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Edwin Hubble's early experiences were a bit exceptional for an astronomer. Hubble matriculated at the University of Chicago and studied mathematics and astronomy. After graduating, Hubble became one of the first American Rhodes Scholars and spent three years at The Queen's College, Oxford where he studied law. During his time at Oxford, Hubble adopted some of the affectations of the British upper-classes such as wearing tweed jackets and knickers, unnecessarily carrying a cane, and affecting a Mid-Atlantic accent. In 1919, Hubble returned to the United States and took a position at the Mount Wilson Observatory near Pasadena, California where he would stay the rest of his life. In the introduction of *The Observational Approach to Astronomy*, Hubble described the infantile stage that astronomical cosmology occupied at the time, "Cosmology lay for ages in the realm of sheer speculation. Rational arguments were introduced slowly until the critical period just two decades ago" and only "a preliminary reconnaissance has been completed".[1] Thus Hubble's main contribution to astronomy was the articulation and combination of previously proposed theories and data in order to make novel discoveries about the structure of the cosmos. Hubble's discovery of the expansion of the universe and identification of nebulae as external galaxies do not fit the frame of a traditional Kuhnian analysis. However, when one also considers that Kuhn later modified his system and focused on the linguistic origin of different scientific communities, some striking similarities do emerge. Finally, Hubble himself was an amateur philosopher of science and posited views that largely overlap with those expressed in Kuhn's later works.

Astronomy was clearly not in a pre-paradigmatic state during the period of Hubble's work nor was it suffering from the degradation that would lead it into a Kuhnian crisis. Numerous astronomers engaged in open, consistent debate over the fundamentals of their discipline, which would be impossible under a classical Kuhnian model. For example, American astronomer

Harlowe Shapley was able to produce a new estimate of the size of the Milky Way, 300,000 light-years in diameter, which was enormous compared to past estimates.[2] At the same time, another astronomer Herbert Curtis argued for the older interpretation of a small galaxy. The existence of multiple valid theories in active debate with each other undermines Kuhn's notion of a largely unquestioned paradigm. Without a doubt, these debates challenged the theoretical framework under which astronomers operated, but there is no evidence to suggest that it matched Kuhn's paradigm-shift.

Placing himself in the historical development of astronomy, Hubble viewed such diverse thinkers as Copernicus, Thomas Digges, Newton, Huygens, Thomas Wright, and Kant as his forerunners, whose theories and discoveries set the stage for his own.[4] For example, the astronomer William Herschel used photographic plates to determine the distance of stars as a function of their brightness, but could not use this technique for most nebulae, or clouds of luminous gas in the night-sky, as the tools of his time were too rudimentary. As the centuries passed and scientists made advances in telescopic equipment, Hubble was able to apply Herschel's technique to previously unanalyzed nebulae, making preliminary measurements of their distance from the Earth.[5] In 1908, Henrietta Swan Leavitt of Harvard College Observatory found a close relation between the intrinsic luminosity of a Cepheid and its period of pulsation. Cepheid stars exhibit very high degrees of luminosity and have a regular period of increasing and decreasing illumination that allows astronomers to calculate their distance. Sixteen years later, in 1924, Hubble used Leavitt's method of period calculation to establish the distance to Cepheids in the Andromeda nebula.

In 1912, astronomer Vesto Slipher used an improved camera to obtain spectrograms of light emitted by the Andromeda Nebula and determined that, as a result of redshifts in the wavelengths, that it appeared to be moving at some velocity. A redshift occurs when light-waves become longer and longer over time, shifting toward the red end of the spectrum as compared to the ultraviolet end whose wavelengths are very short. This phenomenon is very similar to the Doppler effect that causes sound sources moving toward an observer to sound different than those produced by an object moving away; the different pitches of approaching and departing ambulance sirens are one such example. Therefore, implicit within Slipher's findings, was the implication that nebulae were moving away from the Earth, a discovery with which Hubble is often credited. When Slipher presented some of his findings at Northwestern University in August 1914, Hubble was in the crowd and no doubt drew inspiration from Slipher's conclusions. However, when Slipher conducted his first tests, his "observations were necessarily restricted to the brighter, nearer nebulae ..."[6] so that he was limited in the accuracy and persuasiveness of his conclusions. As the tools developed, Hubble was able to apply Slipher's methods to more distant objects, as he had previously done with the techniques of Herschel and Leavitt. Clearly, Hubble drew upon the theoretical and methodological advances of his forbearers and applied them in ways that were necessarily different due to the changing nature of the discipline. Kuhn harbors a similar viewpoint as new paradigms "ordinarily incorporate much of the vocabulary and apparatus ... that the traditional paradigm had previously employed. But they seldom employ these borrowed elements in quite the same way."[7] However, the astronomical tradition in which Hubble practiced did not have any hard paradigmatic breaks that, in his early works, Kuhn details as key to the scientific enterprise. Thus Hubble's use of the methodological and theoretical heritage of astronomy did differ from the way in which his forbearers had used it, but maintained a striking continuity that resembles a research-tradition more than a paradigm.

On October 4, 1923, Hubble took a four-minute exposure of one of the spiral arms of the

Andromeda Nebula. When he did so, Hubble was acting as a member of the community that included Lemaitre, Herschel, Leavitt, and Slipher, and without which he would have been unable to form his conclusions. Among the objects that Hubble detected was a Cepheid variable in the nebulae H335H with a period of thirty-one days. Once Hubble was able to locate Cepheid variables in nebulae, he could use existing techniques to estimate their distance as he notes in this passage from the *Observational Approach to Astronomy*: "a change in either the rate of arrival of the quanta, or in the individual energies they carry, will alter the measured luminosity."[8] In early 1924, Hubble wrote to Harlowe Shapley, a contemporary astronomer and rival, about the discovery of Cepheid variables in spiral nebulae and the implications that their periods posed for the size of the Milky Way: "You will be interested to hear that I have found a Cepheid variable in the Andromeda Nebulae ... the distance comes out something over 300,000 parsecs [about a million light-years] ..."[9] In a reaction that echoes Kuhn's rapid *gestalt* shift, Shapley lamented upon reading Hubble's letter, "here is the letter that has destroyed my universe."[10] Shapley was unsure as to whether anyone could reliably calculate the distance to a Cepheid star with such a long period and he must surely have bristled against the fact that Hubble was finding empirical evidence that contradicted his own theories.[11] In spite of initial skepticism, Shapley soon came to accept Hubble's new estimations of the size of the universe, but if one is to use Kuhn's initial epistemological model, it is impossible to explain how Shapley suddenly came to embrace a new *gestalt*. Only Kuhn's updated conception of incommensurability, rooted in linguistic theory, accurately explains scientists' ability to accept a new ontological taxonomy, which merits further elaboration after discussion of the man who discovered "Hubble's Law" before Hubble.

Georges Lemaitre, a Belgian priest and astronomer, also used Vesto Slipher's data to conduct research on the recessional velocities of nebulae and formulated a law of the universe's expansion years before Hubble did. In April 1925, Lemaitre presented his findings to the American Physical Society in Washington D.C., positing that nebulae exhibited recessional velocities, that such velocities were the result of the expansion of space, and that the velocities should be proportional to the distance of the systems from the Milky Way. Later, in 1927, Lemaitre recorded these conclusions in a paper published by the Scientific Society of Brussels and estimated what we now call the Hubble expansion constant H at 630 (km/s)/Mpc, compared to Hubble's measurement in 1929 of 500 (km/s)/Mpc.[12] However, American astronomers did not learn that Lemaitre had made his discoveries because he published in French, a language that few of them could read.[13] Consistent with Kuhn's linguistic analysis, Lemaitre was unable to participate fully in the astronomers' scientific community because he did not *speak* the common language.

As Lemaitre formulated Hubble's Law before Hubble, and many of Hubble's forerunners invented techniques that he used, it is difficult to determine who "discovered" the universe's expansion and the extragalactic nature of certain nebulae. Kuhn argues that it is impossible to date a scientific discovery because individual scientists must simultaneously discover the existence of a phenomenon and have a full conception *of what it is* according to the modern standards of the historian and the reading audience. However, individual scientists nearly always have different conceptions of phenomena than modern readers as they can only perceive experience in the epistemological network of their age. According to Kuhn's later works, the true mechanism of scientific change is a group of scientists, as "it is that structure, not its various individual embodiments, that members of the community must share."[14] At the same time, Hubble did not break with the previous tradition of astronomy, which precludes the paradigmatic shift so characteristic of Kuhn's earlier model. As a result, Hubble did not necessarily "discover" the expansion of the universe; rather the astronomical tradition, of which Hubble was a member, was responsible.

Kuhn asserts the importance, and even dominance of non-rational factors in theory-choice, which had some influence on the development of the theories of Hubble and others. For example, Lemaitre's theological perspective probably informed his theory-formation. As Lemaitre believed in the Christian notion of a created universe with a finite beginning, he was disposed toward arranging data to support the concept of a big-bang[15] even though the idea violated the vast majority of contemporary views of the universe's creation. In a similar way, Hubble made theoretical assumptions prior to conducting his experiments such as assuming that the universe was consistent with both Eisenstein's general relativity and the cosmological principle. General relativity posits that the universe is unstable, either expanding or contracting, while the cosmological principle posits that the universe is isotropic - absolutely homogenous from any position, with systems evenly spread throughout the universe.[17] In *The Observational Approach to Astronomy*, Hubble let general relativity and the cosmological principle shape his theory selection as "the kinds of universes that would be compatible with the relativity principle and the assumption of homogeneity ... will be unstable [and thus expand or contract]."[18]

In some instances, Hubble did reject a hypothesis that was generally better supported by the available data. For example, the astronomer Clyde Tombaugh who discovered Pluto, asserted that the universe was not homogenous based on his own observations of galactic clustering. Even though Hubble's observations were based on smaller sections of the sky compared to those taken with Tombaugh's wide-field telescopic camera, Hubble retained his belief in a homogenous or isotropic universe. No doubt Hubble's personal stake in the theory may have prejudiced him against accepting others, but it is more likely that Hubble thought that Tombaugh had insufficient data to support his claims.[19]

In his early work, Kuhn contends that, since two scientific systems are entirely incommensurable, scientists cannot rationally move from one system to another for "like the gestalt switch, it must occur all at once (though not necessarily in an instant) or not at all."[20] Kuhn argues that new paradigms are necessarily less-articulated that older paradigms. Therefore, since there is an asymmetry of information that flows in the direction of the older paradigm, and rational judgement operates on empirical data, scientists must make a non-rational decision when they adopt a new paradigm[21] akin to a Kierkegaardian leap-of-faith. However, in the case of Hubble's discoveries, most scientists quickly moderated their biases in the face of Hubble's growing body of empirical data, as in the case of Albert Einstein.

In October 1927, Einstein and Georges Lemaitre met in Brussels. When Lemaitre presented his hypothesis that the universe was expanding, Einstein shocked him by stating that "from the point of view of physics, the notion of an expanding universe was an abomination ..."[22] In this instance, Einstein was playing the role of the Kuhnian irreconcilable who cannot make the *gestalt* switch to a new paradigm because of a non-rational commitment to the old paradigm and the inability to compare it against the new. However, this feature of Kuhn's early work does not appear to hold in the case of Einstein. It is more plausible that Einstein was simply not familiar with the increasingly detailed empirical data emerging from the telescopes of observatories in the western United States.[23]

In August 1931, after Hubble had collected exhaustive data to support Lemaitre's original hypothesis, Einstein visited the Wilson observatory and accepted the theory of the expanding universe.[24] Contradicting Kuhn's early conception of incommensurability, once Einstein realized that Hubble's observations were sufficiently thorough and the sample-size of observations was much larger, he eagerly supported the expansion theory. Consequently, Einstein eliminated a cosmological constant in his formulas which buttressed the existence of a static, nonexpanding universe. While this elimination matches some of Kuhn's observations about scientists' care for the aesthetic quality of theories, it is dubitable that Einstein held any such considerations when he removed the variable. As in the case of Einstein, within a few years, most other scientists accepted the idea of the expanding universe because of Hubble's increasingly large pool of data. One possible explanation for the scientists' willingness to accept Hubble's theory is that they did not have access to telescopes of sufficient power with which they could disprove or verify Hubble's findings.[25] Regardless, the development always took place as a part of continuous debate and development, and there is no convincing evidence that a sharp paradigmatic break took place.

In all of his writings, Hubble took time to examine all the theoretical possibilities and explore their implications, which defies Kuhn's claim that scientists operate under a largely unquestioned paradigm. For instance, in Hubble initial 1929 paper, he did not argue for an expanding universe and suggested that mathematician Willem de Sitter's cosmology of a non-expanding, static universe could very well be the norm.[26] Moreover, Hubble gave the expanding model and the contracting model equal weight as he writes "the universe might even be an expanding model," but "for that matter, the universe might even be contracting."[27] Hubble denied that he exhibited the aspects of the creative scientist and contended that he was "primarily an observer." Moreover, he characterized his analysis as entirely objective and not upon interpretations, "whether theoretical or speculative".[28]

Hubble took care to not overstate the support for his own theory such as when he held that the interpretation of the redshift changes as velocity-shifts "is *generally adopted* by theoretical investigators" and the velocity-distance relation "*is considered"* as the observational basis for theories of an expanding universe.[29] In a similar fashion, when Hubble argued in favor of the isotropic nature of the universe, he used value-neutral language, "neither observer, no matter where he may be located, will see the nebulae all receding from his position" and called the hypothesis an "assumption."[30] Hubble acknowledged the multiplicity of possible theories that could be applied to data, but argued that though "many theories are formulated ... relatively few endure the tests."[31] Thus, even though Hubble presented multiple theoretical viewpoints, he identified an objective, empirical standard by which scientists can judge theories. Kuhn and Hubble both agree that scientists cannot appeal to some objective criteria outside of the ability of theories to account for physical phenomena as "the decision involves the comparison of both paradigms with nature and with each other”.[32] However, only Hubble argued that the scientific community is able to make objective judgements in the process of theory-selection on a regular basis.

Both Kuhn and Hubble agree that empirical observation must limit "the list of possible universes which must contain our own."[33] However, Kuhn stresses that there is a personal component while Hubble emphasizes the relative objectivity of the scientific field, "when the actual data are found and reported, the theories are always reviewed in the light of the new information."[34] Hubble stresses that the scientist "tends to develop healthy skepticism, suspended judgment, and disciplined imagination."[35] Thus even though Kuhn and Hubble maintain that science is simultaneously rigid and flexible, they advocate different mechanisms by which theories change, one which relies upon a type of empirical verification and the other that depends upon primarily non-rational factors. However, it is not clear when and why Kuhn's normal science breaks down while Hubble's simple conception of verification operates whenever the data shows a certain theory to be incorrect. Kuhn claims that normal-science degrades as problem-solving ability breaks down, but scientists only decide to switch paradigms when their faith in the prevailing paradigm erodes. Since faith is a highly personal matter and necessarily individual, it is hard to create a hard-and-fast rule of scientific development to account for people's personal beliefs. In opposition to Kuhn, Hubble argued that a scientist is always ready to recognize that he or she may be wrong and will give up their theories fairly easily when confronted with convincing data. According to Hubble, "he [the scientist] is the first to admit that he is likely to be wrong - and he knows how wrong he is likely to be" and never makes recourse to personal ethos as an effective argument.[36]

Hubble directly contradicted Kuhn's claim that revolutionary science is not cumulative as he writes that "science, by its very nature, is accumulative" and that scientific knowledge contributes to a "growing structure."[37] In Kuhn's early work, he maintains that cumulative knowledge is only possible during a period in which scientists do not critique the overriding macro-theory or paradigm. When scientists believe that a paradigm no longer possesses normal-problem-solving power, they undergo a process of soul-searching until they encounter a new paradigm that eases their anxiety. The only concrete progress that Kuhnian revolutionary science makes is through being able to explain an ever-wider variety of natural phenomena for “at least part of that achievement always proves to be permanent.”[38] Hubble stoutly argues that science is cumulative and, in his later work, Kuhn focused more and more upon the cumulative dimension of science.

Noting the linguistic divide that exists between scientists and civil-society, both Hubble and Kuhn and maintained that the scientific community was distinct from the common public and other communities. In one passage from *Realm of the Nebulae,* Hubble described how scientists re-appropriate words and imbue them with meanings that are only present in the scientific community as "the words themselves are familiar, but ... translation into the language of general discourse is a difficult art and frequently blurs the meaning for the dubious advantages of specious familiarity."[39] The evolution of the word *nebulae* in particular seems to match Kuhn's analysis of linguistic drift and change in scientific communities. Hubble divided *nebulae* into two types: "intragalactic nebulae," or clouds of gas and dust illuminated by surrounding stars, and "galactic nebula," which are collections of systems outside the Milky Way Galaxy. Hubble wrote that "the interpretation of these objects [nebula] has frequently changed, but the name has persisted."[40] Even though astronomers used the term *nebulae* in different ways, that corresponded to different linguistic networks, the word itself remained the same. Once Hubble made his crucial discovery that certain nebulae existed outside of the Milky Way, a problem arose of how to reclassify their terminology. The controversy was whether "since nebulae are now known to be stellar systems they should be designated by some other name" as nebulae no longer accurately described the extragalactic systems that Hubble had discovered. Describing the attempted solutions to the controversy, Hubble noted that "the proposal most frequently discussed is a revival of the term external galaxies,"[41] which Hubble's earlier rival Shapley began to champion. Kuhn argues that such a change in terminology creates local incommensurability wherein the historian has to interpret the terms that scientists used as translating would lose the meaning that a term like *nebulae* had in connection to the science of its time.

After Shapley agreed that the nebulae were extragalactic, he began to debate Hubble as to their new classification. Hubble continued to refer to the systems as nebulae; in doing so, he was emphasizing the ontological distinction between the Milky Way and other systems while Shapley focused upon the shared ontological characteristics of the Milky Way and other systems, calling them all galaxies. In fact, Shapley's popular book *Galaxies* popularized the term and established an ontological connection between the Milky Way and other extragalactic systems.[42] In championing the term galaxy, Shapley demonstrated that scientists can accommodate and change their theories according to the rhetorical persuasiveness of arguments and the stark gleam of empirical data. The whole sequence of events is a compelling example of Kuhn's concept of linguistic incommensurability in action.

Hubble portrayed science as a Darwinian process of speciation as Kuhn also came to argue. Specifically, Hubble wrote [Astronomy] is called the mother of them all ... When the same ideas were dragged down from the skies to the earth, Physics was born."[43] Arguing for the biological model, Kuhn writes "the biological parallel to revolutionary change is not mutation, as I thought for many years, but speciation."[44] As scientists become more involved in their individual disciplines with their specialized goals, procedures, journals, and methods, and language, they become less able to communicate effectively with other disciplines. Additionally, as Kuhn notes, scientific disciplines, though they often maintain features of their parent disciplines, at least for a time, never collapse back into the old discipline. In nature, once a species has established genetic incompatibility with its forbearer species, it becomes impossible for the two populations to meaningfully interact. However, Hubble directly contradicts Kuhn as he argues that older theories can act as limited cases for newer theories that are more expansive, using as his example the absorption of Newtonianism into General Relativity.[45] In this way, once a species becomes distinct, it can actually merge back with the mother species - a possibility that Kuhn resoundingly denies.

Both Kuhn and Hubble agree that science advances quickly because it focuses upon specific phenomena and provides the requisite methods to measure that phenomena. Accordingly, scientists should not make extra theoretical assumptions for, as Kuhn writes, “as in manufacture so in science – retooling is an extravagance to be reserved for the occasion that demands it.”[46] In the same way, Hubble stresses that "the accumulation of assumptions is uneconomical."[47] The latter Kuhn's epistemology fits in well with Hubble's conception of theory-choice. For instance, Kuhn gives the example of a young child who learns to suppress the differences between ducks while mentally emphasizing the characteristics that make them different from swans. However, the young child does not extend the taxonomic category of duck beyond what he has empirically seen so as to not waste mental effort. If the child has only seen white ducks and suddenly sees a black duck, only then does he or she rearrange the criteria of what it means to be a duck, and includes the black duck within the category. In the same way, Kuhn's paradigms or disciplinary matrices indicate what sort of entities are in the world so that scientists do not waste time hypothesizing how to deal with nonexistent entities. However, when scientists do confront a phenomenon that violates their preconceived notions, they are able to adjust their theories to incorporate it. This model of scientific progress based on the epistemology of linguistic change is incredibly compelling and solves the paradox of rigidity and flexibility present in the older Kuhn's conception of the paradigm.

Kuhn's paradigm dictates what problems are important, what entities inhabit the universe, how those entities interact, and how the scientist may interact with them; in short the paradigmatic commitments of the scientists are "both metaphysical and methodological".[48] Once scientists are able to recognize what sorts of phenomena are important and the ways in which they must interact, they can design increasingly specialized apparatuses to interact with them. In the case of Hubble, once he and other astronomers called for the development of increasingly powerful telescopes to examine systems outside the Milky Way, engineers set about to design them. Hubble remarked that his 100-inch telescope could observe galaxies out to 15 million light-years and that that distance constituted just one-eighth of a percent of the radius of the observable universe. As a result, Hubble suggested making improvements in photographic emulsions and manufacturing larger telescopes.[49] Responding to the call, George Ellery Hale designed a new 200-inch telescope to calibrate Cepheids and redshifts with greater accuracy. The newly completed camera telescope at the Palomar Observatory was capable detecting galaxies that were so faint so as to have escaped detection by previous astronomers. In June 1948, Hubble used the new 200-inch telescope to photograph the variable nebula NGC 2261; Hubble's earlier observations of this same system helped him to support his theory of the expanding universe. Moreover, increasingly specialized tools helped to further define the paradigm. For instance, additional observations demonstrated that Hubble's cosmological principle was only operative on the level of galactic superclusters rather than galaxies in themselves.[50]

When Edwin Hubble died of a stroke on September 28, 1953, he passed the baton to Allan Sandage who would seek to articulate further the paradigm established by Hubble by overseeing the cosmology program at the Mount Wilson and Palomar telescopes. Centuries earlier, Tycho Brahe had bestowed his astronomical data to his young protege Johannes Kepler who would continue his master's work: the cycle continued with Hubble and Sandage. Under Sandage, the goals were the recalibration of Hubble's extragalactic distance scale and the determination of standard candles - objects of fixed brightness. Sandage used the 200-inch telescope to great effect in order to measure the rate of expansion, the so-called Hubble constant H0 (the ratio between the velocity of a distant object and its distance from the Earth), and how that constant is changing with time.[51] As scientists sought to extend the discoveries established by Hubble, new facts about the universe slowly emerged. The Hubble Space Telescope is the most refined tool that Hubble's paradigm brought about and is a testament to his influence on the development of modern astronomy and cosmology.

When Edwin Hubble discovered that the universe is expanding and that the Milky Way is one of many galaxies, he was acting as a member of his astronomical tradition. The astronomical tradition of Hubble's time featured intense debate and scrutiny of the fundamentals, defying Kuhn's claim that a paradigm is largely unquestioned. Hubble used the methodological and theoretical advances of his predecessors in new ways, but he always maintained continuity with the tradition as whole. Those who initially opposed Hubble's new discoveries quickly changed their opinions once the empirical data began to accumulate. Even the most ardent supporters of the non-expanding universe such as Einstein accepted the empirical data and acted rationally in doing so. Many features of Hubble's discovery, such as the changing definition of the term nebulae, fit well with Kuhn's latter theories, but most of Kuhn's former assertions seem to not apply. Hubble's own philosophical analysis, if a bit underdeveloped, was largely consistent with the way in which he made his discoveries, overlapping with Kuhn's most effective arguments. Overall, Hubble's discoveries fit well with Thomas Kuhn's later paradigmatic analysis in *The Road Since Structure*, but are hard to reconcile with the model that he initially puts forward in his seminal work, *The Structure of Scientific Revolutions*.

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