THE AGE OF THE EARTH

A Discussion of Recent Evidence From Geology and Astronomy

By Harlow Shapley

"Nature vibrates with rhythms, climatic and diastrophic, those finding stratigraphic expression ranging in period from the rapid oscillation of surface waters, recorded in ripple-mark, to those long-deferred stirrings of the deep imprisoned titans which have divided earth history into periods and eras. The flight of time is measured by the weaving of composite rhythms—day and night, calm and storm, summer and winter, birth and death—such as these are sensed in the brief life of man. But the career of the Earth recedes into a remoteness against which these lesser cycles are as unavailing for the measurement of that abyss of time as would be for human history the beating of an insect's wing. We must seek out, then, the nature of those longer rhythms whose very existence was unknown until man by the light of science sought to understand the Earth. The larger of these must be measured in terms of the smaller, and the smaller must be measured in terms of years. Sedimentation is controlled by them, and the stratigraphic series constitutes a record, written on tablets of stone, of these lesser and greater waves of change which have pulsed thru geologic time."[1]

The measurement of geologic time is of much importance outside of the realms of geology and biology. Closely related to the history of sedimentary rocks are the age of the Earth as an astronomical body and the evolution of the planetary system. We shall see from the discussion of the following pages that the nature and speed of stellar development are also involved in this problem, and even the fundamental physical problem of the source of the radiant energy of stars. Thus the recent important studies of the age of the habitable Earth by geologists and paleontologists—Holmes, Schuchert, Matthews, Barrell, and others—have high significance in general problems of cosmogony. The progress of science frequently demands and utilizes close co-operation of its many branches. We may study the stars, indeed, with the aid of fossils in terrestrial rocks, and acquire knowledge of atomic structure from the climates of Precambrian times.

I have begun this paper with the introductory paragraph of a remarkably comprehensive and important memoir on the duration of geologic time by Professor Joseph Barrell of Yale University. In the growth of our concepts of the age of the Earth, his discussion is likely to mark an epoch because of its consistent carefulness, its great expansion of geologic time beyond the commonly accepted limits, and its decided rebellion against the stringent limitations set by Kelvin and later physicists. Excepting

[1]Barrell, Rhythms and the Measurements of Geologic Time, *Bulletin of the Geological Society of America*, 28, 745-904, 1917.

a few others, such as Arthur Holmes[1] of England, geologists have heretofore hesitated to correlate directly the radioactive evidence of the age of rocks with the records of stratigraphy.

The Time Scale in the History of the Earth

Before reviewing some of the more salient points in Barrell's revision of geologic time, a chronological table of earth history may be given, incorporating his final estimates. I have adapted the tabular data from numerous sources[2]. The scheme of eras and periods follows traditional lines rather than the more logical arrangement of eras based upon organic evolution and of periods based upon modern views of the relative importance of the major disturbances that punctuate geologic history. It should be noted that the birth of the various mountain systems usually extended over more than a single period; the time indicated in the last column is that of greatest activity or of maximum uplift.

Numbers of the third and fourth columns, referring to the total time elapsed since the beginning of the corresponding period, are taken from Barrell's memoir. He states that the column designating the minimum values is "regarded as the more probable, but it is desirable to give maximum and minimum estimates in order to prevent a single column of figures conveying the idea of a precision or certainty which is not yet attained." The divergence of the two columns shows the order of uncertainty given to the results by the summation of the estimated probable errors of all the various factors which enter the determination of the relative and absolute ages.

Some of the points in geologic history are determined with much greater accuracy than others; the beginning of the Cambrian is far from certain, while the age of Devonian and Carboniferous rocks is fairly definite. The numbers for Precambrian times, which I have added parenthetically to the table, are just short of being hypothetical, in that a considerable uncertainty arises in estimating the actual beginning of a division. The ages of some of the rocks of these periods are accurately known; but the precise geologic positions within the periods are in general not as yet determined. Barrell remarks (p. 752) that "surprising as it may seem, the date known with the greatest precision lies far back in

[1]The Age of the Earth, (London), 1913.

[2]They include: Barrell, *op. cit.*; James Geikie, Mountains, their Origin, Growth, and Decay, (Edinburgh), 1913; Huntington, The Climatic Factor, (Washington), 1914; Matthews, Climate and Evolution. *Annals of the New York Academy of Sciences*, 24, 171-318, 1915; and the geologic manuals of Pirsson and Schuchert, Chamberlin and Salisbury, and Scott.

Precambrian time. From Norway, Texas, Quebec, and German East Africa uranium minerals associated with granites give an age which approximates 1,120,000,000 years." The great masses of Precambrian rocks have long been held to represent at least as great an interval of time as the whole of subsequent history. It now appears that the oldest known rocks, the granite-gneisses of the Laurentian system in Canada for example, were in existence nearly a billion and a half years ago.

"Beyond these most ancient milestones lies the Primordial era, whose stratigraphic record has been destroyed by engulfment in magmas from below and by repeated cycles of erosion from above. As to its length, there is no indication other than that the oldest known rocks which mark the beginning of the following era contain sediments testifying to an earth surface on which air and water played their parts, much as in later times. Crust, ocean, and atmosphere had by the opening of the Archeozoic already attained a condition of stability."[1]

The last entry in the table, that for the origin of the Earth, is certainly hypothetical, but it is of interest as an independent determination that is not out of harmony with geologic evidence. It is given by Jeffreys[2] as a rough theoretical value of the age of the planetary system, being derived, on the basis of the tidal evolution theory, from a consideration of the present orbital elements.

Rhythms and the Measurement of Geologic Time

Professor Barrell's discussion is primarily an analysis of geologic evidence, considering especially the influences of "the fundamental factor of composite rhythms." It is in the recognition of these age-long rhythms—the pulsatory deviations from strict uniformity in all geologic processes—that he reaches conclusions differing widely from the usual results. Chamberlin, Holmes, Schuchert, and a few others also recognize that the average rate of erosion, sedimentation, and crustal movement in the remote past cannot be closely equated with the rates in recent and present times. We now live in an epoch of great continental uplift and all processes are conspicuously accelerated. Chamberlin writes:[3]

"Because of the relatively high gradients, the wash of clastic material from the slopes and its deposition in the basins, as well as the transfer of salts to the sea, are today more rapid than in average times. We seem to be at, or near, one of the great extremes of intensification of the processes of solution and degradation. And so, whether conclusions are based upon degradation and clastic deposition, or upon solvent action and the accumulation of solutes in the sea, the present rates are high rates."

[1]Barrell, p. 881.
[2]*Monthly Notices*, 78, 424, 1918.
[3]Quoted by Holmes from a private letter, *op. cit.*, p. 79.

ERA	PERIOD	TIME SCALE IN MILLIONS OF YEARS		CHRONOLOGICAL NOTES
		MINIMUM	MAXIMUM	
Psychozoic	1. Recent	1	1.5	Dominance of man
(Age of mental life)	2. Pleistocene			Periodic glaciation; primitive man
Cenozoic	1. Pliocene	7	9	Himalayas; man-apes
(Age of mammals and modern floras)	2. Miocene	19	23	Modern Alps; three-toed horses
	3. Oligocene	35	39	Pyrenees; Apennines
	4. Eocene	55	65	Mt. Wilson[1]; modern mammals; four-toed horses
	5. Paleocene			Primitive mammals; five-toed horses?
Mesozoic	1. Cretaceous	95	115	Andes; Rocky Mountains
(Age of reptiles)	2. Commanchian	120	150	Rise of flowering plants
	3. Jurassic	155	195	Sierra Nevada; flying reptiles; first birds
	4. Triassic	190	240	Rise of dinosaurs
Paleozoic	1. Permian	215	280	Appalachians; Ural Mountains
(Age of amphibians, fishes, and higher invertebrates)	2. Pennsylvanian	250	330	Paleozoic Alps; primitive insects
	3. Mississippian	300	370	Early Coal Measures
	4. Devonian	350	420	Earliest known land floras
	5. Silurian	390	460	Age of fishes
	6. Ordovician	480	590	Rise of invertebrates
	7. Cambrian	550	700	Dominance of trilobites
Proterozoic	1. Late	(1000)		Oldest known fossils
	2. Early	(1200)		Primitive marine invertebrates
Archeozoic	Paleo-Laurentian, etc.	(1500)		Unicellular life?
Primordial	....	....	....	....
Cosmologic	....	(3000?)		Origin of Earth

[1]Arnold and Strong, Some Crystalline Rocks of the San Gabriel Mountains, California, ***Bulletin of the Geological Society of America*** **16,** 183, 1905; Suess, The Face of the Earth, vol. 4, (Oxford), 1909, p. 425.

Admitting the present high rates of denudation and deposition and their irregularly rhythmic nature, with the resulting breaks in the sedimentary records, Barrell concludes that a fair interpretation of present stratigraphic evidence demands a duration of time perhaps ten or fifteen times longer than that required by a strict uniformitarian treatment.

The hypothesis of compound rhythms is applied by Barrell to all phases of geologic action. Some oscillations are extremely short and indefinite, others are long and more surely recorded in the rocks. The compounding and balancing of the effects of various pulsations give rise to crescendoes and diminuendoes in the resultant flow of geologic events. The sharp oscillations of decades, centuries, and thousands of years may be classed as solar climatic rhythms; the long, slow, and massive movements as diastrophic climatic changes. A cycle of some forty million years appears to mark the crustal and climatic disturbances which terminate the periods; possibly a cycle of two hundred million years separates the eras, if a proposed delimitation of the greater divisions be accepted. The present great continental elevation was matched in the Proterozoic, indicating the most far-reaching rhythm of all geologic time. This doctrine of rhythms is taken by Professor Barrell even to the utmost limits of cosmogony when he subscribes to the argument that "the apparent running down of the visible universe must be but one phase of a recurrent cosmic cycle philosophically necessary in infinite time, or else the running down would have been completed in previous eternity" (p. 904).

Before Barrell's work the principal geologic methods of measuring time were based upon: (*a*) erosion and sedimentation, (*b*) chemical denudation and the sodium in the sea, (*c*) the thermal gradient of the crust. He has carefully examined the postulates underlying these methods, which have generally given estimates of time very much smaller than those given by considerations of rhythms in the sedimentary series and by the measurements based on radioactive processes. Thus the viewpoint of his treatment is strictly geologic, but a full review of the evidence furnished by radioactivity is included, derived mainly from the publications of Holmes and the experimental work of Boltwood and Strutt.

The new scale of geologic time is constructed, therefore, by the dovetailing of two lines of evidence[1]: First, the thicknesses and

[1]Large parts of the next five paragraphs are quoted, with small textual alterations, from various sections of Barrell's memoir.

character of the sediments give stratigraphic ratios of the lengths of the several periods. The ratios are subject to considerable uncertainty; yet, when derived with a knowledge of the variables involved, they give some measure of the relative durations. Second, the quantities of helium and lead in radioactive minerals give minimum and maximum measurements of age. These ages are open to some uncertainty owing to the loss of helium or the presence of original lead, and the stratigraphic positions of the rocks holding the minerals are also in most cases not closely known. Nevertheless, the radioactive minerals give measures of absolute age which are of the right order of magnitude and in proper sequence, as shown by the geologic data.

The adjustment of these two lines of evidence serves as the basis for a scale of geologic time expressed in years. The result is comparable to the first crude measurements of the distances of the stars in space. The progress of research will continually refine the determinations and lead to a higher order of precision; at present the important conclusion is that time, since the beginning of the Cambrian, is from ten to fifteen times longer than has been generally accepted by geologists.

Radioactivity and the Age of Rocks

The method of measuring the age of the rocks that include radioactive minerals is so generally known that little explanation need here be given. From the time radioactivity attains equilibrium in a thorium or uranium mineral, the end products accumulate within it at a uniform rate. These products are not removed from a dense crystalline rock unless the mineral is subjected to passing solvents, which would then surely record their effects by the alteration of the mineral itself. An atom of uranium (atomic weight 238) will ultimately give rise as stable products to eight atoms of helium (atomic weight 4) and one atom of isotopic lead (atomic weight 206). If the quantity of these can be measured and compared with the quantity of uranium in the same material, data are obtained for measuring the age of the mineral and with it the age of the rock-formation of which it is a part.

If a mineral contains a percentage, Pb, of accumulated lead of radioactive origin, and a percentage of uranium, U, then the age of the mineral is given by:

$$\text{Age} = \frac{\text{Pb}}{\text{U} + 0.575\ \text{Pb}} \times 7{,}500 \text{ million years}$$

The numerical values in this formula are based upon an unpublished discussion by Professor Boltwood, who considers that the half-value periods of radium and uranium are known within two per cent.

The rate of decay apparently is not affected by the nature of chemical combination or physical state. Laboratory experiments have duplicated the conditions that exist in the outer crust of the Earth. Temperatures ranging from that of liquid air up to 2,500°C., and pressures up to 160 tons per square inch have been found not to influence the rate of disintegration of the products of radium. It is highly probable but not as yet actually demonstrated that uranium is similarly unaffected. Thus the atoms of uranium break up with a uniform rate whether they are in elemental form or combined in a salt; whether they are in solid, liquid, or gas. Nothing is known to support a hypothesis that there is a change in stability of unstable atoms by a process of aging.

The possibility that uranium is affected by ranges of temperature and pressure that do not affect its less stable derivatives can be and, to some extent, has been tested by geologic evidence. Uranium minerals from the same well-established stratigraphic position, but in different localities, and, therefore, for millions of years under widely different physical conditions, yield accordant results for the age of the rock-formation. Another valuable test is that of proper sequence—invariably reliable analytical work shows that the older the rock-formation, the greater the lead and helium ratios. Believing he has found discordance in such cases, Becker is inclined to discount the whole radioactive method; but Barrell's critical examination of the same data shows that the errors in the adopted stratigraphic positions and in the use of the radioactive analyses wholly account for the supposed discrepancies.

The summation of all the evidence therefore makes clear that the properties of radioactive elements afford a remarkable and reliable means of dating the principal incidents in the ancient history of the Earth.

The Earth's Loss of Heat

In the earlier history of speculations concerning geologic time, those students who were not too much hampered by conventional interpretations of the first chapter of Genesis felt no need of placing a limit to the age of the Earth. "No vestage of a beginning, no prospect of an end" is frequently quoted from Hutton. For the deposition of the known sediments according to uniformitarian principles, Lyell saw the necessity of hundreds of millions of years; and Darwin believed that the transformation of species and the high development of animal life required similar lapses of time.

In propounding the contraction theory of solar energy, Helmholtz in 1856 noted that the past history of the Sun would be limited to some twenty million years. A few years later Lord Kelvin attacked the problem from the standpoint of the flow of internal terrestrial heat, obtaining similar numerical results. Kelvin invaded the domain of geology (thus the geologists are wont to put it) hoping to reform its speculations and bring them into accordance with the doctrines of the conservation and degradation of energy. His mighty prestige and his unimpeachable mathematics silenced the protests of biologists and stratigraphers alike, and for several decades he and contemporary physicists allowed but ten or twenty millions of years for the past duration of the habitable Earth.

It is a result of observation that at least near the surface of the Earth the temperature of the rocks increases on the average about 1°C. for every 100 feet in depth. This of course indicates that the Earth is losing heat, and, supposing an original temperature of the whole Earth equal to that of molten rock, the Fourier theory of heat conduction permits a calculation of the total duration of inhabitable surface temperatures. Such reasoning naturally assumes that the only source is the primal high temperature, and that the Earth is simply cooling off from its molten beginning. Hence, at some past time the surface was too hot for life and, at a future time, all depending on the observed temperature gradient, it will be too cold. That was all there was to the problem and its solution, according to the physical theory, and the recent imposing Ages of Ice were for a time considered as evidence of the approaching, inevitable and eternal frigidity.

The physical argument was adopted, in general, and attempts were made to compress the geologic record into a narrow interval of time; many geologists, however, would not accept the dictum.

For instance, in 1892, Sir Archibald Geikie[1] objected with the following somewhat prophetic statement:

"That there must be some flaw in the physical argument I can, for my own part, hardly doubt, tho I do not pretend to be able to say where it is to be found. Some assumption, it seems to me, has been made, or some consideration has been left out of sight, which will eventually be seen to vitiate the conclusions, and which when duly taken into account will allow time enough for any reasonable interpretation of the geological record."

As a sort of a compromise between the inexorable physics and their own feelings as to the duration of geologic time, a value of a hundred million years came to be pretty generally accepted by geologists with no insistence on certainty, for the age of the oldest known sedimentary rocks.

Professor Harker[2] points out that Kelvin also had at one time an inkling of the true state of affairs; he recognized that, while the Earth is certainly losing heat, "it is possible that no cooling may result from this loss of heat, but only an exhaustion of potential energy, which in this case could scarcely be other than chemical affinity between substances forming part of the Earth's crust." This, however, Kelvin dismissed as "extremely improbable," and proceeded on the assumption that primal heat is the only form of energy to be reckoned with.

Kelvin's surmise as to potential energies and chemical affinities was an interesting prophecy; for, as we now know, the solution of the dilemma was the discovery, less than twenty years ago, of radioactivity in terrestrial rocks, which provides enormous stores of thermal energy. The discovery was, in fact, more than a solution; the percentage of radium in surface rocks is one hundred times too much to just counteract the observed loss of heat. The explanation of this condition must be that the radioactive minerals are confined to surface formations only, as otherwise the Earth would be heating up with "geologic rapidity." "The most probable depth of the radioactive layer may therefore be placed at 30 miles," Holmes concludes (p. 135), after considering other values, "and the basal temperature in this case would be about 750°C, which would be more in agreement with the requirements of volcanic action." This approximate result is independent of the observed temperature gradient, involving only the character of terrestrial rocks, "for there can be no doubt that the radium and thorium content decreases with depth for the same reason that the type of rock varies with depth. * * * There is a rough proportionality between the

[1] *Annual Report of the Smithsonian Institution for 1892*, p. 124.
[2] *Nature*, 95, 107, 1915.

acidity or percentage of silica of a rock and its radium content. The more basic rocks are much poorer in radium, and as would be expected, in thorium also. Now we have good reason to suppose that the more deep-seated rocks of the Earth's crust are of basic and ultra-basic composition, and that below the 30-mile crustal zone they are exclusively ultra-basic, perhaps similar in composition to the material of stony meteorites. * * * Within the stony zone, which extends down several hundred miles, lies the heavy core of the Earth, probably of metallic composition, like the iron meteorites. If we may judge from the latter, this nucleus is entirely free from radium."[1]

With no prospect of ever knowing accurately the amount and distribution of radioactive elements in the Earth's crust, there is no longer any solid basis for calculating age from the temperature gradient of the Earth. The observed loss of heat is not an indication of previous thermal conditions. The Earth may be growing hotter; it may be cooling more rapidly than it would do if in radio-thermal equilibrium; or it may be in thermal equilibrium (the most probable condition, according to Holmes), gaining as much heat as it loses and eventually cooling only as the slow decay of the radio-elements permits.

We are thus justified, it appears, in believing in a greatly prolonged future for the inhabitants of the Earth. In terrestrial climates during geologic times we recognize no evidence of sensible secular change. Atmospheric temperatures are, of course, almost wholly dependent on the radiation of the Sun. The secular progression of solar energies, however, as we shall observe in following paragraphs, is apparently so small, when judged by our base line of a thousand million years, that we may consider the radiation as essentially constant. There is probably much better justification, therefore, in expecting the termination of terrestrial life in catastrophe, whether earthly or cosmic, rather than in climatic senility. To be sure, there is strong evidence that we now live in an interglacial epoch of the quickening ice pulsations of the Pleistocene, and we may indeed reasonably expect another advance of the oscillating ice sheets in the near (geologically-speaking) future; but in former times there have been equally extensive invasions of ice, followed by unknown millions of years

[1] *Op. cit.*, p. 133. Recent corroborative evidence of this viewpoint is afforded by studies of the radioactivity of Archeozoic rocks of southern India by Smeeth and Watson, *Philosophical Magazine*, 35, 206, 1918.

of genial climates. In the past the fluctuations of land forms and of meteorological conditions have profoundly tho slowly affected conditions for organic existence; but later than Proterozoic times there has been no complete interruption of plant and animal life, and as far as can be seen or intelligently predicted, the future, for similar eons, promises conditions no less favorable.

Radioactivity and Solar Radiation

The discovery of radium rescued the problem of the age of the inhabitable Earth as far as its own interior cooling is concerned, from the narrow limitations set by the thermal gradient. But radioactivity will not suffice to account for the radiation of the Sun during geologic ages. We admit no potent source of energy back of terrestrial life other than solar radiation; and we have seen that, in supplying radiant energy at the required rate, the Helmholtzian contraction, which is the only very powerful origin of stellar energy now definitely recognized by astronomers, would suffice only for a few million years. Hence, the geologic time scale is again embarrassed by physical theory. This circumstance, however, does not continue to divert faith from the testimony of the rocks, for, remembering the case of the thermal gradient, we look to a temporary ignorance of the properties of matter in accounting for this presumed discrepancy.

It is readily shown that the normal decomposition of known radioactive elements might be amply sufficient in the Sun (as on the Earth's crust) to account for the *duration* of solar radiation; but in the case of the Sun this device is woefully deficient as to *amount*. If the Sun were composed entirely of uranium, in equilibrium with its disintegration products, the heat generated by known radioactivity would not be a third of the actual output. "The importance of radio-thermal phenomena is not felt until cooling has progressed to a more advanced stage, as exemplified by the Earth, when the heat lost is balanced against that set free by atomic disintegration."[1] Jeans considers that even all known electrical properties of matter, radioactive or otherwise, are incapable of prolonging the solar radiation sufficiently to meet geologic requirements.

We are left, then, with two main sources of solar energy: (1) gravitational contraction, which we must admit is quite inadequate in

[1]Holmes, p. 117.

the light of earth history and of the direct observations that will be mentioned later; (2) "unknown" sources, which we are prone to consider quite sufficient for all requirements, and which are, in fact, often freely and vainly discussed under the vague designation of "sub-" or "infra-" atomic. Further elemental disintegrations, because of the peculiar high-temperature and electrical conditions of the Sun, may be proposed as the energy source—or the complete or partial transformation of mass, by some magical means, into free radiant energy—or other similarly indefinite plans for unraveling the secret of the storing up and releasing of the observed energies of suns. It is hardly probable that we shall long be without the solution of this problem, or at least we may expect an acceptable, workable, and non-magical hypothesis; and when it comes (with its probably enormous consequences) it is to be hoped that our present laws and tentative theories of stellar radiation will not prove to have been wholly unavailing.

Observational Inquiries Relative to Stellar Radiation

Whatever may be the explanation of the energy radiated by the stars, it now appears as a fairly definite result of direct observation that the amount of radiation is so great that only a minute percentage can be supplied by gravitative contraction, infall of meteoric matter, primitive heat, radioactivity, and other recognized atomic sources. One observational result comes from astronomy, another from geology; the latter seems more decisive because of the greater interval of time involved in the test.

From the time of the first spectroscopic studies of stars, the different colors and spectral types were accepted as representing different stages in stellar evolution. The life of man and of his present astronomical records were recognized as too brief to prove directly the change in spectrum as stars grow old; but the continuous gradations from type to type, combined with extensive information as to motions and brightness and chemical nature, left little doubt that, given time enough, a typical star will progress thru many of the spectral stages now observed as essentially static. The actual variation in spectral characteristics of Cepheid variables is periodic rather than secular, and the spectral changes of Novae appear to be catastrophic rather than normal.

Observation and theory alike permit the arrangement of the typical spectral types into a presumably definite evolutionary sequence—Russell's astrophysical hypothesis of the order of development being strongly supported by Eddington's mathematical analysis and by vast and varied quantities of observational material. The mathematical theory, based mainly on known properties of gases, naturally involves directly in its present form only known sources of energy. Fortunately the theory permits estimates of the speed of spectral development, and it is when this theoretical result is compared with certain geologic and astrophysical evidence that we bring to light the glaring discrepancy mentioned above. We shall first describe the astrophysical test.

Suppose a star, exactly similar to the Sun in all respects including the date of origin, were so distant that a great interval of time were necessary for its light to reach the Earth. A study of the two stars by a terrestrial observer would involve a comparison of the youth of the distant star with a more advanced age of the Sun; and, if the evolution is fast enough and the observations sufficiently refined, there should be direct evidence of stellar change. The test obviously cannot be used on the nearby stars ordinarily studied because, first, we do not know that any one of them closely resembles the Sun (or another star) in all respects, and second, their distances from the Sun (or each other) of some hundreds of millions of millions of miles are entirely too small to show measurable change in stellar radiation during the corresponding hundred or so years necessary for the passage of their light. The method may be applied, however, in a qualitative way to the highly luminous giant stars of distant stellar clusters. Eddington has computed that with known sources of energy a hundred thousand years is sufficient for the development of a giant star thru all spectral types to the stage where it no longer behaves as a perfect gas. Since the development presumably is slower for the more advanced stage represented by the Sun, the giant stars are more suitable for the observation of evolutionary change.

Recent studies of globular clusters show their approximate similarity in size, form, and stellar content. We have also learned to estimate their distances, and find them exceedingly remote from the Earth and from each other.[1] From the list of 80 known

[1] *Mount Wilson Contributions*, Nos. 151-157, 1917-1918.

globular systems, I have selected those for which the numbers and colors of their giant stars are known, expressing in round numbers the distance of each from the Earth in terms of the number of years required for the transmission of its light across intervening space:

Messier 22,	25,000 years
Messier 13,	35,000 "
Messier 5,	40,000 "
Messier 3,	45,000 "
Messier 15,	50,000 "
N. G. C. 7006,	220,000 "

As observed from the Earth these clusters differ in age by the differences in the tabulated numbers, the first being nearly two thousand centuries older than the last. If, as the theory predicts, it takes but 25,000 years for the change of a giant red star into a giant yellow star, we should find evidence of such progression in the photometric study of these typical giants of globular clusters. None is found, however, as the frequency of giant stars of all colors is much the same in all six clusters. It would therefore appear that, ignoring improbable alternatives such as the supposition of an equilibrium in color statistics by means of a continual creation of giant stars, this observation must be considered as direct qualitative evidence of slow evolution. To be sure, we do not know the time of origin of these systems relative to each other, but that it is in any way dependent upon distance from the Earth is too improbable to believe.

The similarity of color statistics for the bright stars in globular clusters thus bears on the inadequacy of known energy sources in accounting for the observed radiation phenomena of gaseous giant stars. The paleo-meteorology of the Earth bears on the same problem for the Sun itself, and therefore for the "dwarf" stages in stellar development. It appears, moreover, that this geologic evidence is much more definite and incontrovertible than the somewhat provisional results from clusters; and to a limited extent it may be quantitative. The case is briefly stated.

The new time scale shows that the fossil-bearing rocks of the Paleozoic era were formed some five hundred million years ago. Animal life was then already far advanced compared with its earliest unicellular stages. At the beginning of the Cambrian period all the invertebrate phyla had become differentiated, and the degree of evolution up to that time is generally conceded to have required at least as great an interval of time as all the succeeding ages. Aside from the duration of time, a requisite for the slow development of plant and animal forms is moderate climatic conditions during all the eras of the past, and that such was the case is amply attested by the records of the rocks. Hence the distribution of ancient life, the seasonal effects in the old formations, the characteristic products of denudation, the petrified imprints of the rain drops of Paleozoic showers, all testify against pronounced non-cyclic alteration of terrestrial climate since Archeozoic days. We may be sure, Holmes declares (p. 114), that "for at least as long as the Earth has been a habitable globe, so long has the Sun emitted its life-giving rays at a rate not very different from that of the present."

The consequences are obvious. The Sun has certainly not been a highly luminous giant star during geologic time; nor has it been a dwarf in luminosity. In fact, the evidence suggests that it has been stationary in temperature, light-emission, and spectral type since the recoverable records began in the earth's crust. Possibly we may assume a stabilizing effect of the Earth's atmosphere that might allow in the surface temperature of the Sun a range of a few hundred degrees without dire consequences for terrestrial life. A difference of even a single spectral type, however, would correspond to a change of several hundred per cent in light-emission, and that appears to be wholly out of question. I believe we may assume, therefore, that the time required for the Sun, or any similar star, to change in spectrum from G0 to G5, or from G0 to F5 (whichever way it is going, and if it goes!), is not the few million years provided by existing theory but is indeed far in excess of a thousand million years.

If such is the case a new point of view of the expanse of time enters problems of sidereal systems. During the formative period of stars and stellar groups their wanderings in space, as indicated by observed velocities, may be very far. The globular clusters, to which we may possibly look for the origin of our galactic system, have completely changed in distribution since the first known vertebrates appeared in the Ordovician fauna. If its present high velocity of approach has always been about the same, the great Hercules cluster, which now is visible to the unaided eye at a distance of less than 40,000 light-years, was probably more than a million light-years distant when life first appeared upon the Earth;

it was scarcely a thousandth as bright then as now, it was much less than a minute of arc in diameter, and would have appeared as a faint hazy star in the largest of modern telescopes. The Sun at its present speed would have travelled, since the origin of the Earth, much more than a hundred thousand light-years, and probably many times as far since it itself came into being. We know something of its direction of motion, something perhaps of its dynamical affinities, and it may be possible with the observational accumulations of the future to trace roughly its past course in space and guess at its earlier environment.

Mount Wilson Solar Observatory,
September, 1918