of course by that time—or perhaps later—the expansion of the universe may give place to a contraction, which continues till everything—including the radiation now in remote depths—has been crowded together again in small compass; and the universe may start afresh.

Whether this may be so or not we have no knowledge; but it is surprising to me how strong an aesthetic hold this conception has on many people. (I say deliberately aesthetic and not religious, for religion has never concerned itself much about the fate of material things.)

With this wide-spread desire to believe in some cyclical restoration of activity at however great intervals, I admit frankly that I am not in sympathy. I agree with Eddington, "I am an evolutionist, not a multiplicationist. It seems so tiresome to be doing the same things over and over again." But it is in other words that I would leave the expression of this attitude with you—Rupert Brooke's:

> There are waters blown by changing winds to laughter
> And lit by the rich skies, all day. And after
> Frost, with a gesture, stays the waves that dance
> And wandering loveliness. He leaves a white
> Unbroken glory, a gathered radiance,
> A width, a shining peace, under the night.

SCIENTIFIC EVENTS

THE NEW CHEMICAL LABORATORY BUILDING OF THE UNIVERSITY OF PENNSYLVANIA

PLANS to begin construction during the bicentennial year of the University of Pennsylvania of the first of three units of the new Chemical Laboratory Building have been announced.

Dr. Paul P. Cret, professor emeritus of design, architect and alumnus, has been authorized to draw complete specifications for the first unit and plans for the two additional units to be added as funds become available. For construction and endowment of the entire building the sum of $2,000,000 is required.

The present John Harrison Laboratory of the university was established by gifts from the late Provost Charles Custis Harrison and his brothers as a memorial to their grandfather, who founded in Philadelphia, in 1792, the first permanent chemical plant in this country. The laboratory was first occupied in the fall of 1894, the department of chemistry having previously been quartered in College Hall.

In 1894 the registration of students in the department of chemistry was 57. Now there are 450 students. This number represents an increase during the past seven years of more than a hundred per cent.

Including students enrolled in other schools or departments and not majoring in chemistry, there are now more than 3,000 in the courses in chemistry and chemical engineering.

The building is one of many advances made possible by the more than 15,000 alumni and friends who have given to the Bicentennial Fund the sum of more than $4,300,000. There will be presented to the university on September 20 a Bicentennial Honor Roll containing the names of all alumni, alumnae, students, friends, firms and corporations, foundations and other organizations contributing to the fund up to that time. It will be placed with other memorabilia of the times in a sealed packet, to be preserved unopened until the year 2040, which will be the three-hundredth anniversary of the university.

THE VIRGINIA JUNIOR ACADEMY OF SCIENCE

ACCORDING to Dr. E. C. L. Miller, secretary-treasurer of the Virginia Academy of Science, there are now fifty-three organized science clubs in the secondary schools of the state of Virginia, sponsored by teachers in the various schools. Some forty-five more are in the formation period. Steps have been taken to organize these clubs into a Junior Academy of Science. At a meeting on June 5 two committees were appointed for this purpose; the members of the first committee to function as officers of the Junior Academy for the rest of this year, the second committee to function as an advisory committee from the senior academy, with final organization plans to be made at the Richmond meeting of the academy next spring.

Members of these committees are:

VIRGINIA JUNIOR ACADEMY OF SCIENCE

H. J. Davis, *chairman,* Pocahontas.
W. W. Nofsinger, *vice-chairman,* Jefferson Senior High School, Roanoke.
Miss J. Frances Allen, *secretary,* Alfred Belle Apartments, Pulaski.
J. T. Christopher, George Washington High School, Danville.
C. G. Gibbs, Floyd High School, Floyd.
Miss E. Gillespie, Maury High School, Norfolk.
Wm. T. Hall, Clarksville High School, Clarksville.