THE NEBULAR HYPOTHESIS AND THE EVOLUTIONARY WORLDVIEW

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I. FROM NEWTON TO DARWIN?

One of the most striking changes in our view of the world during the three centuries since Isaac Newton published his *Philosophia naturalis principia mathematica* is the replacement of Newton’s assumption that the world was created by God in essentially its present form by the assumption that it has evolved by natural processes from a radically-different previous state. We usually associate this change with Charles Darwin’s theory of evolution by natural selection (1859), and thus it is natural to look for its causes in the development of biology. Yet the question is occasionally raised: Was the idea of biological evolution itself inspired or at least encouraged by a line of theorizing in astronomy, which was in turn an outgrowth of Newton’s work?

The suggestion that evolution was imported from astronomy into biology was made quite explicitly by the American astronomer F. R. Moulton in 1938. Moulton claimed that the ‘nebular hypothesis’ for the origin of the solar system “accustomed scientists to thinking of change in long periods of time and thus prepared the way psychologically for the theory of organic evolution”. This hypothesis, whose origin will be discussed below, explained the formation of planets by a combination of gravitational, rotational, and thermal effects, and thus is squarely in the historical tradition of Newtonian physics.

More recently historian Philip Lawrence argued that the nebular hypothesis fostered theories of organic development in a more general way:

On at least the philosophical level the “historical theme” of the nebular hypothesis caught the imaginations of almost all thinking men and strongly influenced the forms of scientific and historical explanations they were willing to entertain. The same pattern of development was detected not only in the inorganic world but in the course of human history. The fossil record revealed the history of living forms to have been both directional and progressive. Why in this sphere should there be an
"Nebula to Man", painting by Lancelot Speed, published as the frontispiece to *Nebula to Man* by Henry R. Knipe (London, 1905). Barely visible on either side of the human figures are monkeys, representing the intermediate stages in the evolutionary sequence.
exception to the pattern of the Universe? Why was the development of life not also a result of the workings of the secondary laws of nature?²

This statement is supported by the research of Ronald Numbers, who presents evidence from mid-nineteenth century American publications to show that “the nebular hypothesis helped to create, in both the scientific and religious worlds, that climate of opinion that made possible the rapid assimilation of organic evolution”.³

There is little evidence that Darwin himself based his theory on the analogy of the nebular hypothesis, although he could certainly have learned about it from contemporary discussions in general as well as scientific publications during the 1830s.⁴ As far as I know, Darwin came closest to a reference to the nebular hypothesis in a passage that appeared only in an unpublished notebook entry, sometime before February 1838:

Astronomers might formerly have said that God ordered each planet to move in its particular destiny. — In same manner God orders each animal created with certain form in certain country, but how much more simple, & sublime power let attraction act according to certain law such as inevitable consequences let animals be created, then by the fixed laws of generation, such will be their successors.⁵

In the historical context of this quotation, “attraction” means the force of gravity that causes the nebula to condense into planets. Darwin seems to be making the leap from creation to evolution in biology just as it has been made in astronomy.

But on closer examination it appears that Darwin in this quotation is not talking about natural selection acting on chance variations, but rather about a deterministic sequence of organisms. In other words, the analogy from astronomy is to evolution but not to Darwinian evolution as Darwin himself later conceived it.

Indeed, in the nineteenth century the term evolution could even include the nebular hypothesis, as the following authoritative definition of the “fundamental proposition of Evolution” by T. H. Huxley makes clear:

This proposition is, that the whole world, living and not living, is the result of the mutual interaction, according to definite laws, of the forces possessed by the molecules of which the primitive nebulosity of the universe was composed. If this is true, it is no less certain that the existing world lay potentially in the cosmic vapour, and that a sufficient intelligence could, from a knowledge of the properties of the molecules of that vapour, have predicted, say the state of the Fauna of Britain in 1869, with as much certainty as one can say what will happen to the vapour of the breath on a cold winter’s day....⁶
Or even the state of its human inhabitants (cf. Figure 1.).

To understand the historical connection between the astronomical theory—the nebular hypothesis, and the biological theory—Darwinian evolution, we must inquire into the relation between the nebular hypothesis and the more general ‘evolutionary worldview’, as well as the relation between that worldview and Darwin’s theory.

What role did the nebular hypothesis play in the development of the evolutionary worldview? Any discussion of this question must begin with a definition of those terms since they are now used in ways that tend to obscure their historical connections. A major theme of this paper will be that the nebular hypothesis, as it was understood in the nineteenth century, favoured some evolutionary theories but not others.

II. THE EVOLUTIONARY WORLDVIEW

‘Evolution’ has come to mean Charles Darwin’s theory of the transformation of biological species by natural selection. But that theory, which I will call ‘Darwinism’, is only the most important special case of a collection of hypotheses and attitudes designated by the more general phrase ‘evolutionary worldview’. The major feature of this worldview is a tendency toward long-term change in some direction, so that the future is different from the past. Change may be from simplicity to complexity, or from order to disorder; it may involve progress or degeneration; it may be predetermined or random, controlled by a grand purpose or governed by many acts of individual will. While allowing chance and human action to shape the details of the process, the evolutionary worldview demands that its gross features be subject to natural law, whether or not the specific physical mechanism that drives change is fully understood.

The evolutionary worldview emerged in the nineteenth century, in cooperation with Darwinism, as a replacement for the static, cyclic worldview sometimes called the “clockwork universe” or “Newtonian world machine”. Theories of social/cultural evolution, sometimes said to be influenced by Darwinism, were either developed prior to the publication of Darwin’s *Origin of species* or inspired by other mid-century works such as those of Herbert Spencer; the same is true for ideologies like ‘social darwinism’. Even in biology, while evolutionary theories were widely accepted in the late nineteenth century, only a minority (not always including T. H. Huxley) subscribed to Darwinism. Finding natural selection inadequate as a driving force, scientists frequently postulated some internal developmental principle or divine guidance. Thus, while Darwin may be credited with “establishing an evolutionary point of view in biology”, this does not mean that his work
“established the theory of natural selection and Darwin’s general assumptions and methods as the norm of scientific thought and practice among biologists”.12

A notable source of confusion is the variety of meanings carried by the word ‘evolution’ in the nineteenth century.13 It was sometimes used to include the development of a single organism as well as the descent of one organism from another or the transformation of one species to another;14 thus an hypothesis such as Gregor Mendel’s that dealt only with heredity might not be considered an adequate theory of evolution and dismissed for that reason.15

To sharpen the distinction between Darwinism and many other versions of the evolutionary worldview we may note three aspects of the former often absent in the latter:

(1) random variation and lack of any goal or purpose in evolution,16
(2) competition and natural selection,
(3) gradualism, denial that large variations or environmental catastrophes play a significant role in evolution.

Each aspect challenged a cherished belief of a group of people who might be receptive to some form of evolutionary theory. Many scientists as well as theologians and pious laymen believed that evolution is guided by divine providence and were repelled by the idea that man is merely the outcome of a lottery.17 Their idea of ‘progress’ did not include a brutal struggle for survival; the outcome of such a selection process would surely be a race possessing the qualities of aggressiveness, low cunning and selfishness.18 Finally, gradualism implied an indefinitely long time scale for evolution, contrary to the idea that the Earth was formed at a definite time, either the few thousand years ago inferred from Mosaic chronology or the few million years ago deduced from the theory of a cooling Earth.19

Of course each of these features also played an important role in theories other than Darwinism: randomness was seen as the basis for irreversibility in thermodynamics and ultimately in atomic behaviour in general;20 selection under the name of ‘reinforcement’ plays a crucial role in the development of individual behaviour in Skinnerian psychology.21 But these examples belong for the most part to the twentieth century and therefore do not directly concern us here.

III. THE COSMOGONIES OF LAPLACE AND WILLIAM HERSCHEL

To modern astronomers the phrase ‘nebular hypothesis’ means a theory of the origin of the solar system proposed by Immanuel Kant and Pierre Simon, Marquis de Laplace.22 The name of William Herschel, though well known in other contexts, is almost never mentioned in connection with the nebular
hypothesis. But in the nineteenth century Herschel's nebular hypothesis was widely discussed as a complement to Laplace's, and had certain features that made it more nearly analogous to theories of biological evolution. The omission of Herschel's theory from the standard historical summaries is probably a result of Whig attitudes toward the history of science; it was based on an assumption now considered completely erroneous.

Laplace introduced his hypothesis in order to explain the remarkable regularity of motions in the solar system: all the planets move in the same direction around the Sun; the Sun and planets rotate in the same direction (to the extent that planetary rotations were known); and all satellites revolve in the same direction around their primaries. Moreover, all planetary and satellite orbits are nearly circular and lie in almost the same plane. That, at least, was the state of astronomical knowledge in 1796 when Laplace first published his theory.

The same regularity, based on somewhat less information, had been noted by Isaac Newton, who concluded that it could not reasonably be attributed to chance and therefore should be taken as evidence of provident design. In fact he considered the orbits of the planets a possible proof of the existence of God. Laplace, as is well known, had "no need for that hypothesis", but believed instead, following the lead of Daniel Bernoulli, that the development and present state of the solar system could be adequately explained through the workings of natural law. In particular, the planets moved in the same way because they had all once been part of the same rotating body.

Laplace considered unsatisfactory Buffon's attempt to explain the regularities by postulating a catastrophic encounter of the Sun with a comet, extracting from the Sun hot gases which later condensed into planets. Instead he assumed that the Sun once had a very hot atmosphere which extended at least as far as the present orbit of Uranus (the planet discovered by William Herschel in 1781). Laplace assumed that the entire atmosphere rotated at the same angular speed, as if it were a solid body. As it cooled down, it would contract; by the law of conservation of angular momentum, it would then have to spin faster. Eventually the centrifugal force due to its rotation would surpass the gravitational force at the outside (but only at the equator, where the linear speed is greatest) and a ring of gas would be detached from the rest. Laplace suggested the ring would eventually collect into a single spherical mass, and that a series of such rings would be generated as the atmosphere continued to cool, contract, and spin faster. The spheres would rotate in the same direction as their motion around the Sun (if the previously-mentioned assumptions are valid) and could spin off satellite rings by a similar process.

Some historians have pointed out that Laplace himself did not view the solar system as being in a continuous state of development but merely wanted to show how its present (stable) state could have arisen by natural causes
without the need for the action of divine providence at every stage; hence one cannot credit Laplace with promulgating an evolutionary worldview. By the same token, neither can one credit Charles Darwin with establishing such a view — except that, like Laplace, Darwin proposed a hypothesis, limited in scope, that was so attractive that others were led to generalize it.

William Herschel played a double role in the development of the nebular hypothesis. His study of the satellites of Uranus led him to the conclusion that their motion is retrograde, thus spoiling the complete regularity on which Laplace had relied. This anomaly does not seem to have induced anyone to abandon Laplace's cosmogony. More important was Herschel's research on nebulae during the period 1781-1814. Although some nebulae could be resolved into separate stars, others could not (with the telescopes available to Herschel), and he concluded that they are clouds of "shining fluid". It was these objects that gave their name to the "nebular hypothesis" and were thought for a time to be precursors of stars and other planetary systems.

Herschel described and classified hundreds of nebulae. He was able to arrange them in a regular sequence, starting with those of uniform brightness, going through stages with a bright region in the centre, then a star surrounded by a halo, and finally a star with only the faintest suggestion of a surrounding haze. Even before he had concluded that certain nebulae are protostellar clouds rather than clusters of stars, Herschel had explicitly compared himself to "the natural philosopher, who sometimes, even from an inconsiderable number of specimens of a plant, or an animal, is enabled to present us with the history of its rise, progress, and decay". But the astronomer can go further: he can speak of "the power which is moulding the different assortments of stars into spherical clusters" and thus is "enabled to judge of the relative age, maturity, or climax of a sidereal system, from the disposition of its component parts". He concluded his 1789 paper with the remark:

The heavens ... are now seen to resemble a luxuriant garden, which contains the greatest variety of productions, in different flourishing beds; and one advantage we may at least reap from it is, that we can, as it were, extend the range of our experience to an immense duration. For, to continue the simile I have borrowed from the vegetable kingdom, is it not almost the same thing, whether we live successively to witness the germination, blooming, foliage, fecundity, fading, withering, and corruption of a plant, or whether a vast number of specimens, selected from every stage through which the plant passes in the course of its existence, be brought at once to our view?

So far there is no suggestion of biological evolution, only an analogy between the aggregation of groups of stars and the life cycle of a single organism. But in 1791 Herschel presented a different biological analogy — one
that brought him dangerously close to evolution — in attempting to comprehend the collection of all celestial objects:

When I pursued these researches, I was in the situation of a natural philosopher who follows the various species of animals and insects from the height of their perfection down to the lowest ebb of life; when, arriving at the vegetable kingdom, he can scarcely point out to us the precise boundary where the animal ceases and the plant begins; and may even go so far as to suspect them not to be essentially different. But recollecting himself, he compares, for instance, one of the human species to a tree, and all doubt upon the subject vanishes before him. In the same manner we pass through gentle steps from a coarse cluster of stars ... till we find ourselves brought to an object such as the nebula in Orion....

Since Herschel did not accept the transmutation of one biological species to another, he needed a contrast such as that between man and tree to refute the impression that one can go by small steps from species to species. Pursuing the analogy, he proposed a celestial object that will perform the same function: a star whose surrounding nebulosity “is not of a starry nature”. But then Herschel came to the conclusion that one can construct a sequence of nebulae in different stages of condensation, such that “every succeeding state of the nebulous matter is the result of the action of gravitation upon it while in a foregoing one”. Laplace then adapted Herschel’s earlier (1789) metaphor to his later hypothesis of nebular condensation: “as in a vast forest we trace the growth of trees, in the individuals of different ages which it contains.” If one used instead Herschel’s second biological analogy and introduced the notion that nebulae grow into stars, one could easily reach the conclusion that (contrary to Herschel’s view) one species can evolve to another. But it is only with hindsight that one can list Herschel as a contributor to the evolutionary worldview.

Alexander von Humboldt, one of the most widely-read naturalists of the nineteenth century, quoted this metaphor in Herschel’s original sense: to reason from biological to astronomical development rather than the reverse.

The genetic evolution — that perpetual state of development which seems to affect this portion of the regions of space — has led philosophical observers to the discovery of an analogy existing among organic phenomena. As in our forests we see the same kind of tree in all the various stages of its growth, and are thus enabled to form an idea of progressive, vital development; so do we also in the great garden of the universe recognise the most different phases of sidereal formation. The process of condensation ... appears to be going on before our eyes.
The tree-star analogy survives in the discourse of twentieth century astronomers.\textsuperscript{39} One of them has even argued that biologists should abandon the term ‘evolution’, leaving it to astronomers who still use it in its proper sense of ‘unrolling’.\textsuperscript{40}

IV. MINIMUM AGE OF THE UNIVERSE

William Herschel contributed to the evolutionary worldview (again, unintentionally) in one other way, by helping to undermine the doctrine that the universe had been created only a few thousand years ago. He was aware that his conception of the sidereal heavens implied immense distance and time scales. These scales could not be determined directly in the absence of a reliable measurement of distances by trigonometric parallax. Herschel was nevertheless able to obtain reasonable order-of-magnitude estimates by assuming that all stars have about the same intrinsic brightness as the Sun, so their distances could be estimated from their relative brightnesses using an inverse square law. Using this method he concluded that he was seeing stars “above $11\frac{1}{2}$ millions of millions of millions of miles” away \([1.18 \times 10^{19} \text{ miles}]\).\textsuperscript{41} Because of the finite time taken for light to travel these distances, he emphasized that his telescope had the power of penetrating into the past, and that in fact the light coming from the most distant nebulae must have originated two million years ago. The consequence, which directly contradicted the current ‘literal’ interpretation of Genesis, was that “so many years ago this object must already have had an existence in the sidereal heavens”.\textsuperscript{42}

Herschel’s estimates of stellar distances were roughly confirmed when F. W. Bessel finally succeeded in establishing the parallax of a nearby star, 61 Cygni, in 1838. One of the first scientists to perceive the implications of these astronomical discoveries for biblical creationism was Marcel de Serres, Professor of Mineralogy and Geology at the University of Montpellier in France. In his book on the creation of the Earth and the celestial bodies, Serres pointed out that some nebulae must be at least 230,000 light years away, on the basis of Herschel’s and Bessel’s observations.\textsuperscript{43} This conclusion did not depend on the assumption that all stars have the same intrinsic brightness but only that at least one star in a nebula that had been resolved into stars is as bright as 61 Cygni. It also does not depend on the accuracy of other methods of measuring distances, but only on the idea that apparent brightness decreases as the square of distance. (The presence of interstellar absorbing matter would affect the precise numbers but not the order of magnitude.) By this primitive but effective method Serres proved that some stars that we now see in the sky must have existed much more than a few thousand years ago.\textsuperscript{44}
William Whewell was probably the first writer to apply the term 'nebular hypothesis' to the ideas of Laplace and William Herschel, as well as being one of the first to discuss its theological implications. His book was one of the series of "Bridgewater treatises" whose authors were commissioned to demonstrate "the power, wisdom, and goodness of God, as manifested in the Creation". The series was an influential exposition of 'natural theology', and each author attempted to show divine purpose in some area of the natural world. Since these teleological arguments in biology constituted precisely the kind of reasoning that was opposed and eventually replaced by Darwinism, we might expect to find here a philosophy antagonistic to the evolutionary worldview.

Whewell did argue, in line with the general theme of the Bridgewater Treatises, that the present arrangement of the solar system shows evidence of intelligent design. For example, if the Earth's orbit were much more eccentric than it is, the variation of climate would be "destructive to the existing species of living creatures". The stability of the system as a whole, against gravitational perturbations that might conceivably cause the planets to fall into the Sun or escape to infinity, depends (according to Whewell) on the fact that the planets all move in the same direction in orbits of small eccentricity and inclination, and that those bodies which have the most eccentric orbits also have the smallest masses. Similarly, the fact that the most massive body in the system, the Sun, also provides heat and light, is not a consequence of any natural law but must be due to divine providence, as Newton had already pointed out. Moreover, the satellites of the planets have been created for the purpose of furnishing nocturnal illumination; that is why the planets further from the Sun, which receive less light from it, have more satellites in compensation. Whewell dismissed Laplace's suggestion — that if that was the purpose of our Moon it should have been put in a different place so that it would nearly always appear full — as being "contrary to the whole known analogy of cosmical phenomena".

In view of Whewell's teleological attitude toward the construction of the solar system one might have expected him to reject the nebular hypothesis. Instead he supposed that it might be valid, and proposed merely to refute "those ... who put forwards the Nebular Hypothesis in opposition to the admission of an Intelligent Creator". He did not mention who these people might be, but seemed to assume that they would use Laplace's cosmogony to replace the design argument as an explanation of the regularities in the solar system. Implicitly conceding that this might indeed be done, Whewell insisted that natural causes cannot provide an ultimate explanation of the origin of the solar system. Even if one goes back in thought to an expanded primitive Sun
or, as Herschel had suggested, "an extremely diffused nebulousness", one still has to account for the existence of that state and, more importantly, the laws that govern its development to the present state. 50

Whewell criticized Laplace for claiming that the supposed evidence of final causes will disappear as our knowledge advances, so that the invocation of final causes is merely an expression of ignorance. Whewell seemed to be protecting the design argument of natural theology from attack by proponents of the nebular hypothesis, but the effect of his argument, whether intended or not, was partially to protect the nebular hypothesis from attack by theologians, by showing that it does not negate the assumption of divine creation. At least that was the interpretation of the English writer W. H. Smith, who stated that if the nebular hypothesis is accepted, "this, as Mr. Whewell has shown in his 'Bridgewater Treatise,' would only serve to enlighten and elevate our conception of the power of God". 51 Since Smith was also one of those who suggested that the nebular hypothesis had made it "a legitimate object of science" to consider evolution in biology as well as in astronomy, we may suspect that Whewell's book assisted the adoption of the evolutionary worldview. 52

VI. GENERAL IMPLICATIONS OF THE NEBULAR HYPOTHESIS

To simplify the presentation I will distinguish between two major ways in which the nebular hypothesis influenced the evolutionary worldview: first on the general philosophical level, and second, indirectly, through geological theories of the thermal development of the Earth. Thus on one hand there was the abstract idea that everything is changing because of the action of physical laws on material atoms, with the nebular hypothesis providing a model from astronomy that could be carried over into other sciences. 53 On the other hand there was a fairly specific concept, embodied in a 'progressive' or 'directional' synthesis, of how the Earth had cooled down from its initial molten state — a state which was consistent with either Buffon's or Laplace's theory of the origin of the solar system — and how the physical forces involved in cooling and contraction had shaped the Earth's surface and made it habitable by different forms of life.

In 1830 John Herschel, son of William Herschel and at that time one of the most respected scientists in England, ranked astronomy first and geology second among the sciences. 54 If this opinion was common, it is reasonable to suppose that the other sciences would look to astronomy and geology for models of method and philosophical viewpoints. The nebular hypothesis was associated with the names of Laplace, the most famous theoretical astronomer of the day, and William Herschel, the most eminent observer. Henry de la
Beche (1834) was one of the first to use it as a basis for geological speculation.\(^5\) It provided the basis for the theory of terrestrial refrigeration and contraction, widely accepted by geologists.\(^6\) Thus it should not be surprising to find a connection between the nebular hypothesis and evolution; it remains to be seen what was the precise nature of that connection.

The general philosophical influence of the nebular hypothesis has already been convincingly demonstrated for the American scene by Ronald Numbers, who shows that it eased the acceptance of Darwinism by raising and settling many of the religious objections to a naturalistic explanation of the past.\(^5\) The earlier debates had elicited plausible arguments that "Christianity had nothing to fear from theories of development".\(^5\) I will take Numbers's proposition as proved for the American case — with some qualifications pointed out by J. H. Brooke\(^5\) — and confine my discussion to Britain, where many of the ideas originated or were most influential.\(^5\)

As we have seen, the question of an analogy between nebular development and organic development had already been raised by William Herschel, in connection with the epistemological problem of inferring the temporal change of an individual entity from synchronic observations of many similar entities at different 'stages'. The issue was raised again by John Pringle Nichol, Professor of Astronomy at Glasgow, who is generally credited with popularizing the nebular hypothesis to the Anglo-American public. In an article on nebulae in the *Westminster review* (1836), Nichol reported the views of John Herschel, who seemed sceptical of his father's theory. Herschel argued that "even the complete establishment of an uninterrupted gradation would not suffice as a confirmation of the nebular hypothesis" on the basis of the "supposed parallel case of the chain of organized being". In the latter case we see a similar gradation yet we reject the possibility that one species can change into another. But, Nichol points out, in the case of nebulae we know of forces that can cause one state to pass into another, whereas in the case of organic species we do not. And yet we should not dogmatically reject the possibility of a similar transmutation of species, as do those who ridicule Lamarck, but encourage zoologists to look for a force that might play the same role that gravity does in nebular condensation.\(^5\)

By the 1840s, as a result of the popular writings of Whewell and Nichol, the nebular hypothesis was well known in Britain and could be used as a basis for speculation even by writers who had little formal training in science. The most famous example is a book entitled *Vestiges of the natural history of creation*, published anonymously by Robert Chambers in 1844 with many later editions.\(^5\) Chambers presented a grand scheme of cosmic evolution beginning
with the development of stars and planets from a "universal fire mist" as described by William Herschel and Laplace. The chemical elements might also be constructed in this process, from a primordial form of matter. Organic species arise by a law of progressive development, each type giving birth to the next more complex type. This was indeed an evolutionary worldview, and there is no doubt that it is firmly based on the model of the nebular hypothesis. Chambers argues that it would be beneath the dignity of the Creator to produce "the progenitors of all existing species by some sort of personal or immediate exertion", especially since this would require Him to hop from planet to planet throughout the immense number of inhabited worlds in order to create each of the many species that probably live on each one.

Some other idea must then be come to with regard to the mode in which the Divine Author proceeded in the organic creation. Let us seek in the history of the earth's formation for a new suggestion on this point. We have seen powerful evidence, that the construction of this globe and its associates, and inferentially that of all the other globes of space, was the result, not of any immediate or personal exertion on the part of the Deity, but of natural laws which are expressions of his will. What is to hinder our supposing that the organic creation is also a result of natural laws, which are in like manner an expression of his will? More than this, the fact of the cosmical arrangements being an effect of natural law, is a powerful argument for the organic arrangements being so likewise, for how can we suppose that the august Being who brought all these countless worlds into form by the simple establishment of a natural principle flowing from his mind, was to interfere personally and specially on every occasion when a new shell-fish or reptile was to be ushered into existence on one of these worlds? Surely this idea is too ridiculous to be for a moment entertained.

Just about the time when Vestiges was published, the credibility of the nebular hypothesis was severely damaged by the astronomical observations of Lord Rosse, who succeeded in resolving into separate stars some of the nebulae that William Herschel had considered to be clouds of hot gas. This result was cited by critical reviewers of Vestiges as evidence against the hypothesis of organic evolution. For example, the physicist David Brewster argued that if the nebular hypothesis was overturned as an example of creation by law, "we render infinitely improbable the existence of such a law in the creation and development of animal life; and prepare the intelligent mind for the reception of those noble truths which Scripture and Reason so clearly reveal". Numbers cites a number of similar examples of critics who used the failings of the nebular hypothesis to reinforce their objections of the transmutation of species. Louis Agassiz might be considered a counterexample since he supported the nebular hypothesis while opposing evolution; yet in 1850,
when he wrote the introduction for an anti-*Vestiges* tract, he lumped that hypothesis together with organic creation under the general heading of "the development hypothesis" and seemed pleased that it had been "driven by the discoveries of Lord Rosse from the domains of astronomy".\(^67\)

*Vestiges* undoubtedly created a great deal of interest in the evolutionary worldview, comprising both the nebular hypothesis and the transmutation of organic species, but cannot be said to have established it in Britain. For that we must look to Herbert Spencer.

Spencer became a Lamarckian "through his reading of Lyell in 1840, and although critical of the *Vestiges of Creation*... he accepted its basic tenet, 'the development hypothesis'".\(^68\) His attitude toward the nebular hypothesis was based on a fairly sophisticated technical analysis of its logic and consequences. For example, he refused to accept the usual argument that the Earth acquired its roughly spherical form because it had once been molten as the nebular hypothesis required. He had been a railway engineer for a short time, and his understanding of the strength of materials was put to good use in a short paper showing that the spheroidal state of the Earth does not prove its original fluidity.\(^69\)

Spencer started to publish essays on mental and organic evolution in the 1850s. While revising them for book publication he started to reflect on the connection of various evolutionary ideas and to synthesize them in the light of the recently-established principle of conservation of energy.

There naturally arose the perception that the instability of the homogeneous and the multiplication of effects, must be derivative laws; and that the laws from which they are derived must be those ultimate laws of force similarly traceable throughout all orders of existences. There came the thought that the concrete sciences at large should have their various classes of facts presented in subordination to these universal principles, proximate and ultimate. Clearly the astronomic, geologic, biologic, psychologic, and sociologic groups of phenomena, form a connected aggregate of phenomena: the successive parts having risen one out of another by insensible gradations, and admitting only of conventional separations. Clearly, too, they are unified by exhibiting in common the law of transformation and the causes of transformation. And clearly, therefore, they should be arranged into a coherent body of doctrine, held together by the fundamental kinships.\(^70\)

A draft outline of his general system, dated 6 January 1858, shows the following sequence of headings:

Vol. I

Part I. The Unknownable.
THE NEBULAR HYPOTHESIS

Part II. The Laws of the Unknowable
Part III. Astronomic evolution
Part IV. Geological Evolution

Vol. II. The Principles of Biology
Part I. Life in General
Part II. Evolution of Life in General (the Development Hypothesis)
Part III. Evolution of Individual Organisms
Part IV. Morphology (Law of Organic Symmetry)
Part V. Law of Multiplication

This was to be followed by volumes on psychology, sociology, the principles of rectitude, and miscellaneous Essays.

Spencer recalled that as a result of Lord Rosse's observations, astronomers concluded that all nebulae consist of stars.

As the doctrine of evolution in its widest sense sets out with that state of matter and motion implied by the nebular hypothesis, it naturally happened that this tacit denial of the nebular hypothesis did not leave me unmoved. I saw reasons for questioning the legitimacy of the inferences above described, and was prompted to look more nearly into the matter.

The result was a long article published in the Westminster review defending and extending the nebular hypothesis, several times called the "hypothesis of evolution".

Spencer mentioned the nebular hypothesis frequently in his First principles (1862 and later editions) as a prime illustration of his general concept of "instability of the homogeneous". The trend of evolution is not only from simplicity to complexity but from confusion to order; "not only a multiplication of unlike parts, but an increase in the distinctness with which these parts are marked off from one another". Thus the pre-solar nebula, as it concentrated and began to rotate, "became more specific in outline, and had its surface more sharply marked off from the surrounding void". Its parts began to rotate in planes which "more and more merged into a single plane". Similarly in the evolution of planets and satellites, the change from gaseous to liquid to solid signifies greater definiteness. With the formation of a stable solid crust on the surface of a planet, relative locations can be established and "there arise distinct and settled geographical positions". Similarly in organic evolution, species become more sharply marked off from other species; and in social evolution, occupational duties become more specialized and laws more strict.
VII. COOLING, PROGRESS, AND DECAY

The nebular hypothesis implied that the Earth had been formed as a hot fluid sphere, and thus was easily connected with geological theories that described the development of the Earth as governed by cooling from a former molten state. Such theories often postulated that more complex organic species appeared as the surface temperature declined to its present value; thus they were called 'progressive' or 'directionalist' theories. Even though the species were assumed to be separately created, it would seem that progressive theories could easily be converted into transmutation theories by removing the separate-creation postulate, and thus these theories permitted or encouraged the growth of an evolutionary worldview. However, the historical facts are somewhat more complicated.

The major alternative to the progressive theory in geology was the 'uniformitarian' theory of Charles Lyell. Here the confusion begins. The assumption (not entirely false) that Darwinism depended on geological uniformitarianism has obscured the historical connection between evolution and geology until recent years. It is linked to another assumption, now rejected by most historians of geology, that Charles Lyell's uniformitarian theory provided the basis for modern geology and was generally accepted in the mid-nineteenth century. The error is partly due to reliance on historical accounts written by Lyell and his followers, which portrayed themselves as the victors in a battle between objective science and obscurantism, and partly to conflation of different meanings of the term 'uniformitarian.' As a methodological principle stating merely that one should explain the past using the laws found to hold in the present, it was accepted by both Lyell and his opponents; but Lyell used it to justify the quite different empirical claim that the intensity of forces governing geological change has always been the same. The evidence against that claim was very strong in the nineteenth century, and therefore most geologists did not accept Lyell's theory.

Lyell rejected the progressive theory in geology. Following James Hutton and John Playfair, Lyell accepted the postulate that the Earth contains internal heat which can power geological change, but which does not decrease with time. Thus there is no overall directional tendency in the history of the Earth, and in fact there may be recurrences of past ages with their characteristic flora and fauna. So Lyell, and those who followed his extreme uniformitarian doctrine, were clearly opposed to the evolutionary worldview.

In any case Lyell argued that geology should not include cosmogony. He objected to the proliferation of highly speculative theories of the Earth's origin, insisting that the original formation of the Earth must have involved forces not now in operation and thus not accessible to geological science.
Uniformitarian geology requires an immense span of time in which certain causes (observed to act very slowly at present) may gradually produce the present configuration of the Earth's surface. Lyell and his colleagues were reluctant to say exactly how much time they needed, although numbers like millions or even hundreds of millions of years were occasionally mentioned.\(^1\)

The dominant theory in geology throughout most of the nineteenth century was not Lyell's but the directional 'contraction' theory derived from the assumption that the Earth was originally formed as a hot fluid ball.\(^3\) Measurements of underground temperature indicated that there is a regular increase as one goes down toward the centre, though of course data could be obtained only for a relatively small distance below the surface. From this increase it was inferred that the Earth still has a store of heat left over from its formation.

The French mathematician J. B. J. Fourier developed a theory of heat conduction in solids, motivated in part by his interest in the problem of terrestrial cooling.\(^4\) He estimated from his theory that the periodic temperature variations at the Earth's surface would be washed out at a depth of less than 100 metres, and if there were no internal source of heat the temperature would be constant down to the centre of the Earth. Since existing data showed that there is an increase of temperature with depth below 100 metres, there must be an internal reservoir of heat. But the effect of this internal heat on the surface temperature is at present negligible, and it cannot have had any significant effect on the climatic variations during the past several thousand years, contrary to what was thought by Buffon and other scientists in the eighteenth century.

Fourier derived a theoretical formula for the time required for a homogeneous sphere to cool down from a specified initial temperature to its present temperature, in terms of the present temperature gradient at the surface. Though he suggested numerical values for the terms in his formula he did not actually give an estimate for the cooling time. Perhaps he considered the value obtained by such a calculation — which could be as great as 200 million years — so absurdly large that it was not even worth writing down. The outcome, in any case, was that while the Earth does have an internal heat that has been diminishing very slowly over a very long period of time, the actual amount of heat passing through the surface is so small as to have no significance on the time-scale of interest to geologists in the early nineteenth century.

Just before Lyell published the first volume of his *Principles of geology* he visited Paris and heard the French geologist Leonce Élie de Beaumont describe an extension of the contraction theory to explain the Earth's surface features. According to Élie de Beaumont, the cooling fluid nucleus would contract more rapidly than the solid crust, so that the latter would repeatedly become
unstable and collapse. Each of these ‘revolutions’ would create a system of parallel mountain chains.  

Élie de Beaumont’s theory avoided the arbitrary postulation of ‘catastrophes’ to explain geological phenomena, by providing an underlying uniform physical cause for the successive collapses of the crust. For that reason it was consistent with methodological uniformitarianism and was attractive to many geologists, though the regularity of mountain chains predicted by the theory was found to be greatly exaggerated. But Lyell rejected the theory entirely. He was willing to admit that the Earth has a store of central heat which provides the energy for volcanic eruptions and earthquakes, but — citing Fourier’s results — he denied that the store has diminished with time, or that the Earth has suffered any contraction. Lyell was even able to support his position with calculations by Laplace which showed that there had been no observable change in the length of day over two thousand years, whereas if the Earth were shrinking it should be spinning faster. Ironically it was the success of Lyell’s own claim, that geological processes extend over periods much longer than two thousand years, that ultimately made Laplace’s calculations on this point irrelevant.

Although Fourier’s application of heat conduction theory to the Earth seemed to undermine the contraction theories, at least until they could accommodate a much longer time scale, the theory itself was a major contribution to the evolutionary worldview. For the first time it incorporated into a fundamental equation of physics the principle of irreversibility: as time moves from past to future, heat flows from hot to cold, so that temperature differences are gradually wiped out. Whereas in Newtonian mechanics one can ‘run the system backwards’ by reversing the time variable (assuming that there are no dissipative forces like friction, at least on the atomic level), this is not true when heat flow is involved.

Soon after Fourier published his theory, Sadi Carnot arrived at a more general principle from completely different considerations in his analysis of the maximum possible efficiency of steam engines. Carnot’s principle, reinterpreted in the light of the principle of conservation of energy by Rudolf Clausius and William Thomson, Lord Kelvin, became known as the Second Law of Thermodynamics. It establishes a limit on the transformation of heat into mechanical work at thermodynamic equilibrium; it also implies, as Carnot himself pointed out, that whenever heat flows irreversibly from hot to cold, the opportunity to gain work has been lost and so each such flow represents a dissipation (not loss) of energy.

The Principle of Dissipation of Energy, or “generalized Second Law of Thermodynamics”, was first explicitly stated in 1852. William Hopkins, a geophysicist and famous mathematics tutor at Cambridge University (his students included Kelvin, Maxwell, and other major British physicists),
presented it in the context of geological speculation. Noting that uniformity is
valid in the short run because the rate of heat flow through the Earth's surface
is so small, he insisted that long-term refrigeration is nevertheless inevitable
and must play a role in the 'progressive development' of inorganic matter.
Conversely the truth of the dissipation principle is so certain that no evidence
of approximate uniformity during geological epochs can refute this idea of
"progressive change towards an ultimate limit".90

In the same year Lord Kelvin proclaimed even more generally a "universal
tendency to the dissipation of mechanical energy". His interest was also in the
cooling of the Earth and its consequence that

Within a finite period of time past the earth must have been, and within a
finite period of time to come the earth must again be, unfit for the
habitation of man as at present constituted, unless operations have been,
or are to be performed, which are impossible under the laws to which the
known operations going on at present in the material world are subject.91

A quantitative measure of energy dissipation in thermodynamics was
developed by Rudolf Clausius. He introduced the quotient: heat transfer
divided by absolute temperature, later called 'entropy'.92 In an irreversible
process entropy always increases.93 The Second Law of Thermodynamics,
according to Clausius, can thus be expressed in the form "the entropy of the
universe tends toward a maximum".94

This final state was called the "Heat Death of the Universe" because it is
characterized by a uniform very low temperature throughout space. Accor­
ding to thermodynamics it is impossible to extract any mechanical work from
heat unless there are differences of temperature, and presumably life is also
impossible.

The Second Law soon became a cornerstone of the evolutionary worldview
as understood by physical scientists in the late nineteenth century. The "Heat
Death" concept shows already that it implies decay rather than progress, and
thus seems to contradict the optimistic flavour of evolutionary theories in
biology and the social sciences.95 This contradiction became even sharper with
the development of the statistical theory of thermodynamics by James Clerk
Maxwell and Ludwig Boltzmann.96 They showed that the flow of heat from
hot to cold corresponds, on a molecular level, to the change from ordered to
disordered states; thus entropy is a measure of randomness.

One might think that the establishment of a physical principle which states
that systems tend to pass from ordered to disordered states would undermine
the credibility of any theory of biological evolution based on natural causes,
and especially one that claims to infer the development of complex ordered
structures from random variations. In fact this is just what happened, and
indeed thermodynamics is still being used by creationists to 'prove' that
The simplest reply to the thermodynamic objection against evolution is the remark that thermodynamics applies only to closed systems, and does not forbid a local decrease in entropy (corresponding to construction of an organized biological system) if this is compensated by a greater increase in entropy elsewhere (e.g. in the emission of radiation by the Sun). But one can do better than merely knock down the contradiction: one can argue that evolution should be expected to occur according to the statistical theory of atomic motion.

In a public address on the Second Law of Thermodynamics in 1886, Boltzmann declared that the nineteenth century would be remembered above all for “the mechanical view of nature, for Darwin” and he also expressed his enthusiasm for Darwin on other occasions. Not only did Boltzmann consider Darwinism consistent with thermodynamics, he suggested how it might be derived:

Without in the course of aeons the first protoplasm developed ‘by chance’ in the damp mud of the vast waters on the Earth, whether egg cells, spores or some other germs in the form of dust or embedded in meteorites once reached Earth from outer space, is here a matter of indifference. More highly developed organisms will hardly have fallen from the skies. To begin with there were thus only very simple individuals, simple cells or particles of protoplasm. Constant motion, the so-called Brownian molecular motion, happens with all small particles as is well-known; growth by absorption of similar constituents and subsequent multiplication by division is likewise explicable by purely mechanical means. It is equally understandable that these rapid motions were influenced and modified by the surroundings. Particles in which the change occurred in such a way that on average (by preference) they moved to regions where there were better materials to absorb (food), were better able to grow and propagate so as soon to overrun all the others.

In this simple process that is readily understood mechanically we have heredity, natural selection, sense perception, reason, will, pleasure and pain all together in a nutshell....

The usual argument that living structures cannot arise by chance combination of atoms is based on the assumption that all possible arrangements of a certain number of atoms are equally probable. But, as Boltzmann pointed out in the passage quoted above and elsewhere, fluctuations generated by random molecular motion are acted on by the environment — in the simplest case, forces that give some arrangements preference over others (lower
potential energy). This is completely consistent with the Second Law of Thermodynamics. The fact that individual biochemical reactions important to evolution proceed in a manner consistent with thermodynamics was explained long ago by Harold Blum and others.

Boltzmann could accept Darwinism because he could translate it into his own terms; thus it was not necessarily inconsistent with the evolutionary worldview of the physicists. But Hopkins and Kelvin, whose research was more closely related to the nebular hypothesis than Boltzmann's, rejected it.

VIII. SCIENTIFIC OBJECTIONS TO DARWIN'S THEORY

Hopkins is known to historians of Darwinism as the author of one of the most damaging reviews of the *Origin of species*:

He did not dismiss evolutionary theory simply because it conflicted with accepted views in biology, nor did he rant against it because of any theological objections he might have had. Rather, he argued that all phenomena which nature presents are legitimate objects of scientific investigation, including the origin of man. He proposed to judge evolutionary theory according to the same canons of reasoning and evidence applied to physical theories. He found it impossible "to admit laxity of reasoning to the naturalist, while we insist on rigorous proof in the physicist." If naturalists wanted to be considered scientists, then they had to meet the standards of science, and these standards were exemplified by the theory of gravitation and the undulatory theory of light. His was no casual reference to "Baconian induction" but a detailed criticism of evolutionary theory on the basis of the best views then current on the nature of science.

While not opposed in principle to the construction of evolutionary theories, Hopkins concluded that Darwin's evidence was not sufficient to show that natural selection had actually produced the observed phenomena, and he objected to the cavalier way in which Darwin dismissed contrary evidence such as gaps in the fossil record. His moderate tone suggests that he might have heeded rational arguments on the other side and might even have become a convert to Darwinism. His death in 1866 deprived Darwin of a possible ally on another front: Hopkins was one of the few scientists who could have refuted Kelvin's estimate of the age of the Earth.

Kelvin is even better known than Hopkins as an opponent of Darwinism, because of his argument that the Earth is too young for evolution to have taken place by the slow process of natural selection. As an indication of the small world in which these debates were conducted, I note that he had been
introduced to Fourier’s heat conduction theory by his teacher at Glasgow, J. P. Nichol, the popularizer of the nebular hypothesis; he studied with William Hopkins at Cambridge; and George Howard Darwin, the son of Charles, worked with him on geophysical problems.

Kelvin had initially rejected the nebular hypothesis but then accepted it as a “necessary truth.” He considered himself an “evolutionist” in geology, as that term was defined by T. H. Huxley. Later he referred to the “evolutionary philosophy” in a broader sense to include G. H. Darwin’s theory of the Moon’s origin.

Kelvin’s estimate of the ‘age of the Earth’ was essentially a rehearsal of Fourier’s calculation mentioned above, with up-to-date values of the parameters. He concluded that the time for the Earth to cool down from a temperature just above the melting point of rocks to its present state was probably no more than about 100 million years and perhaps only 20 million years. He considered these limits sufficient to refute the geological ‘doctrine of uniformity’, whose proponents had assumed that physical conditions on the Earth’s surface were essentially unchanged over the past several hundred million years.

Darwin had suggested in the Origin that periods like 300 million years, derived from the rate of geological processes such as denudation, might be available for evolution. Even though he had withdrawn this figure in later editions and, as T. H. Huxley pointed out in 1876, biological theory did not require any specific time scale, Kelvin’s argument was considered a serious blow to Darwinism. Kelvin himself wrote in 1869:

The limitation of geological periods, imposed by physical science, cannot, of course, disprove the hypothesis of transmutation of species; but it does seem sufficient to disprove the doctrine that transmutation has taken place through ‘descent with modification by natural selection.’

Kelvin’s opposition to Darwin’s theory has been exaggerated by many later commentators. His writings show that he fully subscribed to the evolutionary worldview, but disliked the aspect of randomness and lack of conscious direction implied by the theory of natural selection. Whereas modern creationists continue to cite Kelvin as a famous scientist who was a creationist, his 1871 presidential address to the British Association specifically rejected creationism in favour of what is now called ‘theological evolutionism’. In this address, Kelvin asserted that life cannot arise from dead matter but can only proceed from life.

How, then ... did life originate on the earth? Tracing the physical history of the earth backwards, on strict dynamical principles, we are brought to a red-hot melted globe on which no life could exist. Hence, when the earth
was first fit for life, there was no living thing on it. There were rocks solid and disintegrated, water, air all around, warmed and illuminated by a brilliant sun, ready to become a garden. Did grass and trees and flowers spring into existence, in all the fullness of ripe beauty, by a fiat of Creative Power? Or did vegetation, growing up from seed sown, spread and multiply over the whole earth? Science is bound, by the everlasting law of honour, to face fearlessly every problem which can fairly be presented to it. If a probable solution, consistent with the ordinary course of nature, can be found, we must not invoke an abnormal act of Creative Power.\textsuperscript{113}

Having thus rejected the doctrine that life was suddenly created in its present form, Kelvin proposed instead that seed-bearing meteoric stones from another world started life on Earth. He evaded the question of the origin of life on other worlds by postulating that such worlds of life have existed "from time immemorial".

Kelvin then accepted the hypothesis that present forms of life have evolved from these seeds:

From the earth stocked with such vegetation as it could receive meteorically to the earth teeming with all the endless variety of plants and animals which now inhabit it, the step is prodigious; yet, according to the doctrine of continuity, most ably laid before the Association by a predecessor in this chair [Mr. Grove], all creatures now living on earth have proceeded by orderly evolution from some such origin.\textsuperscript{114}

Kelvin quoted part of the last paragraph of Darwin's \textit{Origin of species} (the famous "tangled bank" passage), adding that he sympathized with the general idea of evolution but could not accept the particular mechanism of natural selection proposed by Darwin: "I have always felt that this hypothesis does not contain the true theory of evolution, if evolution there has been, in biology." He noted that

Sir John Herschel, in expressing a favourable judgment on the hypothesis of zoological evolution (with, however, some reservations in respect to the origin of man), objected to the doctrine of natural selection, that it was too much like the Laputan method of making books [by random combination of words] and that it did not sufficiently take into account a continually guiding and controlling intelligence. This seems to me a most valuable and instructive criticism. I feel profoundly convinced that the argument of design has been greatly too much lost sight of in recent zoological speculations.\textsuperscript{114}
IX. CONCLUSIONS

The nebular hypothesis did promote the evolutionary worldview in general and theories of organic evolution in particular, but in a context that made it difficult for scientists to accept most of those theories. Chambers, Spencer, and Darwin found a large audience receptive to evolutionary ideas, but scientists judged the ideas by the standards and results of physical sciences. Change in the physical universe was explained by the action of well-defined, quantifiable forces: nebulae condense because of gravity, heat flows out of hot bodies, gases contract as they cool, energy and angular momentum are conserved. Change in the world of life could not occur except by the action of forces — either divine or natural, or both. Random variation did not seem to be a force that could lead to progress toward complexity; the example from physics (entropy theory) seemed to suggest just the opposite, despite Boltzmann's view that Darwinism was perfectly consistent with statistical thermodynamics.

Moreover, change had to occur within the period of time allowed by the evolution of the Earth itself — a period so short that the purely natural process proposed by Darwin seemed inadequate to produce the observed result.

It has often been noted that Darwinism was consonant with other movements of thought in the nineteenth century. But in some essential respects it was not consistent with one of the most important of those movements, the evolutionary worldview. That worldview was limited in certain ways that Darwinism was not: to unidirectional change, to finite domains of space and time, and to mechanistic causation.

Other evolutionary theories could not cope with the radical new factors introduced in the twentieth century: discontinuities (quantum effects), indeterminacy, liberation from mechanistic preconceptions, breakdown of the distinction between subject and object or between cause and effect. That is why the evolutionary worldview remains tied to the nineteenth century universe of thought.

Darwinism, like the hypothesis of continental drift, was ultimately accepted because of a preponderance of evidence that could not be ignored or explained by any other theory; like continental drift, it is not yet a completed theory but a stimulus to further research. Similarly the nebular hypothesis, after being out of favour during the first part of the twentieth century, has been revived in a modified form no longer tied to nineteenth century ideas about nebulae and terrestrial refrigeration, and provides a general framework for modern theories and the interpretation of new observations. 115

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7. Thus it includes 'historicism' in the sense denounced by Karl Popper, *The poverty of historicism* (London, 1957), but not the mere assertion that the present should be understood in terms of the past. Modern historians frequently stress the uniqueness and contingency of historical events and the impossibility of comprehending them under any kind of universal law or tendency; thus they reject the evolutionary worldview though their attitude if sufficiently rationalized may resemble a weak form of Darwinism. The concept of 'social evolution' as defined by Robert A. Nisbet, *Social change and history* (New York, 1969), is very close to the 'evolutionary worldview' considered here. According to Nisbet, nineteenth century social evolution theories had six major premises: (1) change is natural (to the entity being studied); (2) change is directional; (3) change is immanent (in the entity being considered), not due to external influences; (4) change is continuous (including Marxian 'revolutions'); (5) change is necessary; (6) change proceeds from uniform causes (as in the geological doctrines of J. Hutton and C. Lyell). Darwinian evolution explicitly violates (3) and is only weakly consistent with (2) and (5).
historians like J. H. Randall, Jr, *The making of the modern mind* (New York, 1940), ch. 11, and others, obscures the fact that Newton himself rejected this view; see D. Kubrin, "Newton and the cyclical cosmos: Providence and the mechanical philosophy", *Journal of the history of ideas*, xxviii (1967), 325-46, for a more accurate account.

Similarly the term 'evolutionary worldview' is an abstraction that exists primarily in the minds of historians and may not correspond precisely to the outlook of any particular scientist or philosopher; it is nonetheless useful in getting a rough understanding of a complex subject.


10. See especially the excellent surveys in *The comparative reception of Darwinism*, ed. by Thomas F. Glick (Austin, Texas, 1974); the popularity of non-Darwinian versions of evolution is noted in England (pp. 4, 289), Germany (p. 97), France (p. 117), the United States (pp. 182, 199) and Spain (p. 318). Alvar Ellegård, *Darwin and the general reader* (Göteborg, 1958), also reported that many writers who accepted evolution rejected natural selection. Peter Bowler, *The eclipse of Darwinism* (Baltimore, 1983), has documented the rise of "anti-Darwinian evolutionary theories in the decades around 1900". Mario DiGregorio, "The dinosaur connection: A reinterpretation of T. H. Huxley's evolutionary view", *Journal of the history of biology*, xv (1982), 397-418, argues that Huxley integrated evolution into his own scientific work only after 1868 and even then failed to use the concept of natural selection. The *New York Times* obituary of Darwin (21 April 1882, reprinted in *Science in the twentieth century*, ed. by Walter Sullivan (New York, 1976), 298) shows that misunderstandings of 'Darwinism' were already widespread during his lifetime.

11. David Hull, "Darwinism and historiography", in Glick (ed.), *Comparative reception* (ref. 10), 388-402, p. 392.


15. Iris Sandler and Lawrence Sandler, "A conceptual ambiguity that contributed to the neglect of Mendel's paper", *History and philosophy of the life sciences*, vii (1985), 3-70.

16. The terms 'random' and 'chance' did not have any generally-agreed meaning among nineteenth century scientists. In physics they shifted from being descriptive of *knowledge* about reality to being descriptive of reality itself (see below, ref. 20). Darwin himself denied that he assumed random variations (*The origin of species* ... (London, 1859 and later edns), beginning of ch. 5) but in the absence of any specific cause his followers have generally adopted that assumption (Eiseley, *Darwin's century* (ref. 3)), or have suggested that the causes are random only in the sense of "being unrelated in origin and nature to
the functional requirements of the organism, though still having determinate causes" (a formulation suggested by one of the referees).


23. For example, the historical account by D. ter Haar and A. G. W. Cameron (two experts on the modern theory) goes back to Descartes but omits Herschel. See their "Historical review of theories of the origin of the solar system", in *Origin of the solar system*, ed. by R. Jastrow and A. G. W. Cameron (New York, 1963), 1-37.

25. Laplace's famous reply to Napoleon is usually quoted in connection with his establishment of the clockwork universe theory in his *Traité de mécanique céleste* (5 vols, Paris, 1795-1825). But the best contemporary source is William Herschel's diary of his visit to Paris in 1802. He and Laplace had an interview with Napoleon in which the conversation turned to the "extent of the sidereal heavens". Napoleon asked "And who is the author of all this!" According to Herschel, "Mons. De la Place wished to shew that a chain of natural causes would account for the construction and preservation of the wonderful system. This the first consul rather opposed. Much may be said on the subject; by joining the arguments of both we shall be led to 'Nature and Nature's God'." See J. L. E. Dreyer, "A short account of Sir William Herschel's life and work", in Herschel's *Scientific papers* (London, 1912), i, pp. xiii-lixiv, p. lxi; Constance A. Lubbock, *The Herschel chronicle* (New York, 1933), 310. This would imply that Laplace had in mind his hypothesis about the origin of the solar system. On the other hand one should probably interpret the word "construction" in a strict sense as a process that is now completed: Laplace did not see the world as being in a state of continual change. On this point see J. Merleau-Ponty, "Laplace as a cosmologist", in *Cosmology, history, and theology*, ed. by Yourgrau and Breck (ref. 2), 283-91, p. 289.

In 1735 Daniel Bernoulli, as noted by Laplace in 1776, estimated the probability of the present arrangement of planetary orbits and attributed their uniformity to the action of the extended rotating atmosphere of the Sun. J. J. Dortous de Mairan had suggested a year or two earlier that the aurora borealis is caused by gas ejected from the Sun's atmosphere, and that other stars could have a "nebulous" appearance because of similar phenomena. See Daniel Bernoulli, "Recherches physiques et astronomiques sur le problème propose pour la second fois par l'Académie Royale des Sciences de Paris: Quelle est la cause physique de l'inclinaison des plans des orbites des planètes par rapport au plan de l'équateur de la révolution du soleil autour de son axe", in *Pièces qui ont remporté les prix de l'Académie Royales des Sciences, 1734* (Paris, 1735); P. S. de Laplace, "Mémoire sur l'inclinaison moyenne des orbites des comètes, sur la figure de la terre et sur les fonctions", *Mémoires de l'Académie Royale des Sciences, Paris, savants étrangers, année 1773*, reprinted in his *Oeuvres complètes* (Paris, 1891), viii, 279-321; Charles Whitney, *The discovery of our Galaxy* (New York, 1971), 58-59.


29. William Herschel, "On the discovery of four additional satellites of the Georgium Sidus. The retrograde motion of its old satellites announced; and the cause of their disappearance at certain distances from the planet explained", Philosophical transactions of the Royal Society of London, lxxxviii (1798), 47-79; reprinted in his Papers (ref. 25), ii, 1-21.

Herschel himself did not consider this a serious exception to the rule. See "On the quantity and velocity of the solar motion", Philosophical transactions of the Royal Society of London, xcvi (1806), 205-37; reprinted, Papers (ref. 25), ii, 338-59, pp. 352-3. Subsequent research led to the conclusion that the satellites do revolve in the same plane as the rotation of Uranus, but that this plane is almost perpendicular to that of Uranus's orbit around the sun. See A. F. O'D. Alexander, The planet Uranus (London, 1965).


31. Ibid., 336.
32. Ibid., 337.

34. Herschel, Papers (ref. 25), i, 416.
35. William Herschel, "Astronomical observations relating to the construction of the heavens, arranged for the purpose of a critical examination, the result of which appears to throw some new light upon the organization of the celestial bodies", Philosophical transactions of the Royal Society of London, ci (1811), 269-345, p. 331; reprinted, Papers (ref. 25), ii, 459-97, p. 494.

36. Laplace, System (ref. 22), 336.

38. Alexander von Humboldt, Cosmos (London, 1848), 67. See also J. Lamont, Ueber die Nebelflecken (Munich, 1837), 5-6.
40. Edward Harrison, Masks of the universe (New York, 1985), 117.
41. William Herschel, "On the power of penetrating into space by telescopes, with a comparative determination of the extent of that power in natural vision, and in telescopes of various sizes and constructions; illustrated by select observations", Philosophical transactions of
the Royal Society of London, xc (1800), 49-85, pp. 83-84; reprinted, Papers (ref. 25), ii, 32-52.


44. The creationists tried to get out of this difficulty by claiming that God created the light “in space” to make it appear to have come from a star thousands or millions of light years away. See David J. Krause, “Apparent age and its reception in the 19th century”, Journal of the American Scientific Affiliation (Sept. 1980), 146-50; “Astronomical distances, the speed of light, and the age of the universe”, ibid., (Dec. 1981), 235-9. This argument is still used by modern creationists; see Henry M. Morris, The remarkable birth of Planet Earth (Minneapolis, 1972), 61-62.


46. Whewell, Astronomy (ref. 45), 135.

47. See ref. 24.

48. Whewell, Astronomy (ref. 45), 149. For another example of teleology in early nineteenth century astronomical writing see Henry Brougham, Dissertations on subjects of science ... (2 vols, London, 1839), i, 45; ii, 57-58.

49. Whewell, Astronomy (ref. 45), 178.

50. A similar argument was made by Edward Hitchcock, Religious truth, illustrated from science (Boston, 1857), 32-33.


54. “Geology, in the magnitude and sublimity of the objects of which it treats, undoubtedly ranks, in the scale of the sciences, next to astronomy.” John Herschel, Preliminary discourse on the study of natural philosophy (London, 1830; repr. New York, 1966), 287.


57. Numbers, Creation (ref. 3), 110.
58. Ibid., 111.
59. Brooke, "Nebular contraction" (ref. 28).
60. Auguste Comte, whose evolutionary view of society was influential in Britain as well as in France, was an enthusiastic advocate of the nebular hypothesis. He even claimed to have found a mathematical confirmation of it, though this proved to be based on circular reasoning. C. C. Person, ["Sur une prétendue explication de la théorie du système solaire de Laplace, par M. Comte"], title given only in index to volume, *Précis analytique des travaux de l'Académie Royale des Sciences, Belles-Lettres et Arts de Rouen* (1835), 51-52; S. S. Schweber, "Auguste Comte and the nebular hypothesis" (preprint, Department of Physics, Brandeis University and Department of History of Science, Harvard University, 1977).

64. [David Brewster], "Explanations. By the author of the Vestiges of the natural history of creation", *North British review*, iv (1846), 487-504, p. 490.
65. Numbers, *Creation* (ref. 3).
67. Louis Agassiz, "Hugh Miller, author of 'Old red sandstone' and 'Footprints of the creator'", in *Foot-prints of the creator*, by Hugh Miller (Boston, 1851), xi-xxxvii, p. xxv.
68. J. D. Y. Peel, "Spencer, Herbert", in *Dictionary of scientific biography*, ed. by Gillispie (ref. 9), xii, 569-72, p. 570.
71. Under Part III the draft listed three chapters, two of them on the nebular hypothesis and the other on equilibration of light and heat. In the published work, *First principles* (London, 1862), Parts III and IV are omitted but the nebular hypothesis is discussed in other chapters (see David Duncan, *Life and letters of Herbert Spencer* (2 vols, New York, 1908), ii, 159).
73. Ibid., ii, 25.
76. Ibid., 338.
77. Ibid., 344.
78. Lawrence, “Heaven” (ref. 2).
79. “...uniformitarianism in geology seems almost to cry out for evolutionism in biology”. Charles Coulston Gillispie, Genesis and geology (Cambridge, Mass., 1951; repr. New York, 1959), 131. The same phrase is used in his The edge of objectivity (Princeton, N.J., 1960), 300, omitting “almost”. See similar claims by Eiseley, Darwin's century (ref. 3), 160. See also Gertrude Himmelfarb, Darwin and the Darwinian revolution (London, 1959), 78-83; Gavin de Beer, Charles Darwin (Garden City, N.Y., 1965), 104. For more recent contrary interpretations see Bowler, Evolution (ref. 13), 20, 103.
81. “All these changes are to happen in the future again, and iguanodons and their congeners must as assuredly live again in the latitude of Cuckfield as they have done so.” Letter to Gideon Mantell, 12 February 1830, published in Life, letters and journals of Sir Charles Lyell, bart., ed. by Katherine Murray Lyell (London, 1881). For further discussion of this aspect of Lyell’s theory see Martin J. S. Rudwick, “The strategy of Lyell’s Principles of geology”, Isis, lxi (1970), 5-33; idem, “Uniformity” (ref. 56); P. Lawrence, “Charles Lyell versus the theory of central heat: A reappraisal of Lyell’s place in the history of geology”, Journal of the history of biology, xi (1978), 101-28.
83. Lawrence, in his articles “Heaven” (ref. 2) and “Charles Lyell” (ref. 81), presents an excellent account of the early development of this theory and its relation to the nebular hypothesis. Greene, Geology (ref. 56), shows how it was applied to geotectonics throughout the nineteenth century and provides an essential part of the background for Alfred Wegener’s theory of continental drift.
85. See Greene, Geology (ref. 56), for detailed discussion and references. Robert Muir Wood presents Élie de Beaumont as a seminal figure in the “battle for the earth sciences” in The dark side of the Earth (London, 1985).
87. Sadi Carnot, Réflexions sur la puissance motrice du feu (Paris, 1824); idem, Reflections on the motive power of fire, transl. and ed. by Robert Fox (Manchester, 1986). Fox discusses the historical background and includes references to the extensive literature on Carnot. For a general survey see D. S. L. Cardwell, From Watt to Clausius: The rise of thermodynamics in the early industrial age (London, 1971).
88. See Edward E. Daub, “Clausius, Rudolf”, in Dictionary of scientific biography, ed. by Gillispie (ref. 9), iii, 303-11.
89. William Thomson (1824-1907) was knighted in 1866, primarily for his role in the successful laying of the Atlantic Cable. In 1892, as the most eminent scientist in Britain, he received a peerage of the realm and chose the title Baron Kelvin of Largs. Of his many discoveries and inventions, some carry the name “Thomson” and some “Kelvin”. For simplicity I
will refer to him from now on as “Lord Kelvin” or “Kelvin”. His contributions to thermodynamics are discussed by Crosbie Smith, “A new chart for British natural philosophy: The development of energy physics in the nineteenth century”, History of science, xvi (1978), 231-79 and other papers cited therein.

90. William Hopkins, “Anniversary address of the President”, Quarterly journal of the Geological Society of London, viii, pt I (1852), xxi-lxxx, p. lxxv. For earlier statements about irreversibility in nature see Brush, Kind of motion (ref. 20), 545-59.

91. [Kelvin], “On a universal tendency in nature to the dissipation of mechanical energy”, Philosophical magazine, series 4, iv (1852), 304-6.


93. Thus when a quantity of heat $Q$ is transferred from a body at a high temperature $T_1$ to another body at a low temperature $T_2$, the former loses entropy $Q/T_1$ while the latter gains $Q/T_2$; if $T_1 \geq T_2$, the net entropy increase $(Q/T_2 - Q/T_1)$ must be positive.

94. R. Clausius, “On the second fundamental theorem of the mechanical theory of heat”, Philosophical magazine, series 4, xxxv (1868), 405-19. This version has caused some unfortunate misunderstandings. Under normal laboratory conditions (e.g. where the temperature is controlled) the equilibrium state toward which the system moves is determined not merely by entropy but also by energy, which depends on interatomic forces. Thus for example at low temperatures a substance will naturally tend to condense into a solid with a regular lattice arrangement of atoms, that being the state of lowest energy, rather than remain in the maximum-entropy state which would be a gas. This clarification is needed to understand an important point in the creation-evolution controversy (see below).


96. Brush, Kind of motion (ref. 20), 583-637.


100. See ref. 94, above.

101. Harold F. Blum, Time’s arrow and evolution (Princeton, N.J., 1951). See also Peter T. Mora, “The folly of probability”, in The origins of prebiological systems and of their molecular matrices, ed. by S. W. Fox (New York, 1965), 39-64; Duane L. Rohlfing and A. I. Oparin (eds), Molecular evolution (New York, 1972); Sidney W. Fox, “Creationism, the random hypothesis, and experiments”, Science, cxxiii (1981), 290. A detailed molecular-statistical theory of the development of self-organizing systems has been developed by Ilya Prigogine and his colleagues, and earned the Nobel Prize in Chemistry for Prigogine in 1977. According to Prigogine, one must go beyond classical statistical thermodynamics which was designed to deal with systems not far from equilibrium, and consider instead “dissipative structures” which maintain a steady ordered state with the help of a continuous flow of matter and energy. The Second Law is still applicable to such systems but it longer implies a tendency toward disorder. For an exposition of this theory in its historical context see I. Prigogine and Isabelle Stengers, Order out of chaos (New York, 1984).
102. Hull, Darwin (ref. 3), 273; the review, titled “Physical theories of the phenomena of life”, was originally published in Fraser's magazine, lxi (1860), 739-52, lxii (1860), 74-90, and is reprinted by Hull, 229-72.

103. The views in his 1860 review have already moved part way toward Darwinism from those expressed in his earlier article “Geology”, in Cambridge essays (London, 1857). His research on heat conduction led him to conclude that “a part at least of the heat now existing in the superficial crust of our globe is due to superficial and not to central causes” (“Experimental researches on the conductive powers of various substances, with the application of the results to the problem of terrestrial temperature”, Philosophical transactions of the Royal Society of London, cxlvii (1857), 805-49, p. 836) — a result that might have led him to dispute the basis of Kelvin’s estimate. Neither Hopkins nor Kelvin suspected the existence of radioactivity as a source of heat in the Earth’s crust, but Hopkins detected it indirectly.

Darwin had consulted Hopkins on a geological problem in the 1840s; see Joel S. Schwartz, “Three unpublished letters to Charles Darwin: The solution to a ‘geometrico-geological’ problem”, Annals of science, xxxvii (1980), 631-7. He was also (as Keith Stewart Thomson, “Natural science in the 1830s: The link from Newton to Darwin”, American scientist, lxiv (1986), 397-9, has recently pointed out) aware of the need for demonstrating the existence of an adequate cause for evolution, yet his arguments seemed unconvincing to many nineteenth century scientists.


108. Burchfield, Kelvin (ref. 19).

109. Darwin, Origin (ref. 16), 287.


111. Kelvin, “Geological dynamics” (ref. 106), quoted from Popular lectures (ref. 17), ii, 89-90.

112. Henry M. Morris, Men of science — men of God (San Diego, Calif., 1982).

113. Kelvin, “Presidential address” (ref. 17), quoted in G. Basalla et al. (eds), Victorian science (Garden City, N.Y., 1970), 127.

114. Kelvin, “Presidential address” (ref. 17), lxxxiv; Basalla et al., Victorian science (ref. 113), 128. The Herschel source is cited above in ref. 17.