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**Journal Article**

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**Publication date:**
2010

**Permanent link:**
https://doi.org/10.3929/ethz-b-000020454

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**Originally published in:**
Scientometrics 84(2), https://doi.org/10.1007/s11192-009-0107-x

Scientometrics (2010) 84:441–464
DOI 10.1007/s11192-009-0107-x

# How accurately does Thomas Kuhn's model of paradigm change describe the transition from the static view of the universe to the big bang theory in cosmology?

## A historical reconstruction and citation analysis

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Received: 12 August 2009 / Published online: 7 November 2009

**Abstract** Up to the 1960s the prevalent view of science was that it was a step-by-step undertaking in slow, piecemeal progression towards truth. Thomas Kuhn argued against this view and claimed that science always follows this pattern: after a phase of "normal" science, a scientific "revolution" occurs. Taking as a case study the transition from the static view of the universe to the Big Bang theory in cosmology, we appraised Kuhn's theoretical approach by conducting a historical reconstruction and a citation analysis. As the results show, the transition in cosmology can be linked to many different persons, publications, and points in time. The findings indicate that there was not one (short term) scientific revolution in cosmology but instead a paradigm shift that progressed as a slow, piecemeal process.

**Keywords** Thomas Kuhn · Paradigm · Historical reconstruction · Cosmology · Bibliometrics · Citation analysis

## Introduction

Up into the 1960s the prevalent view of science was that it was an incremental endeavor in a slow, piecemeal process "marching ever truthwards" (Marris et al. 2008, p. 1023). This view of science was challenged to a lasting effect by historian of science Thomas Kuhn (see here Mayoral de Lucas 2009) in his book, *The Structure of Scientific Revolutions* (Kuhn 1962b). According to Kuhn's theory, science takes place always following the same pattern: After a phase of "normal science", a scientific "revolution" occurs.

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"Normal science" takes its orientation from what Kuhn calls a *paradigm*, meaning that this science fills in the details of a generally accepted, shared conceptual framework (Marris et al. 2008); the level of consensus among scientists is high (Cole 1992).

> Against the backdrop of an assumed set of questions concerning a particular domain—the heavens, for example, or the nature of combustion—and a set of standards and methods for answering them—scientists attempt to make relatively small changes to the dominant theory of that domain so as to resolve the anomalies that experiment reveals (Boghossian 2006, p. 119).

In their science scientists are thus interested not in falsification but in confirmation of their framework.

Although in science studies there is considerable controversy as to the exact meaning of the term paradigm (Giere 2006; Masterman 1970), we can assume that a paradigm is the set of beliefs, norms, and values shared by members of a group of scientists (producers and validators of scientific knowledge) engaged in studying specific problems in a research area (Crane 1980). These beliefs, norms, and values can refer to the laws of nature, definitions of symbols, explanatory models, theories, and scientific predictions and also to the questions that need to be answered and the technical problem solutions that guide the research of scientists (Crane 1980). In the literature that examines Kuhn's (1962b) paradigm theory by means of examples from the history of science, the paradigm is usually a dominant theory in a particular field.

Scientific revolutions are evoked by deviations (falsifications or anomalies) that do not fit into the paradigms, "where scientists are forced to reconsider some fundamental assumption that had up to then seemed obvious" (Boghossian 2006, p. 119). When the difficulties for the dominant theory posed by new sets of data and observations accumulate to a certain point, they lead to a scientific crisis, and the consensus among scientists under the guise of the paradigm breaks down. There is an increased level of activity (cogitation) in a research area, with the validity of the paradigm being called into question (Tabah 1999). During a crisis of this kind alternative paradigms are proposed (Shimp 2004). In this phase it may be impossible "to determine which of two competing scientific ideas should be accepted" (Cole 1992, p. 22).

The followers of the old and new paradigms can no longer agree on common standards for the assessment of the competing paradigms. Theoretical "propaganda" and scientific strategies play a great role in this phase (Feist 2006). If during the crisis a paradigm shift takes place through changes in the fundamental way of thinking, the old paradigm is replaced with the new one (Morris 2005). These are the scientific revolutions (in retrospect called the milestones of research) that set a new direction for research: There is a new set of puzzles that can be solved in a new cycle of normal science (Gieryn 1995). Nobel Prizes are usually awarded for theories, discoveries, and technologies that have changed the direction of science (Charlton 2007).

Few theoretical approaches in science studies have generated as much interest as Kuhn's (1962b) paradigm theory (Crane 1980). And even though the theory has been well-known since the 1960s, it has become increasingly popular especially recently: Fig. 1 shows the number of published articles with titles containing the words *paradigm* or *paradigm shift* since 1960 (see here also Marris et al. 2008). The number has clearly increased from year to year. Analogously, the number of citations of Kuhn's (1962b) book over time shows that the work has received undiminished attention. But although many papers have been published on paradigm theory, only a few studies have examined it empirically (Tabah 1999). A recently published News Feature, "Disputed Definitions", in *Nature* (Marris et al. 2008, pp. 1023–1024) looks at some of the most difficult definitions in

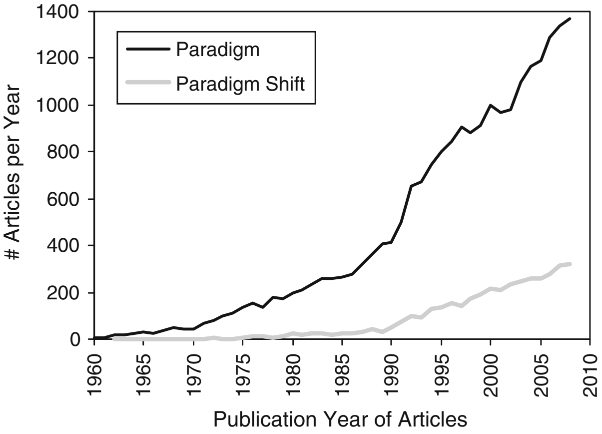


**Fig. 1** Articles published since 1960 with titles containing the words "paradigm" or "paradigm shift" (or "paradigm change" or "new paradigm") (Marx and Cardona 2009, called this kind of citation "informal citations"). *Source*: Web of Science, provided by Thomson Reuters (Philadelphia, PA, USA)

science. The continuing controversy concerning the use of 'paradigm shift' is explained by Marris on the basis of two statements:

> In 2002, Stuart Calderwood, an oncologist at Harvard Medical School in Boston, Massachusetts, used it to describe the discovery that 'heat shock proteins', crucial to cell survival, could work outside the cell as well as in. 'If you work in a field for a long time and everything changes, it does seem like a revolution,' he says. But now he says he may have misused the phrase because the discovery was adding to, rather than overturning, previous knowledge in the field. Arvid Carlsson, of the University of Gothenburg in Sweden stands by his use of the phrase. 'Until a certain time, the paradigm was that cells communicate almost entirely by electrical signals,' says Carlsson. 'In the 1960s and '70s, this changed. They do so predominantly by chemical signals. In my opinion, this is dramatic enough to deserve the term paradigm shift.' Few would disagree: base assumptions were overturned in this case, and Carlsson's own work on the chemical neurotransmitter dopamine (which was instrumental in this particular shift) earned him the 2000 Nobel Prize in Physiology or Medicine (Marris et al. 2008, pp. 1023–1024).

Upon the background of the controversy over the term paradigm shift, our aim in the following is to critically examine Kuhn's (1962b) theoretical approach by means of a case study: the transition from the static view of the universe to the Big Bang theory in cosmology. Did this paradigm shift take place as a scientific revolution at a particular point in time or as a cumulative, piecemeal process over a longer time period? Was there a fundamental shift in the way of thinking, or was the shift merely one step in development within a chain of many other developmental steps? In order to be able to investigate the influence of important persons and publications on the development of modern cosmology, we determined the resonance, or impact, of scientific works among peers based on citation counts. We assume that scientific revolutions would find expression ex post in high citation counts for certain core publications by scientists whose names are connected with the paradigm shift. In contrast, a piecemeal process should be connected with high citation counts for a number of publications by very different scientists that were published over a longer period of time and that contributed decisively to the paradigm shift.

To check Kuhn's (1962b) theory, the present study uses the approach of a historical reconstruction of a paradigm shift in combination with the information sciences technique of bibliometric analysis (Lucio-Arias and Leydesdorff 2009). In “The transition from the static view of the universe to the Big Bang theory—a historical reconstruction” below, we reconstruct historically the development of the transition from the static view of the universe to the Big Bang theory in cosmology and “Bibliometric analysis of the cosmology publications” present the results of a citation analysis of the most important publications in this process. According to Garfield et al. (1964), the origins and history of scientific ideas can be traced and historical dependencies investigated through citation analyses (see here also Davis 2009). Whereas the historical reconstruction represents a subjective appraisal of publications and persons that played an important role in the development of modern cosmology, citation analysis is a quantitative method that determines the significance of publications through unobtrusive measures (i.e., non-reactive data) (Smith 1981).

## The technique of bibliometric analysis

In bibliometrics the resonance, or impact, of a scientific work is measured via the number of citations. It can be assumed that the more important a work is for the further development of a field, the more frequently it is cited (Abt 2000; Bornmann and Daniel 2008b). Lokker et al. (2008) succeeded in demonstrating for clinical articles that publications regarded shortly after their appearance as important by experts in the appropriate research field were cited much more frequently in subsequent years than publications that were less highly regarded. The Chemistry Division of the National Science Foundation (Arlington, VA, USA) carried out a citation analysis with the goal “to explore the use of this relatively new tool for what it might tell about the discipline and its practitioners.” The results of the study “generally support the idea that citations are meaningful” (Dewitt et al. 1980, p. 265). Furthermore, the results of a comprehensive citation content analysis conducted by Bornmann and Daniel (2008a) show that “an article with high citation counts had greater relevance for the citing author than an article with low citation counts” (p. 35).

The data bases for determining citation counts are the citation indexes provided by Thomson Reuters (Philadelphia, PA, USA, formerly ISI, Institute for Scientific Information). The data presented here are based on the Thomson Reuters citation indexes accessible in Web of Science® (WoS), in particular Science Citation Index (SCI) with coverage back to 1900, Social Sciences Citation Index (SSCI) with coverage back to 1956, Arts & Humanities Citation Index (A&HCI) with coverage back to 1975, and also Conference Proceedings Citation Index, Science (CPCI-S) and Conference Proceedings Citation Index, Social Science & Humanities (CPCI-SSH), with coverage back to 1992.

The present study is based on 27 publications that played an important role in the transition from the static view of the universe to the Big Bang theory in cosmology. The 27 publications were carefully selected based on summaries and overviews of this transition. They are the least common denominator of the rather coherent secondary literature (e.g. the many cosmology papers published in Scientific American, challenging popular books like Silk (1980), Singh (2004), or Nussbaumer and Bieri (2009)). The original publications (in particular the early articles) have been consulted as far as possible (the authors are no experts in the field of astronomy or cosmology). The story and the papers analyzed here rely mainly on the persons and publications named by Singh (2004) in the chapter summary notes of his book, *Big Bang*. Further analysis revealed that the inclusion of various additional papers did not change the overall picture. To enable assessment of the importance of the individual publications for the paradigm shift, Table 1 shows for each publication the total, average, and relative citation counts. The total citation counts are the

**Table 1** Total citation counts, average citations per year, and relative citation counts of 27 cosmological papers

| Cosmology paper (ranked by publication year) | Total citation count pre-2008 | Citation count pre-1960 | Citation count 1961–2008 | Average citations per year pre-1960 | Average citations per year 1961–2008 | Relative citation count pre-1960 | Relative citation count 1961–2008 |
|---|---|---|---|---|---|---|---|
| Slipher (1912) | 0 | 0 | 0 | 0.000 | 0.000 | 0.000 | 0.000 |
| Leavitt (1912) | 28 | 1 | 27 | 0.021 | 0.574 | 0.040 | 0.166 |
| Hertzsprung (1913) | 18 | 7 | 11 | 0.149 | 0.234 | 0.281 | 0.068 |
| **Einstein** (1917) | 383 | 31 | 352 | 0.721 | 7.489 | **1.358** | **2.161** |
| De Sitter (1917) | 122 | 6 | 116 | 0.140 | 2.468 | 0.264 | 0.712 |
| Slipher (1917) | 15 | 2 | 13 | 0.047 | 0.277 | 0.089 | 0.080 |
| Wirtz (1921) | 3 | 0 | 3 | 0.000 | 0.064 | 0.000 | 0.018 |
| **Friedmann** (1922) | 342 | 19 | 323 | 0.500 | 6.872 | 0.942 | **1.983** |
| **Friedmann** (1924) | 187 | 4 | 183 | 0.111 | 3.894 | 0.209 | **1.124** |
| Lundmark (1924) | 9 | 1 | 8 | 0.028 | 0.170 | 0.053 | 0.049 |
| Wirtz (1924) | 7 | 0 | 7 | 0.000 | 0.149 | 0.000 | 0.043 |
| Hubble (1925) | 114 | 4 | 110 | 0.114 | 2.340 | 0.215 | 0.675 |
| **Hubble** (1926) | 406 | 10 | 396 | 0.294 | 8.435 | 0.554 | **2.434** |
| Lemaitre (1927) | 135 | 8 | 127 | 0.242 | 2.702 | 0.456 | 0.780 |
| **Hubble** (1929) | 277 | 14 | 263 | 0.452 | 5.596 | 0.851 | **1.615** |
| **Hubble and Humason** (1931) | 193 | 19 | 174 | 0.655 | 3.702 | **1.233** | **1.068** |
| Lemaitre (1931) | 20 | 2 | 18 | 0.069 | 0.383 | 0.130 | 0.111 |
| Jansky (1933) | 12 | 2 | 10 | 0.074 | 0.213 | 0.139 | 0.061 |
| Alpher (1948) | 97 | 6 | 91 | 0.500 | 1.936 | 0.942 | 0.559 |
| **Alpher et al.** (1948) | 199 | 19 | 180 | 1.583 | 3.830 | **2.981** | **1.105** |
| **Bondi and Gold** (1948) | 262 | 35 | 227 | 2.917 | 4.830 | **5.493** | **1.394** |
| **Hoyle** (1948) | 291 | 30 | 261 | 2.500 | 5.553 | **4.708** | **1.603** |
| Alpher and Herman (1949) | 82 | 4 | 78 | 0.364 | 1.660 | 0.685 | 0.479 |
| **Hoyle** (1949) | 79 | 14 | 65 | 1.273 | 1.383 | **2.397** | 0.399 |
| Ryle and Clarke (1961) | 65 | 0 | 65 | – | 1.383 | – | 0.399 |

**Table 1** continued

| Cosmology paper (ranked by publication year) | Total citation count pre-2008 | Citation count pre-1960 | Citation count 1961–2008 | Average citations per year pre-1960 | Average citations per year 1961–2008 | Relative citation count pre-1960 | Relative citation count 1961–2008 |
|---|---|---|---|---|---|---|---|
| **Penzias and Wilson** (1965) | 870 | 0 | 870 | – | 19.773 | – | **5.706** |
| **Dicke et al.** (1965) | 336 | 0 | 336 | – | 7.636 | – | **2.204** |
| Sum | 4239 | 215 | 4024 | 12.754 | 93.546 | 24.020 | 26.996 |
| Average | 169.560 | 9.773 | 160.960 | 0.531 | 3.465 | 1.000 | 1.000 |

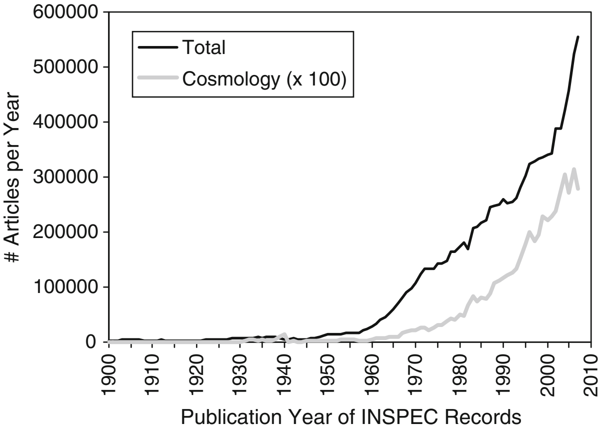
*Notes*: Papers (and their citation counts) that have an above-average citation impact (>1) are shown in bold typeface

*Citation sources*: SCI, SSCI, A&HCI, CPCI-S, CPCI-SSH from Thomson Reuters Web of Science (WoS) number of citations since publication up to the end of 2008, and the average citation counts are the average citations per year. The relative impact is the quotient of the average impact per year of a publication and the average impact per year across all of the important cosmology publications examined here ($n = 27$). Relative impact allows assessment of the importance of an individual publication in comparison with the importance of all of the other publications. This is a standard method in evaluative bibliometrics (Bornmann and Daniel 2009; Radicchi et al. 2008). In the present study we want to propose use of this method as a complement to the historical reconstruction of scientific developments. A value of about 1 for relative citations means that a publication has been cited approximately just as frequently as the average across all of the publications. A value clearly higher than 1 characterizes publications that have had a far above-average impact and have a far above-average importance for the development of modern cosmology (see here van Raan 2005).

The reception of many of the cosmology papers examined in this study took place in two time periods—the period prior to and the period after around the year 1960, which have very different publication and citation cultures. Borrowing the title of a book by de Solla Price (1965), a distinction can be made here between "little science" and "big science." In the first half of the twentieth century, astronomers and cosmologists were few in number, so that overall and also per researcher comparatively few papers were published and the publications were cited on average accordingly rarely. In Fig. 2 it is clearly visible that since the beginning of the 1960s there has been a definite increase in the number of papers published in physics and also the field of cosmology. (The prestigeous *Astrophysical Journal* shows a somewhat different picture: an exponentional growth already since the mid-1930s (Abt 1995).) The reason for the increase in physics is mainly the Sputnik shock and the tests of the first Soviet hydrogen bombs, which triggered a drastic increase in research efforts particularly in the United States. The distinct increase in publications also led to a distinct increase in citations. To take into account these different publication and citation cultures prior to 1960 and after 1960 when assessing the 27 cosmology papers examined in this study, Table 1 shows the total, average, and relative citation counts not only across the entire period of time from publication up to the end of 2008 but also separately for the years prior to 1960 and since 1961.

Citation counts has been a controversial measure of both quality and scientific progress (Bornmann and Daniel 2008b). In the following, four caveats of the measure with specific

**Fig. 2** Time evolution of the publications (total database records and subject area "cosmology") covered by the database for physics, electronics, and computing (INSPEC) since 1900. The clear increase around 1960 divides the "little science" and "big science" epochs (see de Solla Price 1965)



relevance for this study are listed. Although these caveats exist, they are not expected to cause a biased picture with regard to the basic results of this study:

1. *Citation counts of early papers*: The total citation counts of papers that were published at the beginning of the twentieth century cannot be determined by means of the Times Cited function of WoS records, as can more recent papers. Instead, all relevant citation variations have to be determined carefully via the Cited Reference Search and added together. For this procedure a great deal of experience in conducting citation analyses is required.
2. *Low citation rates in the period of "little science*:" According to the small scientific community (in particular in cosmology), the average citation rates of the papers published in the epoche of "little science" before around 1960 were considerably lower than in the "big science" epoche: One single citation in the first decade of the twentieth century corresponds to 10–100 citations at present (Cardona and Marx 2008).
3. *Informal citations*: Seminal work is often cited by mentioning the author's name or name-based items (informal citations, also called eponyms) instead of citing the full references as a footnote (formal citations) (Marx and Cardona 2009). The amount of loss of reference based citations caused by informal citations, however, is difficult to estimate.
4. *Obliteration by incorporation*: Merton (1965, 1968) first described the phenomenon "obliteration by incorporation." The process of obliteration means that seminal works offering novel ideas are rapidly absorbed into the body of scientific knowledge. Such work is soon integrated into textbooks and becomes increasingly familiar within the scientific community. As a result of this absorption and canonization, the original sources fail to be cited, either as full references (formal citations) or even as names or subject-specific terms (informal citations).

## The transition from the static view of the universe to the Big Bang theory—a historical reconstruction

### The previous history

The development of modern cosmology begins from the time that Albert Einstein put forward the theory of relativity and extends up to the projects of the U.S. National Aeronautics and Space Administration (NASA) towards the end of the twentieth century. The development is characterized by increasing internationalization and the dovetailing of research in particular with nuclear physics, high energy physics, and atomic physics. New tools and technologies were developed in addition to the classic telescopes: radio telescopes, space telescopes, and particle accelerators.

Before Einstein established modern cosmology, his famous paper on the special theory of relativity appeared in *Annalen der Physik* (Einstein 1905b). With this, Einstein, who was unknown at the time, went decisively beyond Newton's classical mechanics. The paper must be viewed mainly in the context of its fundamental importance for physics, but it was also the basis for Einstein's cosmology papers from 1915 to 1917 (Einstein 1915, 1916, 1917). Max Planck was among the few scientists to be impressed by these papers immediately after their publication. In spite of his reservations regarding Einstein's light quantum hypothesis that was also published in 1905, Planck became probably the most important supporter of the young Einstein. Planck called Einstein to Berlin in 1914, and expectations that Einstein would produce further scientific breakthroughs were fulfilled as early as 1915, with Einstein's exposition of his general theory of relativity (Einstein 1915, 1916), in which he introduced his theory of gravitation.

## From the static view of the universe to the big bang theory

Shortly after publication of the first systematic exposé of Einstein's general theory of relativity (Einstein 1916) Einstein wrote a paper titled "*Kosmologische Betrachtungen zur Allgemeinen Relativitätstheorie*" [Cosmological Considerations on the General Theory of Relativity] that applied the gravitation theory on the cosmic scale (Einstein 1917). When applying his new gravitation theory to the entire universe, Einstein had to assume for the sake of simplicity that the universe looks to us the same in all directions and the Earth does not occupy a privileged location in the universe (cosmological principle). In line with contemporary thinking, Einstein assumed a static and invariable universe and was then surprised that his theory suggested an unstable universe. Since all bodies gravitationally attract all other bodies, an eventual collapse was inevitable. Einstein solved the problem by arbitrary postulating a kind of anti-gravitation as a repulsion force for matter and introduced it in the equations of general relativity theory as the cosmological constant Lambda. Only with this arbitrary assumption was Einstein's new gravitation theory compatible with a universe generally supposed to be static. However, the assumption was detrimental to the formal beauty of the theory and therefore rather irritating, although at first unavoidable. The Dutch astronomer Willem de Sitter took up Einstein's field equations and also applied them to the entire universe (de Sitter 1917). Whereas de Sitter's universe is also static, it is based on a different geometry, which played a role later on in the interpretation of the redshift.

When Einstein's general theory of relativity became known in Russia, the Petersburg mathematician Alexander Friedmann soon recognized that the cosmological constant could also be zero and that different models of the universe were conceivable: Depending on how much matter the universe contained and how great the impetus against the pull of gravity from a hypothetical singular point was, the universe (1) could expand forever, (2) expand but decelerate at a rate that eventually approaches zero, or (3) expand but then contract and collapse. This notion of a dynamic universe stood in stark contrast to Einstein's static model.

After Friedmann published his ideas in 1922 in *Zeitschrift für Physik* (Friedmann 1922), Einstein's response was unexpectedly critical. Although as a young scientist he himself had often taken a view opposing the authorities, Einstein wrote a letter of complaint to the editors of the journal, finding fault with Friedmann's calculations. But Einstein's bias had apparently kept him from a careful reading, for shortly afterwards Einstein wrote a second note to the journal editorial office, stating that his criticisms had been based on an error in calculation and that Friedmann's calculations were mathematically correct. However, whereas Einstein accepted the mathematics, he still found them to be scientifically irrelevant (Singh 2004, p. 155), and he did not accept the idea of a physically expanding universe. Friedmann (1924) published a second article on the same topic, but he then died at a young age in 1925.

With no knowledge of Friedmann's works, Georges Lemaitre, a Catholic priest and astrophysicist from Belgium, developed his own dynamic model of the world and published a first paper in 1927 (Lemaitre 1927) in French titled "*Un univers homogene de masse constante et de rayon croissant, rendant compte de la vitesse radiale des nebuleuses* *extra-galactiques*" [A homogeneous universe of constant mass and increasing radius]. Lemaitre suggested that at the beginning there was a *primeval atom* that contained all the matter in the universe, and the energy released by its decay caused expansion. The physical interpretation in this model went further than Friedmann's, and it must be seen as the origin of the later Big Bang theory of the universe. The term Big Bang is taken here as synonym for a universe with a definite beginning and is not restricted to the physics in the moment of creation (string theory etc.). Lemaitre spoke with Einstein in Brussels at the Solvay Conference of 1927 and learned from him of Friedmann's works for the first time. Einstein, still unimpressed, commented, "Your calculations are correct, but your grasp of physics is abominable" (Singh 2004, p. 160).

In 1912 Vesto Slipher had discovered the cosmological redshift of spectral lines of galaxies (Slipher 1912). Atoms absorb and emit light of discrete energy and produce typical patterns of spectral lines, which are shifted towards shorter or longer wavelengths. This shift is an exact measure for the speed in motion towards the observer (blue shift) or away from the observer (redshift). In contrast to the common Doppler shift, the cosmological redshift is based on the general theory of relativity, i.e. the expansion of space. The discovery of the redshift of galaxies is often wrongly attributed to Edwin Hubble, who later made extensive use of Slipher's method. From 1912 to 1917 Slipher went onto measure systematically the radial velocities of spiral nebulae and found several nebulae with marked redshifts (Slipher 1917). The fact that most of the galaxies are moving away from us (at velocities of thousands of kilometers per second) clearly contradicted a static universe in which the galaxies moved about in no preferred direction.

Around 1921 the German astronomer Carl Wirtz was the first to derive a relation between the radial velocities of nebulae based on Slipher's measurements and the distance of the measured objects (Priester and Schaaf 1987). At that time cosmic distances were measured via the apparent diameters of spiral nebulae conveyed through photographs, which is a very unreliable method, as galaxies are not uniform in size. Wirtz (1921) wrote: "Dagegen prägt sich in den mit Vorzeichen gebildeten Mittelwerten ein ungefähr linearer Gang in dem Sinne aus, als ob die uns nahen Spiralnebel die Tendenz der Annäherung, die entfernten die des Zurückweichens von unserem Milchstraßensystem besitzen" (p. 352) [The averages with the plus and minus signs suggest an approximately linear relation, as if the spiral nebulae close to us possess a tendency to approach and the nebulae far away from us a tendency to recede from our galaxy]. In a 1924 paper Wirtz stated more clearly that there was no doubt that the positive radial motion of the spiral nebulae increases very considerably with increasing distance (Wirtz 1924). The Danish astronomer Karl Lundmark (1924) published the first diagram that plotted the radial velocity of galaxies against their distance. Lundmark (1924) stated carefully: "Plotting the radial velocities against these relative distances (Fig. 5), we find that there may be a relation between the two quantities, although not a very definite one" (pp. 767–768).

In 1920 the National Academy of Sciences in Washington, D.C., was the scene of what in the history of astronomy and cosmology has come to be called the "Great Debate." Experts came together to discuss whether the Milky Way comprised the universe and the nebulae were located within it, or whether the nebulae were far distant galaxies. The two sides of the controversy were represented by the young astronomer Harlow Shapley (holding that nebulae are inside the Milky Way) and the more senior astronomer Heber D. Curtis (holding that nebulae are galaxies external to our own). The issue could not be decided conclusively based on the sparse data available at the time. But that changed fundamentally only a few years later. Shapley's discussion played a role in refuting his own position.

Henrietta Leavitt was the person who provided the most important prerequisite here. Leavitt (1912) examined 25 Cepheid variable stars in the Small Magellanic Cloud and found a clear relation between the apparent brightness of the stars and the time period it took to vary from bright to dim: the greater the brightness, the longer the period (the period-luminosity relation). Since the variable stars could be assumed to have approximately the same distance from the Earth (that is, all Cepheids were seen as being located in the Small Magellanic Cloud), the apparent brightness was proportional to actual brightness. With this, the relative distance of two Cepheids to the Earth could be determined but not the absolute distance. Measurement of the absolute distance became possible only after Danish astronomer Ejnar Hertzsprung determined (at first still imperfectly, however) the absolute distance of a Cepheid by means of parallax measurement (Hertzsprung 1913). After this calibration of the Cepheid distance scale, the universe could be measured on the basis of Leavitt's discovery.

The first photographs of the spiral nebulae with redshifts in the spectral lines made such a lasting impression on the budding astronomer Edwin Hubble that he devoted his dissertation to the "Photographic Investigations of Faint Nebulae". In 1919 Hubble began work at the Mount Wilson Observatory in California with the 100 inch (2.5 m) Hooker telescope, then the most powerful telescope in the world. In 1923 he found a Cepheid variable star in a spiral nebula, the Andromeda Nebula. Based on Leavitt's period-luminosity relation, Hubble determined the distance of the Andromeda Nebula from the Earth (Hubble 1925, 1926), which he could then place at 900,000 light years away. Since the Milky Way has a diameter of only approximately 100,000 light years, this demonstrated decisively that the Andromeda Nebula (and probably also most of the other nebulae) was located far outside the Milky Way and was thus a large galaxy in its own right—the Andromeda Nebula became the Andromeda Galaxy. The enlargement of the universe far beyond the Milky Way may be considered as equally important as the subsequent transition from the static to the dynamic universe. This made Hubble world-famous beyond the confines of his own field.

Knowing that the Hooker telescope at the Mount Wilson Observatory was considerably more powerful than the Lowell telescope used by Slipher, Hubble felt challenged to solve the puzzle of the redshift of the galaxies that Slipher had found. Working together with an assistant, Milton Humason, who was an experienced astrophotographer, Hubble determined the distances and Humason the redshifts. Graphic representation of their measurements made up to 1929 (together with further data from Slipher) suggested a linear dependency: The radial velocity of the galaxies seemed to increase with increasing distance from the Earth. In his 1929 paper on the findings Hubble (1929) wrote: "The results establish a roughly linear relation between velocities and distances among nebulae for which velocities have been previously published, and the relation appears to dominate the distribution of velocities" (p. 173). Compared to Wirtz's and especially Lundmark's hesitant choice of words, this statement is unambiguous and clear. Through adding a sample of further-distant galaxies in the following two years, the still large scatter of the first measurements could be reduced considerably. In the follow-up paper of 1931 (Hubble and Humason 1931), the measurement points thus lie close to the line of best fit. The conclusion was therefore compelling: The universe had developed out of a compact beginning state and then continued to expand. The generalization that the receding velocity of distant galaxies (the redshift) is proportional to their distance from the observer is called the Hubble law. The ratio of the velocity of the galaxies to their distance is a constant called the Hubble constant.

The value of the Hubble constant can be used to estimate the age of the universe. The first series of measurements yielded an age of two billion years, which is much less than geological estimations of the age of rocks. It turned out later that Hubble had made an error when determining the distance of the Andromeda Galaxy, so that the cosmic yardstick had to be increased. The corrected Hubble constant yielded an age of 10–20 billion years—in accordance with the oldest known cosmic objects. Establishing a precise value for the Hubble constant continues to be an important topic in cosmology. It was the main reason for the building of the Hubble Space Telescope named after Edwin Hubble.

Hubble did not participate in interpreting his findings and let the beginning an untouched question. On this point Hubble and Humason (1931) stated explicitly: “The writers are constrained to describe the ‘apparent velocity-displacements’ without venturing on the interpretation and its cosmologic significance” (p. 80). Later, Hubble adopted Fritz Zwicky’s tired light theory of redshifts that Zwicky proposed as an alternative to the Big Bang theory. But Einstein made an about-turn in another direction: After visiting the Mount Wilson Observatory in 1931 to see the Hooker telescope and view the findings on the photographic plates, he publicly supported the expanding universe and rehabilitated the works of Friedmann and Lemaitre. Einstein called the introduction of the cosmological constant the greatest blunder of his life. Lemaitre received a lot of support from Arthur Eddington, who in 1919 had conducted the first experimental test of the theory of general relativity and confirmed the bending of light in strong gravitational fields at a total solar eclipse in 1919, contributing significantly to Einstein’s later fame. Eddington himself had reservations concerning the Big Bang theory, however, and wanted to see further experimental evidence.

That the speed of the receding galaxies increases proportionally with distance clearly indicated that there had been a moment of creation from a highly concentrated state and an expansion of the universe that still continues today. With Hubble, the Big Bang model had become more than a mathematical model. There was no doubt that the galaxies were moving outward, but the majority of astronomers and physicists continued to reject the idea of the Big Bang. They sometimes thought of an oscillating universe that expanded and contracted periodically. A significant minority was impressed by the agreement between Lemaitre’s theory and Hubble’s measurements and could now feel supported by Einstein. There was also agreement that the galaxies were not racing apart from each other in previously empty space but instead were moving with the expansion of space itself. According to that, there is no expansion IN space but rather the stretching OF space itself, and no evolution IN time but rather a stretching OF time itself. But it took almost two more decades until this discussion got moving again.

After the discovery of nuclear fission and in the wake of the US American nuclear project, nuclear physics had a strong upswing after the Second World War. Some physicists turned away from nuclear technology applications and attempted to utilize the knowledge gained in the fields of astrophysics and cosmology. One of these was the theoretician George Gamow, who investigated the synthesis of the heavier elements out of hydrogen in connection with the Big Bang model. In 1948, together with his PhD student Ralph Alpher, Gamow succeeded in explaining the relative abundances of hydrogen (90%) and helium (9%) based on nucleosynthesis during the Big Bang. The forming of helium through fusion of hydrogen in stars was much too slow and could account for only a small percentage of the existing helium.

A summary of Alpher and Gamow’s results was published in an article titled, “The Origin of Chemical Elements” (Alpher et al. 1948). Because it was appearing on April Fool’s Day, George Gamow, in an unusual advertising move, added to the paper the name of his close friend and renowned physicist Hans Bethe (famed for his work on nuclear reactions in stars, among others), making the authors "Alpher, Bethe, and Gamow", a pun on the first three letters of the Greek alphabet: alpha, beta, and gamma. Bethe had done no work on the paper. The Alpher et al. (1948) paper provided indirect confirmation of the Big Bang model. At first the paper was associated mainly with Alpher's name. However, over time Alpher's name became overshadowed by the names of his famous co-authors, and it became generally assumed (erroneously) that Gamow and Bethe had been the primary contributors to the breakthrough.

After Alpher's later studies failed to explain the production of elements beyond helium, Alpher turned to the early phase of the creation of the universe and began to work in collaboration with Robert Herman. The paper by Alpher et al. (1948) had dealt with the phase of high density and temperature in which nuclear fusion was possible. After that phase, the early universe was made up of hot plasma of electrons, hydrogen, and bare helium nuclei in a sea of light. The transition from plasma to hydrogen and helium atoms (generally known as recombination) was expected to happen after 300,000 years and at a temperature of 3,000°C. At this point the photons in the matter of the early universe did not scatter off the atoms and began to travel freely through space as the radiation echo of the Big Bang. As the universe expanded, the spectrum of this light would have been shifted to longer and longer wavelengths, into the microwave range, and the temperature associated with the spectrum would have decreased as the universe cooled.

Alpher and Herman discussed just this effect and ventured the hypothesis that the entire universe must be filled with uniform background radiation in every direction. They calculated background radiation at a wavelength of approximately one-thousandth of a millimeter, corresponding to the radiation of a blackbody with a temperature of 5 Kelvin; the actual value is now known to be just under 3 Kelvin (see below). Since the release of the background radiation, then, the universe has expanded a thousandfold and cooled to a thousandth of the temperature. Alpher and Herman's findings were published in a 1948 paper in *Nature* (Alpher 1948) and in 1949 in *Physical Review* in a joint article titled, "Remarks on the Evolution of the Expanding Universe" (Alpher and Herman 1949).

Cosmic microwave background radiation is the strongest evidence of the validity of the Big Bang theory. However, with microwave technology being hardly developed at the time, demonstrating the existence of microwave radiation was a challenge. Besides that, there were very few people who had the necessary knowledge in the areas of astronomy, cosmology, theoretical nuclear physics, and microwave technology. As a practical joker and writer of books popularizing science, Gamow was frequently not taken seriously by some of his colleagues. Although Gamow's name had overshadowed Alpher's in 1948, Gamow's image now unintentionally tarnished the reputation of his students. Most astronomers of the time rejected the Big Bang model. Faced with the lack of response to their work, the three men ended their research program; Gamow moved into other research areas, and Alpher and Herman became employed in industrial research laboratories.

Instead of considering searching for the predicted background radiation, some researchers began to consider whether Hubble's findings were compatible with a static model. The activities shifted for a while to the UK. Fred Hoyle (astronomer), Thomas Gold (engineer), and Hermann Bondi (mathematician) had met during the Second World War. In 1948 they developed an alternative to the Big Bang theory that came to be called the Steady State model. The model was presented in two separate papers (Bondi and Gold 1948; Hoyle 1948) and finally by Hoyle in a paper published in 1949 (Hoyle 1949). According to the Steady State theory, matter drifting apart was always replaced by matter that was continuously being created, so that the universe can be always expanding but at the same time remains unchanged, and it does not require a beginning in time. In the ensuing debate, Hoyle coined the term “Big Bang” for the competing model, rather disdainfully, during a talk on a British Broadcasting Corporation (BBC, London, UK) radio program in 1950 (Singh 2004). This catchy phrase for the competing model by its sharp opponent caught on, in both camps. As an alternative to the Big Bang theory there was thus now the Steady State model, a modern variant of the old model of the eternal universe. However, the spontaneous creation of matter seemed unphysical and desperate. Most of the astronomers at that time did not accept the idea of continuous creation seriously.

Independently of the two competing cosmological models, a crucial open question remained: How were the heavier elements beyond helium formed? Temperatures of some millions of degrees suffice for the fusion of helium out of hydrogen, whereas the heavier elements require temperatures of some billions of degrees. Although such hot temperatures existed shortly after the Big Bang, Alpher and Herman found no answers. In two steps, Hoyle found a convincing explanation and thus solved one of the greatest puzzles in astrophysics. First, he recognized that the necessary conditions of the fusion of the heavier elements were found only in the interiors of stars. Hoyle calculated how conditions change during the life of the star and how, when the star dies, element synthesis continues in the relics of the dead stars, the newly formed stars of the second generation (the sun is a third-generation star). The heavy elements form only under the extreme conditions of the death of a massive star (supernova). With this, Hoyle was able to largely explain the observed frequency distribution of the chemical elements in the universe.

But the decisive first step of nucleosynthesis of the heavier elements, the synthesis of carbon out of beryllium, appeared to be blocked for two, mutually dependent and reinforcing reasons: The beryllium isotope is extremely unstable, and the carbon to be formed can not eliminate its excess energy fast enough. Hoyle predicted that there must be a more stable excited carbon nucleus with a precisely defined energy level. He persuaded the American nuclear physicist Willy Fowler to carry out experiments to find it. Fowler succeeded and later received the Nobel Prize. The explanation of the formation of the heavy elements thus came from an opponent of the Big Bang theory, but it confirmed that theory. However, the scientific community continued to be divided, and only compelling experimental data would settle the issue. These data came from experiments that were conducted outside of astronomy and not aimed at cosmology.

In the late 1920s the American Telephone and Telegraph Company (AT&T) began to modernize transatlantic telephone service based on radio waves. At the newly established Bell Telephone Laboratories (Bell Labs) in New Jersey, Karl Jansky was assigned the job of investigating the natural sources of radio waves and the noise or static that could interfere with radio voice transmissions. In 1930 Jansky was the first to discover radio waves from space, and he identified the radio waves as coming from the center of the Milky Way (Jansky 1933). This marked the birth of radio astronomy as a new research discipline.

In 1946 Martin Ryle at the University of Cambridge increased the resolving power of the new method by combining several radio telescopes. This allowed him to conduct a thorough check of the entire sky. Contrary to his original opinion, the source of the radiation turned out to be not stars but young galaxies (radio galaxies). Their energy source is a massive black hole in the nucleus of the galaxy. According to the Steady State model, galaxies of this kind should be distributed evenly throughout the universe, as they would continuously form anew. According to the Big Bang theory, however, they should be found mainly at remote distances, as they had formed during the early universe. Ryle was able to show in 1961 that the latter is the case (Ryle and Clarke 1961), thus providing strong support for the Big Bang model. Ryle was awarded the Nobel Prize in Physics in 1974. This was the first Nobel Prize to be awarded in recognition of a research achievement highly relevant for astronomy. History repeated itself in 1963 with the discovery of the quasars (radio galaxies that due to their extreme intensity first appeared as local stars) and with them the most distant objects ever observed. This was another serious setback for the Steady State model.

Starting in the early 1960s Arno Penzias was at first the only radio astronomer researching at Bell Labs, and he was also working on optimizing the next technology stage of modern communication: the use of satellites. Penzias was joined in 1963 by radio astronomer Robert Wilson. When Penzias and Wilson began to use the giant horn directional antenna as a radio telescope, they found background "noise" (like static in a radio) in regions of space where no radio waves were to be expected. For a year they made meticulous attempts to find the source of the unexpected and annoying level of radiation, which included making diverse technical modifications to the radio telescope, but all to no avail. Finally, they suspected even the pigeons roosting in the big, horn-shaped antenna of causing the background signal. But it made no difference when Penzias and Wilson removed the pigeons and carefully cleaned out all their droppings. The background radiation remained the same, was not accountable as noise from their instrument, and seemed to come from all directions.

At the end of 1964 Penzias attended an astronomy conference in Montreal and happened to mention the background noise to Bernard Burke from the Massachusetts Institute of Technology (MIT, Cambridge, MA, USA). A few months later Burke telephoned Penzias and told him about reading a preprint by cosmologists Robert Dicke and James Peebles at Princeton University that predicted low-level background radiation throughout the universe as an echo of the Big Bang. Dicke and Peebles were in the process of planning to construct an antenna to look for evidence for the theory. Penzias immediately contacted Dicke and told him that he and Wilson had already found this evidence. Dicke visited Penzias and Wilson at Bell Labs and confirmed one of the most important discoveries in the history of astronomy, or cosmology. Most astronomers had already accepted the idea of an expanding universe. But now, the static model of the universe was disproved once and for all.

Penzias and Wilson published their discovery in 1965 in an article, "A Measurement of Excess Antenna Temperature at 4080MC/S," in *Astrophysical Journal* but without including any cosmological interpretation of their findings (Penzias and Wilson 1965). The interpretation was provided by Dicke and his group in a companion paper published in the same issue of that journal (Dicke et al. 1965). But neither of the two papers cites the work of Alpher and Herman. In the ensuing response in the press, Dicke and Peebles were celebrated as the theoreticians who had predicted cosmic microwave background radiation. Gamow tried to set the record straight and to establish priority for his group's earlier work and predictions. When Penzias learned of the 1949 paper by the two Gamow students (Alpher and Herman 1949), he asked Gamow for more detailed information. In 1978 Penzias and Wilson received the Nobel Prize in Physics for the discovery of cosmic microwave background radiation. Penzias used the opportunity of his Nobel lecture to explicitly acknowledge and praise the contribution made by Gamow, Alpher, and Herman (Singh 2004)—almost 30 years after publication of the first prediction.

## The further research

Further research on the Big Bang model dealt mainly with the question of how today's universe with its marked differentiation into massive galaxies separated by vast empty space could develop out of the homogeneous soup of matter at the beginning state. The spacious structure of the universe could never have resulted from the effect of gravitation alone. For that, there must have been very small variations in the density of the almost homogeneous primordial matter; these variations increased under the effect of gravity and led, in the course of the expansion, to the forming of today's complex structures. If this assumption were correct, then the beginning fluctuations in the density of the primordial matter must have been imprinted on the cosmic microwave background radiation that we see today and thus be provable as a pattern of insignificant temperature differences. But despite many attempts in the 1970s, evidence of these fluctuations could not be found. Detectors carried aloft by balloons and high-altitude airplanes sensitive enough to detect differences in radiation down to one-tenth of a percent and finally one–one-hundredth of a percent found completely homogeneous radiation.

Gradually it was recognized that only satellite-supported measurements could yield the necessary data. Interference within the Earth's atmosphere allowed no further increase in the chance of detecting the evidence with the carrier systems previously used. NASA was willing to back the experiment in the framework of the space shuttle program and after some years was finally ready to schedule the launch of a satellite. However, when the space shuttle *Challenger* exploded in 1986, the project had to be adjourned. Finally, a satellite launch rocket was provided, and in 1989 the Cosmic Background Explorer (COBE) satellite was successfully launched into orbit. After two years of measurements, cosmic microwave background radiation was found that varied by 0.001%. After careful analysis and checking of the data, the results were announced at a conference organized by the American Physical Society on April 23, 1992, and published in that year (Smoot et al. 1992; Wright et al. 1992). Meanwhile, the COBE data have been confirmed and upgraded by the cosmic background radiation mapping results of the WMAP satellite launched 2001. As a consequence of the various discoveries, the old notion of an eternal and unchanging universe had eventually been replaced by a dynamic universe that had a definite beginning. This new cosmological standard model offers the best explanation of the observed data: the expansion of the universe, cosmic microwave background radiation, the chemical elements, and the clumpy arrangement of matter.

With the discovery of the pattern of fluctuations in the cosmic microwave background radiation, the research in this area did not come to a standstill. At the start of the 1980s Alan Guth developed the theory of the inflationary universe (Guth 1981). According to the theory, in the very earliest moments of the universe there was a phase of much more rapid inflation than in the following expansion phase. The relatively small variations in the background radiation show that the universe must have come into being out of a region smaller then previously assumed. At present no information is available about the time prior to the decoupling of the background radiation from matter. But according to inflation theory, gravitational waves generated during inflation should have left traces in the form of tiny disturbances in the background radiation. This is what the Planck satellite launched by the European Space Agency (ESA) in the year 2009 was designed to detect.

What is mainly still problematic is the singularity (an unphysical state at the moment of creation), with which space and time first began and which raises the question as to what was before the Big Bang. Also still a mystery is *dark matter* (for the first time proposed by Fritz Zwicky in 1933), the existence of which was necessary to assume because the mass of the visible stars of galaxies is not enough to keep the stars at the rim of the galaxies in their orbits. In the late 1990s, astronomers set their sights on remote supernovae and reached the conclusion that the universe is apparently expanding at an increasing rate. The repulsive driving force for this was postulated to be *dark energy*. Whereas its nature is still a mystery, dark energy is the most probable cause of the ever-increasing rate of the expansion of the universe that must be concluded based on recent measurements of the recessional velocity of supernovae. The spacious distribution of the galaxies and the characteristics of the cosmic background radiation result in the specific composition of cosmic matter as stated by the current cosmological standard model: 5% classical matter, 21% dark matter, and 74% dark energy (according to Einstein, energy and matter are equivalent). The cryptic nature of both dark matter (possibly unknown elementary particles) and dark energy (possibly a specific field or the vacuum energy) as the main components of the universe are driving forces for further research.

## Bibliometric analysis of the cosmology publications

Table 1 shows the total, average, and relative citation counts for the 27 cosmology papers included in the historical reconstruction in "From the static view of the universe to the Big Bang theory" above. To assess which of the 27 papers—in the opinion of peers—made a particularly significant contribution to the transition from the static view of the universe to the Big Bang theory, of interest are mainly the relative citation counts in the period from 1961 to 2008 (that is, in the time of "big science;" see "The technique of bibliometric analysis" above). As the paradigm shift was initially concluded with publication of the papers by Penzias and Wilson (1965) and Dicke et al. (1965), the citation counts after 1960 can yield information on what publication was later assigned especially great importance: If the citation count after 1960 for a publication is (far) above average, then in the eyes of the scientific community it contributed greatly to the paradigm shift.

As Table 1 shows, in the list of cosmology papers sorted by publication year, the paper by Einstein (1917) is the first paper with an above-average citation count. Especially in the time period after 1960, the paper achieved a high relative citation count of 2.161. This can be attributed mainly to the fact that discussion today on dark energy has renewed interest in and increased discussion of the cosmological constant introduced by Einstein in that paper (see above). Einstein's work was realized also for gravitational lensing and the energetics of high-energy sources such as X-ray binaries and black holes. But the paper (Einstein 1917) was already cited with above-average frequency prior to 1960, as it established the model of a static eternal universe. Hence, the paper can be assigned importance mainly in the context of the "old" paradigm.

The next papers in Table 1 with above-average citation counts are the papers by Friedmann (1922, 1924) on the possibility of an expanding universe. It is interesting that these papers were cited with an above-average frequency only after 1960 (and not before). Friedmann deserves recognition for providing a radically new interpretation of Einstein's field equations and for the vision of a changing, dynamic universe, a notion that Einstein had disliked. Friedmann's revolutionary paper of 1922 marked the first crucial step in the paradigm shift, a step that gained appropriate recognition after 1960 in the form of citations.

In comparison, the papers by Lemaitre (1927, 1931), as Table 1 shows, were cited much less frequently than Friedmann's papers written earlier. Although "Lemaitre had moved far beyond Friedman's earlier work" by "setting his Big Bang within a framework of physics and observational astronomy" (Singh 2004, p. 160), Friedmann had arrived at the model of a dynamic universe some years earlier. Friedmann deserves recognition for priority of discovery (see here Merton 1957), as the first scientist to have put forward the notion of a dynamic universe. Also, Lemaitre's (1927) paper predicting the recession of the galaxies was published in an (at the time) relatively invisible Belgian journal, *Annales de Societé Scientifique de Bruxelles*). But Lemaitre's paper, "The beginning of the world from the point of view of quantum theory", published in *Nature* in 1931, also received hardly any notice (only 20 citations from time to publication up to the end of 2008; see Table 1). However, in contrast to Friedmann, Lemaitre later gained public recognition for his contribution, although not in the form of recognition by scientific peers (that is, citations).

The papers by Slipher (1912, 1917), Leavitt (1912), Hertzsprung (1913), Wirtz (1921, 1924), and Lundmark (1924) were cited only rarely (see the total citation counts in Table 1). As the relative citation counts for these papers for the period up to 1960 reveal, these papers apparently hardly gave impetus to fundamental cosmological discussions in the context of the "old" paradigm. In addition to that, their contribution to the paradigm shift was judged less significant in comparison with other papers (e.g., Friedmann 1922), as the low relative citation counts for the period after 1960 show. These papers have to be seen as forerunners of the publications by Hubble (Hubble 1925, 1926, 1929; Hubble and Humason 1931). Three of the four papers by Hubble were cited after 1960 a far above-average number of times; the paper of 1925 is by far overshadowed by Hubble's summarizing paper of 1926 (see Table 1). In the period up to 1960, only Hubble's 1931 paper was cited an above-average number of times. Relatively speaking, the paper of 1926 is the publication that in the run-up to the paper by Penzias and Wilson (1965) has the greatest impact after 1960: The relative citation count for the 1926 Hubble paper is 2.434. This paper provided the foundation for the later papers by Hubble, and it has fundamental importance for all of modern astronomy.

After Hubble, the paper by Alpher et al. (1948) provided a second, independent (although *indirect*) confirmation of the Big Bang model, and the citation count after 1960 is accordingly above average (see Table 1). Because this paper received a lot of attention due to the discussion of papers on the Steady State model published at the same time by Bondi and Gold (1948) and Hoyle (1948, 1949), it was cited a far above-average number of times after 1960. The two other papers by Alpher (and Herman) (Alpher 1948; Alpher and Herman 1949) were not cited more than an average number of times either prior to or after 1960. In the period from 1949 to 1964 (cosmic microwave background radiation was discovered in the year 1964) the paper by Alpher and Herman (1949) was cited only five times, and two of these citations were self-citations. The paper was cited the remaining three times in connection with the problem of nucleosynthesis and not because the paper predicted background radiation. The Alpher-Hermann paper arose in a widely known research environment and was published in a journal (*Physical Review*) that was already a leading worldwide physics journal. But it belonged to the group of publications that were overlooked for a long time and did not receive the recognition that they deserved in the form of citations.

The papers by Bondi and Gold (1948) and Hoyle (1948, 1949) were cited a far above-average number of times in the period up to 1960; they are the papers that received the highest relative citation counts up to 1960 of all of the papers. (The paper by Fowler was not included in the citation analysis, because it has to be assigned to classical nuclear physics and not cosmology.) The Steady State papers were compatible with the paradigm of a static universe. After 1960 the papers were cited clearly more rarely, but two of them were still cited a far above-average number of times (see Table 1). This is probably because the Steady State model was very attractive to cosmologists of the time: It gave up the bizarre notion of a Big Bang and was nevertheless compatible with the recession of the galaxies. The papers by Jansky (1933) and Ryle and Clarke (1961) are very important for radio astronomy, but they are more technical papers. It is probably for that reason that they were cited rather rarely as compared to the cosmology papers examined here (see Table 1).

As expected, the two papers that are generally seen in connection with the paradigm shift from a static universe to modern cosmology—Dicke, et al. (1965) and Penzias and Wilson (1965)—received a far above-average number of citations. The paper by Penzias and Wilson (1965) has a very high relative citation count of 5.706 (in total, the paper was cited 870 times up to the end of 2008). The paper by Dicke et al. (1965) also received a far above-average number of citations in comparison with the other papers examined here: It has a relative citation count of 2.204. The citation history for both of these papers of 1965 shows that they gained considerable recognition in the form of citations rapidly. These papers provided decisive (and theoretically predicted) evidence in favor of the Big Bang; the Big Bang model became established. The papers, and mainly the paper by Penzias and Wilson (1965), thus became important references for modern cosmology.

## Discussion

According to Kuhn's (1962b) paradigm theory, the development of science builds on normal science and scientific revolutions. During normal science, research takes place within a given paradigm, with scientists making rather small changes to the dominant theory (law, model, etc.) in their domain (Andersen and Evans 2009). When too many problems and deviations from the theory (falsifiers or anomalies) are identified, a scientific crisis ensues, and eventually, the older paradigm will be replaced by a new paradigm. Starting out from a recently published News Feature in *Nature* (Marris et al. 2008), in this paper we examined the question of whether we can in fact assume that there are scientific revolutions "which truly 'turn the world upside down'. Does it sometimes happen… that scientists must really 'forget everything that has been learned… and start all over again'?" (Ziman 2000, p. 274). For the appraisal we conducted a historical reconstruction of the paradigm shift from the static view of the universe to the Big Bang theory in cosmology and a citation analysis of the most important cosmology papers connected with that shift.

As the historical reconstruction in "The transition from the static view of the universe to the Big Bang theory—a historical reconstruction" showed, when Einstein applied general relativity to model the behavior of the entire universe (Einstein 1917), the static universe could be maintained only by adding a cosmological constant. Considering this arbitrary assumption, Friedmann (1922, 1924) and Lemaitre (1927, 1931) independently proposed theoretical models of a dynamic universe. Friedmann's paper of 1922 in particular marked the first decisive step to the paradigm shift and accordingly gained strong recognition in the form of citations after 1960. The initially relatively small response to Friedmann's papers (prior to 1960) can be attributed to the fact that his model was at first not verifiable, that it was criticized by Einstein, and that Friedmann was not an astronomer or physicist. The scientific community was fixated on Einstein's static model. However, the empirical discovery of the recession of the galaxies by Hubble (1929; Hubble and Humason 1931) strongly implied a dynamic model. The importance of this step for the shift from a static to a dynamic universe is reflected clearly in the relatively high citation counts (mainly after 1960). That Hubble's papers were not immediately (prior to 1960) cited in accordance with their significance we attribute to the fact that the notion of a Big Bang was at first too bizarre; the majority of cosmologists at first assumed that there were less spectacular reasons for the recession of the galaxies. In addition, a gigantic explosion as creation was seen as unsatisfactory, for it was associated with a more destructive than creative impetus.

Also, Hubble did not wish to venture on the interpretation of his findings and steered clear of drawing conclusions of a cosmological nature.

The Steady State model was an attempt to explain the recession of the galaxies in the context of creation without a Big Bang (Bondi and Gold 1948; Hoyle 1948, 1949). For this reason, the papers on this model had far above-average citation counts mainly prior to 1960. The above-average response to two of these papers also after 1960 can be explained by the fact that Hoyle, although he was an advocate of the Steady State model, unintentionally provided corroboration of the dynamic model with his contributions on nucleosynthesis. A far above average portion of so-called negative citation may play a significant role here, too. The discovery of the cosmic microwave background radiation by Penzias and Wilson (1965) provided the last and unequivocal evidence in favor of the dynamic model. The citation count for the paper by Penzias and Wilson (1965) was accordingly far above-average after 1960. The dynamic model provided the best explanation of the observed data to date (expansion of the universe, clumpy arrangement of matter).

All in all, the citation analysis of the cosmology papers indicates that a paradigm shift is not a short-term revolutionary process but instead a process that takes a longer period of time (in the present case, from 1917 to 1965)—starting with the proposal of a new dominant theory and the later publication of empirical evidence that in the end leads to confirmation of the theory (see here Chen, et al. 2009). For as long as a competing theory has not been validated by conclusive experimental results, recognition of the theory by peers (above-average citation impact) is not expected (see, for example, the citation impact of papers by Friedmann 1922, 1924, in the period prior to 1960). An exploratory study of the characteristics of paradigms in theoretical high energy physics by Crane (1980) came to the same conclusion: “We find that the fundamental principles of the field have not been questioned for decades, while exemplars are rejected if they prove to be untestable or if they are not confirmed” (p. 48). Similarly, Kuukkanen (2007) wrote in a theoretical paper: “If the whole system of beliefs is taken as presumptively justified, it is rational to attempt to improve the justification of the old system, rather than to reject the whole system and try to construct an alternative one … Any evidence that suggests radical changes to the accepted system is likely to be resisted” (p. 558). A paradigm shift is to be expected only when there is a competing theory that not only makes specific predictions based on calculations that have a high level of precision in terms of the standards of the field but also has shown quantitative agreement with convincing experiments, like those published in cosmology by Hubble (1926, 1929; Hubble and Humason 1931) and finally Penzias and Wilson (1965).

A discipline is reserved in its judgment of theories (models, laws, etc.) not least because science must necessarily be conservative, so as not to be continually disrupted by a flood of new theories and constantly having to change positions. It is therefore not pure blindness and stubbornness that make researchers restrained in their response; there is a purpose to it. Leading up to a paradigm shift a number of works usually have to be published that have contributed significantly to theory and empirical investigation (see here Ziman 2000). The discovery by Penzias and Wilson (1965) is often equated with the paradigm shift from a static universe to modern cosmology. However, their (rather accidental) discovery was the culmination of a long development across all of modern cosmology. After publication of Hubble’s papers (1929, Hubble and Humason 1931) the model of a static universe could no longer be maintained, but it remained uncertain whether the universe had a temporal beginning. But there was increasing evidence in favor of the Big Bang model. Finally, the existence of the cosmic microwave background radiation was such compelling evidence that the contest between the two theories had been decided.

Hence, Penzias and Wilson (1965) did not have to take a fundamentally (radical) new point of view but merely make a correct interpretation in the context of the theories on offer. The "Copernican shift" in cosmology had already been introduced by Friedmann (1922, 1924) (as the first to do so) and Lemaitre (1927, 1931) (some years later), in that they allowed (in contrast to a static view) a development of the universe from a singularity—the creation of the world through the Big Bang. Hence, in the transition from a static universe to modern cosmology what is discernible is not THE revolution but rather a sequence of mini revolutions (reflected in far above-average citation counts) that in their sum total appear to be THE revolution. Correspondingly, there is no one point in time for the transition but rather a sequence of important points in time up to the transition (see here also Crane 1980).

The term "scientific revolution" is associated with radical changes that relative to the history of a discipline or the period of modern science should be altogether rather short. If the transition from the static view of the universe to the Big Bang theory is seen as a revolution, then it comprises the entire time period of modern cosmology and is not restricted to a certain point in time. As the historical reconstruction and the citation analysis in this study have shown, the transition in cosmology can be linked to many different persons, publications, and points in time (Kuhn 1962a). Our results thus tend to indicate that there was not *one* scientific revolution in cosmology and that the paradigm shift occurred instead as a slow, piecemeal process. This observation concerning the developments in cosmology can also be applied to the developments in other disciplines, such as the development of the concept of "light quanta." According to Hentschel (2005a, b), the concept of the light quantum also did not emerge suddenly at one or two definite points in time but matured out of a network of developmental strands of ideas. With these strands Hentschel distinguishes many different layers of meaning of light quanta that developed over a longer period; the concept matured in a stepwise enrichment of these layers (Hentschel 2006, p. 2). It was Einstein who in one of his famous papers of 1905 (Einstein 1905a) first drew together all these individual strands into a first halfway consistent quantum theory of radiation. It would be wrong to reduce the discovery of the light quantum concept to Einstein's paper just as it would be wrong to equate the discovery of the recession of the galaxies or the cosmic microwave background radiation with the cosmological revolution from the static view of the universe to the Big Bang theory.

Within the history of modern science it is difficult to find examples that confirm Kuhn's model of comparatively long "normal" periods of unspectacular "tidying up" work, interrupted only every once and a while by revolutions. Upon closer examination (as we have done in this study), the radical changes for the most part have long and complicated previous histories, or run-ups, and the development afterwards proceeds smoothly into the run-up to the next radical change. On the contrary, this does not preclude more quickly occurring shifts, however, they seem to be rare. In a similar way, in an investigation of the BCS theory of superconductivity and the non-conservation of parity Moravcsik and Murugesan (1979) come to the conclusion: "It would appear, therefore, that the simple universal model of 'paradigm change' is too unsophisticated to explain satisfactorily the nature of scientific revolutions" (p. 165).

**Acknowledgments** The authors wish to express their gratitude to the reviewer for his helpful comments. We thank Armin Burkhardt, Karl Syassen (both Max Planck Institute for Solid State Research, Stuttgart, Germany), Hermann Nicolai, Stefan Theisen (both Max Planck Institute for Gravitational Physics, Golm, Germany), and Klaus Hentschel (University of Stuttgart) for careful and critical reading.

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