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WHO DISCOVERED THE EXPANDING UNIVERSE?

Helge Kragh
University of Aarhus

Robert W. Smith
University of Alberta

INTRODUCTION

The recognition that the universe is expanding is one of the greatest ever discoveries in cosmology. It is generally acknowledged that modern cosmology is crucially founded on this discovery, which, until the identification of the cosmic microwave background in 1965, served as cosmology's main observational basis. Given this elevated status, it is natural to ask how the insight was obtained, which may seem to include the question asked in the title of the present paper. The standard answer is undoubtedly that the expanding universe was discovered by the American astronomer Edwin Hubble in 1929. According to the astrophysicist and science writer John Gribbin, "*The* discovery of the century, in cosmology at least, was without doubt the dramatic discovery made by Hubble, and confirmed by Einstein's equations, that the Universe is not eternal, static, and unchanging".[1] This is also what *Encyclopaedia Britannica* tells us:

> In studying the galaxies, Hubble made his second remarkable discovery — namely, that these galaxies are apparently receding from the Milky Way and that the further away they are, the faster they are receding (1927) [*sic*]. The implications of this discovery were immense. The universe, long considered static, was expanding; and, even more remarkably, as Hubble discovered in 1929, the universe was expanding in such a way that the ratio of the speed of the galaxies to their distance is a constant now called Hubble's constant.[2]

Note that the expansion of the universe is first described as an *implication* of the discovery of receding galaxies, and then, in the next line, Hubble is credited with having *discovered* this implication. Similar statements appear frequently in the literature, not least in astronomy textbooks and popular works. A widely used introductory textbook tells how Hubble in 1929 presented his famous diagram that indicated a linear relationship between the recessional velocities of galaxies and their distances. And then: "A number of astronomers since Hubble have surveyed galaxies at greater and greater distances and have come to the same conclusion: The universe is expanding."[3] It is not stated explicitly that Hubble, in his work of 1929, concluded that the universe is expanding, but the message is nonetheless clear.

As we shall argue, Hubble cannot reasonably be credited with the discovery of the expanding universe. A much more sensible evaluation has recently been offered by Stephen Brush: "[O]ne may say that Hubble 'discovered the expanding universe' in the same sense that Max Planck 'discovered the quantum': he established an

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empirical formula that seemed to imply the theory and indeed led others to adopt it (and later to assume that he must have adopted it himself) — yet he drew back from explicitly advocating it as a true statement about the world, and on some occasions even suggested that it was false."[4]

The purpose of the paper is not primarily to discredit Hubble, or to discuss priorities, but rather to problematize the entire notion of a discovery of the expanding universe. Is it at all reasonable to ask who made this discovery, and when? The expansion of the universe became recognized as a fact, but can it be described as a discovery? If it can, who deserves the credit, and for what? As we shall see, these questions are far from simple. It is commonly accepted among historians and philosophers of science that most discoveries cannot be neatly localized in space and time. They are not individual events, but complex and often messy processes extended over a period of time and involving many actors. Many scientific discoveries consist of several, more or less connected insights that in the end result in a consensus as to how the discovery has been made. A discovery does not necessarily require *a* discoverer or *a* discovery event. Moreover, discovery accounts do not end with the discovery event itself. What follows after the announcement of a discovery is often as important as, and sometimes even more important than, what leads up to it. We should not be surprised to find some of the same features in the case of the expanding universe here examined.

Because of the central role of the discovery concept in our discussion, we first give a brief account of some general aspects of the notion of scientific discovery. Thereafter, we recapitulate the main steps in the development that led from Einstein's cosmological theory of 1917 to the acceptance of the expanding universe in the early 1930s. Apart from Hubble, several other scientists have been named as candidates for having discovered the expanding universe, or for having strongly contributed to it. We discuss the most serious of these candidates and address the question of why Hubble won out. The names "Hubble law", "Hubble constant" and "Hubble time" (the inverse of the constant) are closely connected with the history of the expanding universe and give further emphasis to Hubble as its discoverer. They are examples of *eponymy*, the practise of affixing the name of a scientist to what he has found or done. As Robert Merton pointed out, this is perhaps the most prestigious kind of recognition institutionalized in science.[5] Originally, Hubble's name was not associated with the linear law or relationship, a practice that seems to have emerged only in the 1950s when it also became common to denote the proportionality constant H (which of course refers to Hubble). A look at the origin of cosmological eponymy may contribute to a better understanding of how Hubble became recognized as the father of the expanding universe.

ON SCIENTIFIC DISCOVERIES

Much of the uncertainty in the discussion about discoveries in astronomy and the other sciences can be traced back to different conceptions of what constitutes a discovery. It will be helpful briefly to outline some of these conceptions.[6]

First, discoveries come in different kinds. For example, they are often taken to relate to facts, to be empirical in nature: a scientist has made a discovery if he or she has found that *X* exists or is the case. *X* may be an object, as in the case of the discovery of the first pulsar by Anthony Hewish and Jocelyn Bell in 1967; or it may be a relation between data, as in the case of the Hertzsprung-Russell diagram. Factual discoveries may consist of a single observation or experiment, or of an enumeration of data (that may or may not be novel). The discovery of the Hertzsprung-Russell diagram was largely of the enumerative type, as was, for example, the 1819 Dulong-Petit law of specific heats and Mendeleev's 1869 discovery of the periodic system. Hubble's discovery of the redshift–distance relationship in 1929 belongs to the same class. This relation, that the redshifts of distant galaxies are proportional to their distance ($\Delta\lambda/\lambda = Hr$), was an empirical relationship or what is known as a phenomenological or functional law. It was not initially considered a law of nature, but from about 1950 it began to be referred to under the more elevated term "Hubble's law".[7]

We frequently speak of discoveries also in the broader sense of scientific innovations, which includes discoveries of a theoretical or conceptual kind. According to Thomas Kuhn, a discovery is a conceptual reorganization of data or factual domains.[8] Forced by an anomaly, the scientist will organize data into a new conceptual framework, as was the case with Lavoisier's discovery of oxygen and the multiple discovery of energy conservation in the 1840s. To take an example from astronomy, Kepler's discovery of the planets' elliptic orbits may belong to the same class of theoretical discoveries. In our view, the discovery (or rediscovery) of the expanding universe in the spring of 1930 has features in common with Kuhn's discovery model.

According to the individualist-mentalist model of discovery, widely favoured by scientists and philosophers, the historian should be able to identify the moment a discovery occurred and also an individual who can be credited as the discoverer. However, as Simon Schaffer has emphasized, such identification is difficult and frustrating. His examination of four important discoveries of the late eighteenth century, including William Herschel's discovery of Uranus, adds support to the view that discoveries are artefacts constructed within research communities. To label a candidate event a discovery, is a way to mark technical practices that are valued by the community and it involves "the endorsement of a complete research programme".[9] Moreover, Schaffer argued that the 'heroic' or individualist notion of scientific discovery is itself a product of history, as it emerged as a historiographical theme only in the early nineteenth century, at a time when amateur natural philosophy began to be replaced by professional science.[10]

The distinction between factual and theoretical discoveries is useful as a first approximation, but it is too simplistic to cover the complex structure of most discoveries. As Russell Hanson and other philosophers have long pointed out, observation cannot be fully separated from theoretical views, which implies that discoveries are never purely observational.[11] To discover *X* includes more than merely observing *X*, it also includes that it must be identified *as X*. Early astronomers who saw spots on the Sun, but thought they were transitory planets, did not discover the sunspots. Similarly, when in 1846 James Challis noted a 'star' that later turned out to be Neptune, he did not discover the planet. When Arno Penzias and Robert Wilson found a cosmic microwave background in early 1965, they did not discover a fossil radiation from the big bang. And when Hubble found a linear relationship between the redshifts and distances of galaxies, he did not discover the expansion of the universe.

Finally, the discovery of a phenomenon (or object, or relationship) is not identical to the incorporation of the phenomenon into the body of scientific knowledge. Discovery accounts cannot be only intellectual accounts of how an idea entered a scientist's mind, they must also include a social history of how the discovery claim became accepted by the scientific community. For example, if a person makes a discovery but keeps it private, it hardly counts as a *scientific* discovery. (From this point of view, Thomas Harriot's 1610 observation of sunspots does not make him the discoverer of sunspots.) It can be argued that what really matters is how discoveries are socially defined, which is the message of Augustine Brannigan's "attributional model". According to Brannigan, "The question is not what makes them happen, but rather what makes them discoveries".[12] Brannigan, Schaffer and other sociologically oriented historians suggest we pay less attention to discoveries as intellectual phenomena, and instead focus on the local contingencies that determine what counts as scientific progress. On the other hand, it is not obvious why a sociological analysis of discovery should make redundant a more traditional, intellectual analysis. Accounts of how a scientist came to a discovery are not incompatible with a sociological account of how the discovery claim was socially received; on the contrary, they are supplementary.[13]

A SUMMARY HISTORY

The story of how the expansion of the universe became a scientific and social reality has been told many times, often in great detail.[14] Although there is some doubt about how the events are interconnected and should be interpreted, there is little doubt about the main stations along the route to the expanding universe.

Occasionally claims are made that the expanding universe was suggested or foreshadowed even before the advent of Einstein's general theory of relativity. For example, Auguste Calinon, a French mathematician, suggested in a paper of 1889 that the curvature of space might vary in time — oscillate between Euclidean and non-Euclidean forms.[15] But his discussion was of a general philosophical nature and he did not, in fact, suggest an expanding space. We only mention it to point out that Milič Capek's claim that Calinon "anticipated the theory of the expanding space" is unfounded.[16]

It is more sensible to start our history either in 1912, with Vesto Slipher's first discovery of a large spectral shift for a spiral nebula (quickly generally identified as a Doppler shift), or in 1917, with Einstein's cosmological field equations. The same year, 1917, Slipher reported measurements of the radial velocities of 25 nebulae, nearly all of them redshifts. For the eminent cosmologist Fred Hoyle, Slipher's pioneering observations of redshifts should have led to his being credited with the discovery of the expansion of the universe.[17] But when he made these observations, Slipher had no conception that his results might be interpreted in terms of an expanding universe, which again underlines the distinction we made earlier between factual and theoretical discoveries.

Einstein's theory resulted in two rival cosmological models, Einstein's matter-filled universe (Solution A) and Willem de Sitter's empty universe (Solution B). Both models incorporated the cosmological constant Λ that Einstein had introduced in his 1917 theory. The latter model attracted much interest because it predicted redshifts for very distant objects and thus suggested a connection to the data obtained by Slipher. Because De Sitter's solution is today interpreted as an expanding model, with cosmic distances increasing as $\exp(t\sqrt{\lambda})$, it is sometimes claimed that De Sitter in 1917 discovered or anticipated the expansion of the universe. For example, according to the astrophysicist Martin Harwit,

> The Dutch astronomer W. de Sitter, noting that Einstein's general relativistic equations could also describe an expanding universe, had suggested such an expansion as early as 1917, citing Slipher's earliest results in support of this contention. Hubble, nevertheless, is usually credited with this discovery.[18]

However, this is plainly a misunderstanding. The redshifts occurring in De Sitter's theory were not, to begin with at least, regarded by astronomers as caused by the expansion of space and the model was conceived to be no less static than Einstein's, as will also be discussed below.

FRIEDMANN, LEMAÎTRE, AND OTHER CANDIDATES

Alexander Friedmann

Since the Russian physicist and mathematician Alexander A. Friedmann was the first to suggest an evolutionary universe and discuss a possible expansion, he may seem to qualify as discoverer or codiscoverer of the expanding universe. He has indeed been proposed as a candidate, mostly, but not solely, by Russian authors. According to the contemporary cosmologist Jim Peebles, "The expanding matter-filled world model was discovered in 1922 by Friedmann".[19] Such a statement sounds surprising, especially because it appears in a commemorative volume on Lemaître, but it should be noted that Peebles linked the 'discovery' to a world *model*, not to the physical state of the universe. He did not claim that Friedmann discovered the expanding universe, but merely used the term discovery somewhat unconventionally, about a mathematical model.[20] The same cannot be said about the eminent Soviet astrophysicist and cosmologist Yakov Zel'dovich, who in the 1960s and 1970s promoted his long deceased compatriot as the true discoverer of the expanding universe. In an important textbook of 1975, written with Igor Novikov, he referred to Friedmann's work as "proof that the universe expands", and had this to say about the priority issue:

> It is well known that A. Friedmann created the theory of the evolving universe in 1922–1924. The famous discussion with Einstein on the pages of the *Zeitschrift für Physik* called attention to Friedmann's work. We therefore cannot agree that Lemaître (1927) 'independently' established the laws of the expanding universe.[21]

Without saying so directly, Zel'dovich and Novikov hinted that Lemaître must have known Friedmann's work and more or less plagiarized it, an allegation for which there is absolutely no documentary basis.

The same kind of argument in favour of Friedmann is spelled out in detail in a more recent biographical work where the Russian physicist becomes nothing less than "the man who made the universe expand". The strategy in this rather hagiographic work is to picture Lemaître as a follower of Friedmann, one who further developed some of the insights obtained by the Russian genius. The three authors state, wrongly, that in his 1927 paper, "Lemaître himself indicated Friedmann's fundamental works that offered a comprehensive solution of the cosmological problem.... [He pointed out] that the problem of the non-static universe was earlier given full mathematical treatment by Friedmann, although it was unrelated to observation of nebulae".[22] The authors presumably refer to the English translation of 1931, where a note to this effect appears. However, in his 1927 paper, written in French, Lemaître did not mention Friedmann's work, of which he was unaware.

This biography of Friedmann is obviously not just a historical work; it is also, on a number of levels, a political document. Published in 1988, at a time when Russia was still part of the Soviet Union, it is about fashioning a Soviet hero, as well as one more shot in the continuing battle for credit over the discovery of the expanding universe.[23] The shot is a far miss. Russian attempts to credit Friedmann as the true and only founder of relativistic evolution cosmology had a clear political orientation and must partly be viewed in the context of the Cold War situation.[24] The interest started in 1963, at a time when a strong school of Soviet cosmology had recently been established under the leadership of Zel'dovich. The celebration of Friedmann's 75-year's birthday in 1963 was an occasion to highlight Friedmann's priority as the discoverer of the expanding universe and to marginalize the role of his rivals.[25] It led not only to the publication of his selected works (in Russian, 1966) but also to a memorial issue of *Soviet physics uspekhi*. In a review of relativistic cosmology, Zel'dovich wrote about Friedmann's work:

> From this minimum number of assumptions a grandiose conclusion was obtained theoretically: the galaxies cannot be at rest relative to each other. The speed of relative motion of two bodies increases in proportion to the distance between them.... Thus Friedman's theory predicted a grandiose phenomenon, on a scale billions of times larger than that of phenomena in the solar system.[26]

The use of past tense in the first sentence ('was' rather than 'can be') gives the impression that Friedmann derived from his theory the velocity–distance law, which of course was not the case. In the same paper, Zel'dovich, who strongly supported the relativistic big bang model, complained that Western cosmologists ignored "that the correct solution came from the Soviet Union and was due to A. A. Fridman" (p. 494).

Friedmann did not discover the expanding universe. His papers of 1922 and 1924 are of fundamental importance, but they are clearly of a mathematical nature and include no references to astronomical data. "The purpose of this note", Friedmann wrote in 1922, "is ... to demonstrate the possibility of a world in which the curvature of space is independent of the three spatial coordinates but does depend on time".[27] The term "possibility" is significant. It is difficult to avoid the impression that Friedmann did not recognize the physical importance of his calculations and to a large degree considered them to be nothing but a mathematical game. This was also the impression of the Soviet physicist Vladimir Fock, who assisted Friedmann and translated his papers into German. In 1963, in connection with the mentioned celebration of Friedmann's 75-year's birthday, Fock wrote: "Fridman more than once said that his task was to indicate the possible solutions of Einstein's equations, and that then the physicists could do what they wished with these solutions."[28]

Georges Lemaître

As far as Lemaître is concerned, can we be sure that he did not know about Friedmann's papers? If he did, he can hardly be credited with having independently discovered the expansion of the universe. Although in principle the Belgian physicist might have studied the papers in *Zeitschrift für Physik* prior to 1927 — how can it possibly be proved that he did not? — there is no reason to assume that he did. According to his own testimony, published in 1958, he was first made aware of Friedmann's contributions in a conversation he had with Einstein in Brussels in late October 1927 (that is, half-a-year after his own paper had appeared).[29] This is also what he said in letters to Eddington and De Sitter in 1930. In his letter to De Sitter of 5 April 1930, he referred to Friedmann's paper of 1922 and added:

> I did not know about this work when I wrote my paper, it was later made known to me by Einstein. I mentioned it in a popular conference on 'la grandeur de l'espace' (Revue des questions scientifiques, vol. 15, 1929, p. 189 to 218) which I will soon send you a part of.[30]

Apparently, Lemaître was eager to distance his own work from that of Friedmann. In a book review of 1950, he stated in no uncertain terms what were his own contributions:

> If my mathematical bibliography was seriously incomplete because I did not know the works of Friedmann, it is completely up to date from an astronomical point of view; I calculate the expansion coefficient (575 km sec per megaparsec, 625 with a doubtful statistical correction). Naturally, before the discovery and study of galactic clusters, there could be no question of establishing Hubble's law, but only to determine the coefficient. The title of my note left no one in doubt of my intentions: "Un Univers de masse constante et de rayon croissant rendant compte de la vitesse radiale des nébuleuses extra-galactiques." I excuse that all this is much too personally. But, as the author points out (p. 161), "The history of this scientific competition is not unimportant," and it may be useful to point out the details in order to appreciate the range of the argument that it is permissible to make.[31]

Finally, in a posthumously published radio broadcast of 1966, Lemaître repeated that he did not know about Friedmann's paper at the time when he published his theory of the expanding universe.[32] On balance, the evidence that this is true is overwhelming.

We do not know precisely how Lemaître arrived at his idea of an expanding universe, although it is quite clear that it relied on his mathematical discussion of 1925 of De Sitter's world model.[33] According to Michael Heller, the idea came to Lemaître "when listening to Hubble's lecture in the United States", which indicates in the spirit of positivism that it relied on observational data.[34] However, the claim is doubtful. Whatever the roots of the idea, in his 1927 masterpiece, Lemaître started out by considering an Einstein universe "where the radius of space or of the universe is allowed to vary in an arbitrary way".[35] He found differential equations for the time-dependent space curvature $R(t)$ that were the same as Friedmann's except that Lemaître included the radiation pressure. By and large, then, if we admit that a theoretical model can be discovered, Lemaître rediscovered what Friedmann had discovered five years earlier. At any rate, this agrees with the notion of rediscovery as "a novel observation, generalisation or theory [that] was made by a person and was later made by another person in ignorance of the previous person's work".[36]

Yet, to say that Lemaître simply rediscovered Friedmann's solution of an expanding universe is to miss the important difference between the two works. Although quite similar in their mathematics, when it comes to physics the two papers are strikingly different.[37] Lemaître pointed out in clear language that his model universe was expanding and that the velocity of recession was to be understood as "the apparent Doppler effect due to the variation of the radius of the universe". He was not interested in any kind of variation of $R(t)$ allowed by the equations, but only in the expanding solution that seemed to correspond to the redshift data. This is reflected in his manuscript version, where the term *variable* was replaced in the proof with *croissant* (increasing).

From "a discussion of available data" Lemaître found the approximate relationship $v = kcr$, where $k = 0.68 \cdot 10^{-27}\mathrm{cm}^{-1}$, corresponding to an expansion constant kc of $625\mathrm{km} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}$ (Mpc = million parsecs). Unfortunately, in the English translation of 1931 nothing is revealed of what these available data are, and also the title of the paper ignores the references to observational astronomy that are so clearly reflected in Lemaître's own title. As becomes clear from the French original, as well as from the manuscript kept in the archive in Louvain-la-Neuve,[38] Lemaître relied on data from Gustaf Strömberg (for radial velocities) and Hubble (for apparent magnitudes, hence distances). He used data from 42 galaxies and, depending on the effect of the Sun's proper motion, obtained for the expansion constant the value either 625 or 575, in the unit $\mathrm{km} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}$. Does that mean that the theorist Lemaître obtained the linear velocity–distance law and a value of the Hubble constant two years before Hubble? Not quite, for Lemaître used the mean distances and radial velocities to obtain what would later be termed the "Hubble constant", and he did not provide empirical evidence for the linear relationship that he had derived theoretically (compare his statement of 1950 quoted above).

Other Candidates?

Many of the theoretical investigations of cosmology in the 1920s were examinations of De Sitter's model, which is particular because it can be understood both as a static model (as De Sitter did) and as an expanding model (as became the view after 1930). It is clearly problematic to read the pre-1930 literature in the light of later knowledge.[39] 'Expanding' versions of the De Sitter universe were found by Cornelius Lanczos in 1922, Herman Weyl in 1923, and Lemaître in 1925, but these were not conceived as expanding in any real sense. These works, as well as later works by Howard Percy Robertson and Richard Chase Tolman in the United States, consisted in transforming De Sitter's line element in such a way that it formally became non-static, that is, included a term $F(t)$ referring to the time parameter. The metric, giving the distance in space-time between two neighbouring points, would then have the form $ds^2 = c^2dt^2 - F(t)(dx^2 + dy^2 + dz^2)$.

In 1928 Robertson found a non-static line element similar to the one Lemaître had found three years earlier. Also like Lemaître, he derived a linear relationship between apparent recessional velocities and distances, and he discussed it in relation to observation data. Within the same tradition was Tolman's 1929 derivation of a 'Hubble law', that is, a relationship of the form $v = kr$, with $v = d\lambda/\lambda$. Robertson and Tolman generalized the De Sitter model to an arbitrary scale factor $F(t)$, but they remained within the static paradigm and did not realize the significance of $F(t)$. In a paper of 1929, Robertson wrote the general line element of what would later be known as the Robertson-Walker models and he even referred to Friedmann's work. And yet, although he had evidently studied Friedmann, he 'misread' him and failed to realize the significance of the expanding metric. Robertson and Tolman developed much of the mathematics of the expanding universe, but without concluding or predicting prior to 1930 that the universe actually expands. They were not discoverers or codiscoverers of the expanding universe (and never claimed that they were).

In early 1930, shortly before he was reminded of Lemaître's 1927 paper, Eddington was ready to advocate a kind of non-static universe. He did not himself discover the expanding universe, but immediately realized the intimate relationship between Lemaître's theory and the data obtained by Hubble and Humason. Eddington used his position and authority to endorse, promote and further develop the idea of an expanding universe. He was a key figure in the social process that established the idea as a discovery, and in sociological accounts, such as Brannigan's, he may well be counted as no less important than Lemaître and Hubble. If justification is considered to be an essential and inseparable part of the discovery process, as is often the case,[40] it can be reasonably argued that the expanding universe was discovered in the early 1930s and that Eddington (and De Sitter, too) was a kind of codiscoverer.

THE CASE OF HUBBLE

By the late 1920s, Edwin Powell Hubble had established himself as the leading student of extragalactic nebulae (now called 'galaxies', although Hubble himself never used the term).[41] Trained at the Yerkes Observatory, in 1919 Hubble had joined the staff of the Carnegie Institution's Mount Wilson Observatory, the leading astrophysical observatory in the world and where he had access to the largest telescope in the world, the 100-inch Hooker reflector. With its aid, he had established in 1924 and 1925 to the satisfaction of nearly all astronomers that the spiral nebulae are external galaxies lying far beyond our own Milky Way Galaxy.

In the late 1920s, he turned to the problem of the redshifts of these galaxies, that is, why nearly all those observed possessed redshifts, which, if the redshifts were interpreted as Doppler shifts, implied that the galaxies were fleeing from the Earth. In 1928, he journeyed to Holland to attend a meeting of the International Astronomical Union and while there discussed nebular problems with many of the leading practitioners in the field. His collaborator Milton Humason would later recall that Hubble now decided to tackle the puzzle of the redshifts and to test De Sitter's solution.[42] By this point also, the instrumental means at Slipher's disposal were such that his own researches had effectively come to an end with a tally of over forty measured redshifts and blueshifts, and thus the field was open to the Mount Wilson researchers. While his colleague Humason set about measuring the redshifts of galaxies, Hubble sought to determine through various methods the distances of those galaxies for which spectral shifts had been measured (the great majority by Slipher).

When in 1929 Hubble described his first researches on the redshifts, he possessed values for the "radial velocities" for 46 extragalactic nebulae and, he claimed, accurate distances to 24 of them. When he plotted the redshifts of these 24 nebulae against their distances, he judged that a linear velocity–distance relation was the simplest way of representing his data. When he examined those remaining nebulae for which he knew the distances with less certainty, he again reckoned that the results supported the existence of a linear velocity–distance relation. If Humason's recollection is correct, Hubble had planned his research to test De Sitter's model of the Universe, and certainly in his 1929 paper he reported that the major result of his investigation was the "possibility that the velocity–distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space".[43] Hubble also believed that he was conducting a critical test that would soon allow him to dismiss either Solution A or Solution B. "The necessary investigations", he wrote, "are now under way with the odds, for the moment, favoring de Sitter".[44] In fact, during the 1920s, a number of attempts had been made to determine if a relationship existed between redshift and distance, and so Hubble was working within a well-defined problem area.

A paper published in 1931 and co-authored with Humason contained radial velocities for forty more nebulae, and now Hubble measured the most distant object to be some 32,000,000 parsecs distant (that is, about 100,000,000 light years), as compared with 2,000,000 parsecs in the 1929 paper. The linear correlation between redshift and distance seemed to be even clearer than before and effectively ended the debate on the existence of a linear relation.[45]

But how did Hubble interpret the spectral shifts of the nebulae? In 1929, he noted that

> In the de Sitter cosmology, displacements of the spectra arise from two sources, an apparent slowing down of atomic vibrations and a general tendency of particles to scatter. The latter involves an acceleration and hence introduces the element of time. The relative importance of these two effects should determine the form of the relation between distances and observed velocities....[46]

The Harvard astronomer Harlow Shapley challenged Hubble about discrepancies between the radial velocities Hubble had employed in his 1929 paper and other published values, in particular, the value of the radial velocity of the Andromeda Nebula.[47] Hubble conceded there was a difference between his quoted value of –220km per second, as compared to other measurements of around –300km per second. He argued that the value of –220 had been secured from a very fine photographic plate centred on the nebula's nucleus, but he suspected that the velocity was larger outside the nucleus and perhaps this explained why earlier investigators had found a different velocity. Hubble told Shapley that it was as if "there was a relativity shift to the red in the nucleus itself", that is, he indicated that the redshift might be gravitational.[48] Thus in 1929, Hubble did not accept that a nebula's redshift was merely the product of its radial velocity.

Humason followed Hubble in his cautious attitude and wrote that the observations could be explained "both by the apparent slowing-down of light vibrations with distance and by a real tendency of material bodies to scatter in space".[49] Similarly, in their 1931 velocity–distance paper, Hubble and Humason noted that the "present contribution concerns a correlation of empirical data of observation. The writers are constrained to describe the 'apparent velocity-displacements' without venturing on the interpretation and its cosmologic significance".[50] Hubble underlined this point in a letter of 1931 to De Sitter when he wrote that he and Humason "use the term 'apparent' velocities in order to emphasize the empirical features of the correlation. The interpretation, we feel, should be left to you and the very few others who are competent to discuss the matter with authority".[51]

Throughout the rest of his life (he died in 1953), Hubble made no unambiguous claims in his public writings to the effect that the redshifts are indeed Doppler shifts, and his views of the nature of the redshifts have been read somewhat differently by different historians. For Donald Osterbrock, "Hubble never completely accepted that the redshifts necessarily resulted from the radial velocities of the objects alone". John North judges that "Hubble lost his nerve as to the reality of the velocities".[52] But Norriss Hetherington from an extensive analysis of various Hubble manuscripts from the 1930s and his collaboration with Tolman reckoned that despite his agnostic public pronouncements, Hubble did indeed strongly prefer an expanding universe model. Thus, for Hetherington, by the mid-1930s, despite his public words, Hubble in fact had become committed to a belief in a relativistic, expanding homogeneous model of the universe. Hetherington contends that this was a consequence of Hubble's philosophical views' overriding the consequences of his observational evidence.[53]

These claims, it seems to us, go too far. When in 1936 Hubble wrote his most important book, *The realm of the nebulae*, he reported that the interpretation of the redshifts as velocity-shifts was generally adopted by theoretical investigators and that the velocity–distance relation was regarded as the observational basis for theories of an expanding universe. At the same time, he warned that nebular redshifts on a very large scale are "quite new in our experience, and empirical confirmation of their provisional interpretation as familiar velocity-shifts, is highly desirable".[54] He went on to argue that critical tests of the interpretation were available, but that such investigations were beset with

> difficulties and uncertainties, and conclusions from data now available are rather dubious. They are mentioned here in order to emphasize the fact that the interpretation of red-shifts is at least partially within the range of empirical investigation. For this reason the attitude of the observer is somewhat different from that of the theoretical investigator. Because the telescopic resources are not yet exhausted, judgement may be suspended until it is known from observations whether or not red-shifts do actually represent motion.[55]

At this period, many American astronomers shared a strong anti-theoretical streak and Hubble was far from alone in wanting, as he saw it, to stick closely to 'common-sense' and to observations and not get carried away by theories. Thus ideas of the expanding universe did not meet universal approval. One reviewer of *The realm of the nebulae* was Hubble's junior colleague Nicholas Mayall of the Lick Observatory in California. In 1937, Mayall wrote to Hubble and told him that

> It is perhaps unnecessary to mention how pleased are some of the people here to note the way that your interpretation of the nature of the red-shift casts doubt upon the validity of theories of the expanding universe. There is a tendency for an 'I told you so' attitude about this result, but it is also plain that the criticisms of the expansion hypothesis have been in the nature of a priori doubts, rather than constructive suggestions for practical tests to help decide the matter. After you blazed the trail, it was easy enough to fall in line and follow.[56]

We believe, then, that the weight of the evidence lends credence to Brush's claim quoted earlier, that Hubble drew back from explicitly advocating the expanding universe as a true statement of the world and that on some occasions he even suggested it was false.

WHO DESERVES CREDIT?

We may now sum up the situation and the contributions of the three main claimants to the discovery. First, Friedmann found that the universe, if it is governed by Einstein's cosmological field equations and satisfies the cosmological principle, must be non-stationary or evolving; that is, that the curvature of space must vary with time, $R = R(t)$. The Friedmann equations result in a class of evolutionary solutions, including cyclical and contracting, but Friedmann did not suggest or predict that the universe is in fact in a state of expansion. He predicted an evolutionary but not an expanding universe. Since he gave no reasons why the universe should be expanding, he cannot reasonably be said to have discovered the phenomenon.

Lemaître showed that there exists a model of the universe that expands from the static Einstein state and he argued from astronomical data that this model probably reflects the real universe. Contrary to Friedmann, he derived theoretically a linear redshift–distance relationship and calculated the proportionality factor. However, although he explicitly predicted the expansion of the universe, he could not justify the prediction with observational data that convincingly supported the linear law he suspected. In so far as Lemaître did not establish observationally that the universe is in fact expanding, he did not make a discovery; but in so far as he gave theoretical as well as observational reasons for it, he did discover the expansion of the universe.

As far as Hubble was concerned, he, aided by Humason, confirmed that the redshifts of the extragalactic nebulae are proportional to their distances. Although his 1929 data were not quite convincing to other astronomers, with the extended data set of 1931 he and Humason firmly established in the eyes of their colleagues what eventually became known as the Hubble law. Hubble must therefore be considered the discoverer of this empirical law. But the law of receding galaxies is not the same as the expanding universe, a notion that Hubble did not suggest in 1929. If we understand the expansion of the universe in the standard relativistic sense, Hubble cannot be counted its discoverer. While we have seen that he mentioned "the possibility that the velocity–distance relation may represent the de Sitter effect", this does not, however, imply that he interpreted the redshifts as caused solely or even largely by a Doppler effect due to their recession.[57] We need to emphasize that nowhere in his 1929 paper did Hubble conclude that the galaxies recede from us or otherwise suggest that the universe is expanding. Words such as 'recession' and 'expansion' do not occur in the paper.

It is likely that Hubble's remark about the De Sitter effect was related to his contact with Tolman and in particular to a paper Tolman wrote on the subject and that appeared shortly after Hubble's. Tolman stated as a fact that Doppler effects for the nebulae were approximately proportional to their distance, namely as $\Delta\lambda/\lambda \cong \alpha\, r/R$ with $\alpha/R \cong 5.1 \cdot 10^{-10}$ (light years)$^{-1}$. He referred to the "correlation between distance and apparent radial velocity for the extra-galactic nebulae obtained by Hubble", but did not refer to the correlation as Hubble's law or relationship.[58]

HOW HUBBLE BECAME THE DISCOVERER OF THE EXPANDING UNIVERSE

If, as we have argued, Hubble did not discover the expanding universe, how is it that today he is nonetheless generally credited for the discovery? First, it is important to note that Hubble himself did not claim to have discovered the expanding universe. He was however very anxious to establish that the correlation between distance and apparent radial velocity was viewed as a "Mount Wilson contribution". Writing to De Sitter in August 1930 after De Sitter had published a paper on the redshift–distance relation, Hubble insisted that "our [Hubble and Humason] preliminary note in 1929 was the first presentation of the data where the scatter due to uncertainties in distances was small enough as compared to the range in distances, to establish the relation".[59] This was also the argument Hubble advanced in 1936 in *The realm of the nebulae*. As he argued

> Although velocities of forty-six objects were available in 1929, the new criteria gave distances for only eighteen of the isolated nebulae and for the Virgo cluster. Nevertheless, the uncertainties in the distances were so small compared to the range over which they were distributed, that the velocity–distance relation ... emerged from the data in essentially its present form.[60]

In his book, Hubble did discuss the researches of other astronomers (Carl Wirtz, Knut Lundmark, and Strömberg) who had investigated the possible nature of a redshift–distance relation, but only to underline that their evidence had not been clear enough to establish the form (if any) of the relation. At the same time, Hubble underlined the importance of Slipher's early researches. Hubble noted in *The realm of the nebulae* that he had devoted considerable space in this book to the velocity of the Andromeda Nebula, the first spiral measured by Slipher, "on the general principle that the first steps in a new field are the most difficult and the most significant. Once the barrier is forced, further development is comparatively simple". Later he would tell Slipher that the redshift–distance relation was the product of his distances and Slipher's radial velocities.[61]

Hubble, then, was very anxious to protect his and Humason's priority in the discovery of the linear redshift–distance relation, but he did not engage in a debate on credit for the discovery of the expanding universe. Although Fritz Zwicky referred to it in 1929 as "Hubble's relation",[62] the redshift–distance relation was not seen by other astronomers in terms of "Hubble's law", at least not until over two decades after Hubble's initial 1929 paper. Around 1930, prominent authorities such as De Sitter, Eddington and Tolman, who all underlined the importance of the expanding universe, did not point to Hubble as its discoverer.

In 1931, De Sitter announced that the solution to the puzzle of accepting either Solution A or Solution B had been provided by Lemaître, whose "brilliant discovery, the 'expanding universe,' was discovered by the scientific world about a year and a half ago, three years after it had been published".[63] Writing in 1933, Eddington in his book on *The expanding universe* did report that "The simple proportionality of speed to distance was first found by Hubble in 1929. This law is also predicted by relativity theory".[64] He did not link Hubble's name to the law. When he came to discuss the expanding universe, he referred to Friedmann's "deliberate investigations of non-static solutions", which he considered had been rediscovered in 1927 by Lemaitre "who brilliantly developed the astronomical theory resulting therefrom". Eddington then added that the solutions had been discovered for the third time by Robertson shortly after. "The astronomical application, stimulated by Hubble and Humason's observational work on the spiral nebulae, was also being rediscovered, but it had not been carried so far as in Lemaître's paper."[65]

Tolman knew Hubble well. He was based at Caltech in Pasadena, where the Mount Wilson Observatory offices were located, and he collaborated with Hubble on a number of papers in the mid-1930s. Writing in his *Relativity, thermodynamics and cosmology* in 1934, he referred to the "linear relation between red-shift and distance discovered by Hubble and Humason for the light from the nebulae in the actual universe". A little later in the book, Tolman also addressed the reasons for changing to non-static models of the universe, and wrote that "By dropping the previous restriction to static models, we are at once led to the study of a considerable group of non-static homogeneous models, which were first theoretically investigated by Friedmann, and first considered in connexion with the phenomena of the actual universe by Lemaître".[66] He did not name Hubble as the discoverer of the expanding universe. Nor did Edward Arthur Milne in an important paper of 1932 in which he introduced his own (non-relativistic) version of big bang cosmology. The British astrophysicist did not mention Hubble in his account of the velocity–distance relation: "The most commonly accepted explanation of this phenomenon is that due to Friedmann and Lemaître", he wrote.[67]

Nor, from an extensive review of the astronomical literature that we have conducted, have we found any other writer who clearly identified Hubble as the discoverer of the expanding universe until we reach Einstein in 1945. In his *The meaning of relativity*, he wrote that "The mathematician Friedmann found a way out of this dilemma. His result then found a surprising confirmation by Hubble's discovery of the expansion of the stellar system (a red shift of the spectral lines which increases uniformly with distance)". He also referred several times to the ratio R'/R as "Hubble's expansion" and wrote that "one cannot but consider Hubble's discovery as an expansion of the system of stars".[68] But even so, this identification did not become common until considerably later. Also, it would seem that while Paul Dirac made a reference to "Hubble's constant" in 1938, such references did not occur again until the late 1940s and then they became more common in the early 1950s.[69] References to Hubble's law begin to appear in the literature in 1952 and slowly became more common after that.[70] Thus when the British cosmologist Dennis Sciama came in 1959 to write his popular book on *The unity of the universe*, it was a sign of the times that he wrote extensively about Hubble's law and Hubble's constant.[71] The next year, the French astronomer Paul Couderc wrote about Hubble's law as "the law of spectral displacements ... *currently* interpreted as a distance–speed relation".[72] And in 1964, William Bonnor included in a book an entire section under the heading "Hubble's law".[73]

Hubble died in 1953. In the 1930s, as we have seen, a number of writers credited both Hubble and Humason with the discovery of the redshift–distance relation. However, when Humason, his closest collaborator, came to write Hubble's obituary for the *Monthly notices of the Royal Astronomical Society*, Humason wrote of the "important relationship which [Hubble] found between red-shifts and distances" and said that Hubble's "correlation between red-shifts and distances, 'Hubble's Law of the Red-Shifts', is a good example of his ability to obtain results of importance with meagre available data".[74] Later in the obituary, Humason also referred to the

"Hubble expansion constant".[75]

In another obituary from the same year, Walter Adams, who had served as Director of the Mount Wilson Observatory for much of Hubble's time there, noted that Hubble discovered the linear velocity–distance relation, while, like Humason, making no reference to Hubble as the discoverer of the expanding universe.[76] Similarly, Robertson, who also knew Hubble well and was based at the California Institute of Technology and was one of the major figures in the development of relativistic cosmology, made no reference in his obituary to Hubble as the discoverer of the expanding universe.[77] In another paper, "dedicated to the memory of Hubble", Robertson merely referred to "the linear velocity–distance relationship, for the knowledge of which we owe so much to the work of Edwin Hubble and Milton Humason".[78]

Yet, within a few years, we can read more regularly of Hubble as the astronomer who had discovered the expanding universe. In a popular article of 1956, Allan Sandage, who had been Hubble's assistant and after his death took over the observational programme at Mount Palomar, gave his version of the history. Apparently referring to the year 1927, he wrote: "Hubble made the daring conjecture that the universe as a whole was expanding. He predicted that the more remote galaxies would show larger red shifts, still in proportions to their distance. To test Hubble's speculation, Milton L. Humason began a long-range program of spectral analysis...."[79] Again, when in 1962 David Bergamini and the editors of *Life* magazine wrote a volume on *The universe*, they referred to "the kind of cosmic expansion Hubble discovered ..." as well as to "Hubble's expansion law".[80] By the 1970s, these claims had become standard fare in astronomy textbooks and popular works. Some thirty years, then, after we can reasonably speak of the discovery of the expanding universe, Hubble was receiving credit for it, a claim he did not in fact make himself and which no one suggested in the 1930s or 1940s. Moreover, by then Hubble was receiving the *sole* credit. Until about 1960, as we have seen, Humason's name regularly appeared together with Hubble's. For example, in 1950 Fred Hoyle mentioned "the famous Hubble-Humason velocity–distance relation", and Couderc as well as Evry Schatzman wrote of "the Hubble-Humason law".[81] However, during the 1960s the eponymous companionship dissolved. The law, constant, or relationship now became associated with Hubble's name only, apparently a result of what sociologists of science have called the Matthew effect.[82] Obviously, something happened in the 1960s that changed Hubble's status in relation to the expanding universe. What?

CONCLUSION: SHAPING A DISCOVERER

First, many of the astronomers and cosmologists who played influential roles in the discovery of the expanding universe or in the cosmology of the early 1930s, when it had become entrenched in astronomical practice, were no longer alive. Friedmann had died in 1925, De Sitter in 1934, Eddington in 1944, Hubble in 1953, Tolman in 1959, Robertson in 1961, and Lemaître in 1966. Thus by the late 1960s those writing textbooks and popular works that dealt with the expansion of the universe had no first-hand knowledge of the debates that had taken place in the late 1920s or early

1930s, nor did they have a direct, personal stake in any priority battles. But in writing textbooks and popular accounts of the expanding universe, astronomers were also often writing very brief notes on or histories of its discovery.

Some years ago, Thomas Kuhn wrote on the sort of history produced in science textbooks. He argued that this kind of history makes, and is intended to make, students and professionals feel like participants in a grand historical tradition that has progressed cumulatively and according to definite methodological norms. Yet, he suggested, the textbook-derived tradition has in fact never existed.

> For reasons that are both obvious and highly functional, science textbooks (and many of the older histories of science) refer only to that part of the work of past scientists that can be easily viewed as contributions to the statement and solution of the texts' paradigm problems. Partly by selection and partly by distortion, the scientists of earlier ages are implicitly represented as having worked upon the same set of fixed problems and in accordance with the same set of fixed canons that the most recent revolution in scientific theory and method has made seem scientific.[83]

Kuhn also contended that "the sciences, like other professional enterprises, do need their heroes and do preserve their names. Fortunately, instead of forgetting these heroes, scientists have been able to forget or revise their works". The result, in Kuhn's view, "is a persistent tendency to make the history of science look linear or cumulative, a tendency that even affects scientists looking back at their own research".[84] Thus rather than a messy, contextualized discovery account in which nuances (as we have seen) are important, it was much simpler for textbook writers to give an account of how the discovery of the linear redshift–distance relation (the discovery of which was, from the early 1930s on, generally indeed accorded to Hubble or to Hubble and Humason) was in fact the discovery of the expanding universe by Hubble alone. This grossly simplified version of history thus elevated Hubble's own role at the expense of everyone else's, most especially Lemaître's, who until the 1980s was largely a forgotten figure among astronomers. Consequently, he did not even figure as a, and certainly not the, leading contender for the accolade of discoverer of the expanding universe in astronomy textbooks. Thus the complex historical process that gave rise to the establishment of the expanding universe was, we suggest, very largely reduced to an unproblematic discovery by Hubble by the demands of textbook and popular writings.

This sort of crediting was also discussed many years ago by Robert Merton in his classic 1957 paper, "Priorities in scientific discovery". Here Merton pointed out that those credited with having fathered a new science or a new branch of science do so through a kind of parthenogenesis for which they apparently needed no collaborators.[85] Thus a growing community of American astronomers who by the 1960s were concentrating to an unprecedented degree on the study of galaxies had fashioned a hero, a founding father and a figure around whom they could drape a simple version of the history of the discovery of the expanding universe. Perhaps, we would like to suggest, the label "Hubble's law" is an example of what has been called Stigler's law of eponymy, namely, "No scientific discovery is named after its original discoverer".[86]

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been in Hermann Bondi, "Review of cosmology", *Monthly notices of the Royal Astronomical Society*, cviii (1948), 104–20. Symptomatically, perhaps, in 1949 Robertson did refer to Hubble's constant, but in quotation marks only. Six years later, the quotation marks were dropped. Howard P. Robertson, "On the present state of relativistic cosmology", *Proceedings of the American Philosophical Society*, xciii (1949), 527–31, and "The theoretical aspects of the nebular redshift", *Publications of the Astronomical Society of the Pacific*, lxvii (1955), 82–98.

70. The first case of "Hubble's law" that we have encountered appears in George Gamow, *The creation of the universe* (New York, 1952), 37, and in Couderc, *The expansion of the universe* (ref. 31), 108, 110, 215, 221. As mentioned, Lemaître used the term in 1950, in his review of Couderc's book.

71. Dennis W. Sciama, *The unity of the universe* (London, 1959). See also George C. McVittie, *Fact and theory in cosmology* (London, 1961), where the author preferred to use "Hubble parameter" rather than "Hubble constant" (p. 111), and Hermann Bondi, William B. Bonnor, Raymond A. Lyttleton and Gerald J. Whitrow, *Rival theories of cosmology* (Oxford, 1960), where we can read of "Hubble's Law" on pp. 34, 39, 47, and 58.

72. Paul Couderc, *The wider universe* (London, 1960), 93 (our emphasis).

73. William Bonnor, *The mystery of the expanding universe* (New York, 1964), 50–53.

74. Milton Humason, Obituary notice of Edwin Hubble, *Monthly notices of the Royal Astronomical Society*, cxiv (1954), 291–95, p. 293.

75. *Ibid.*, 294.

76. Walter Adams, "Obituary. Dr. Edwin P. Hubble", *The observatory*, lxxiv (1954), 32–35.

77. H. P. Robertson, "Edwin Powell Hubble 1889–1953", *Publications of the Astronomical Society of the Pacific*, lxvi (1954), 120–5.

78. Robertson, "The theoretical aspects" (ref. 69), 89.

79. Allan R. Sandage, "The red shift", in *The universe*, ed. by G. Piel *et al.* (New York, 1956), 89–98, p. 92. In a much later paper, written on the occasion of the centennial of Hubble's birth, Sandage carefully avoided assigning the discovery of the expanding universe to Hubble and merely noted that the linear redshift–distance relation of 1929 "lead [*sic*] to the notion of the expanding universe": Sandage, "Edwin Hubble 1889–1953", *Journal of the Royal Astronomical Society of Canada*, lxxxiii (1989), 351–62, p. 353.

80. David Bergamini and the editors of LIFE, *The universe* (New York, 1962), 154.

81. Fred Hoyle, *The nature of the universe* (Oxford, 1950), 120; Couderc, *The expansion of the universe* (ref. 31), 89, 93, 112, 179; Evry Schatzman, *The origin and evolution of the universe* (London, 1966; translation of the French original of 1957), 189.

82. Robert Merton, "The Matthew effect in science", *Science*, clix, issue of 5 January 1968, 56–63, reprinted in Merton, *The sociology of science* (ref. 5), 439–59. Merton, "The Matthew effect in science, II: Cumulative advantage and the symbolism of intellectual property", *Isis*, lxxix (1988), 606–23.

83. Thomas S. Kuhn, *The structure of scientific revolutions*, 2nd edn (Chicago, 1970), 138.

84. *Ibid.*, 138 and 139. Similar views are expressed in Stephen Brush, "Should the history of science be rated X?", *Science*, clxxxiii (1974), 1164–72, and M. A. B. Whitaker, "History and quasi-history in physics education", *Physics education*, xiv (1979), 108–12, 239–42. See also Nathan Reingold, "Science, scientists, and historians of science", *History of science*, xix (1981), 274–83.

85. Robert Merton, "Priorities in scientific discovery", *American sociological review*, xxii (1957), 635–59. Reprinted in Merton, *The sociology of science* (ref. 5), 286–324.

86. Stigler, "Stigler's law" (ref. 5).