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CONTEMPORARY COSMOLOGY AS A CASE STUDY IN SCIENTIFIC METHODOLOGY

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CONTEMPORARY COSMOLOGY AS A CASE STUDY IN SCIENTIFIC METHODOLOGY

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by

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Abstract

This thesis examines two recent research projects in cosmology with the aim of presenting them as a case study of the use of evidence in science. Descriptions of scientific reasoning commonly use language reminiscent of simple hypothetico-deductive methodology. However, a number of philosophers of science have argued that this model of scientific reasoning is inadequate. In particular, recent work has looked to the methodology of Isaac Newton for an addition to the standard hypothetico-deductive account. This methodology seeks to deliver a richer notion of empirical success through providing warrant for scientific claims on the basis of the ability of a theory to deliver agreeing measurements of its theoretical parameters from diverse and independent sources. One aspect of recent work in cosmology is the introduction of specific measurements of a positive value of the cosmological constant, Λ, a theoretical parameter that, prior to recent results, most cosmologists either ignored or assumed to be set at zero. This thesis claims that, in accordance with Newton's methodology, it is through the use of this richer notion of empirical success that the current research provides empirical support for the inclusion of the parameter and for the standard cosmological model in general.

The thesis examines the core of the course of cosmological reasoning regarding the relationship between observation and the mass-energy density parameters of the universe. Following an introductory chapter, Chapter Two reviews the standard cosmological model prior to the recent work on Λ, with a focus on the use of agreeing measurements in this research. Chapter Three reviews recent cosmological research on type Ia supernovae and the use of these events to produce measurements of cosmological parameters. Chapter Four reviews recent cosmological research on the cosmic background radiation and the use of phenomena related to the background radiation to produce measurements of cosmological parameters. Chapter Five reviews the use of the agreement in the measurements produced by these theories and the nature of the empirical support that this agreement delivers to the standard cosmological model against systematic error and against alternative theories that may be potential rivals of the standard cosmological model.

Keywords: Philosophy of Science, Cosmology, Isaac Newton, Evidence, Methodology of Science, Empirical Success, Standard Cosmological Model, Cosmological Constant

Dedication

This work is dedicated to my wife, Rebekkah: all the universe I will ever need.

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My heartfelt thanks and appreciation for the work of my advisors, Bill Harper and Wayne Myrvold. Their instruction and questions have made me a far better philosopher than I would otherwise have been.

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Chapter One: Cosmology and Empirical Success

Cosmology, as the science of the universe at the largest scales, involves claims about the physics of regions of the universe far removed from those regions where we perform the bulk of our physics experiments. The physical systems in these distant areas are often quite different from our own and the physical relationships involved in cosmology are often at a much greater scale than those physical relationships of what we might call local physics. Evaluating the evidence for these claims thus involves the challenge of supporting novel claims in novel circumstances; this challenge, one not unknown in science, may seem more daunting in the case of cosmology.

One response that cosmologists and philosophers have produced to meet this challenge is to point to not merely the predictive success of cosmological theory, but to point also to the ability of cosmological theory to provide a convincing account of remote physical systems through the coherence of the theoretical explanation from the evidence. Such claims rely on the idea that the ability of a theory to provide a coherent account of the physical system provides an understanding of the system beyond the ability to provide predictive success with that theory on a case-by-case basis. Ernan McMullin uses the following example in his discussion of coherence in cosmology:

> Even more significant [than the increase of observational evidence in cosmology], perhaps, is the impressive *coherence* of the emerging picture. When, for example, pulsating radio-frequency sources ("pulsars") were discovered in 1967, they were explained in a matter of months as tiny neutron stars only a few miles across, the remnants of supernova explosions. The theory of such stars had been worked out by Zwicky, Oppenheimer, and others in the 1930's on the basis of the quantum theory of terrestrial matter. Despite the fact that nothing remotely like the extreme conditions of energy, gravitation, and density, of the super-nova [*sic*] or the neutron star can be recreated in the laboratories of earth, the hypothetical

> extension of the basic theories of terrestrial physics to these quite unfamiliar conditions accounts beautifully and convincingly for pulsar phenomena.[1]

Though we may view this as a merely astronomical or astrophysical example and not a cosmological one, the challenge here of novel circumstances is, if not exactly the same, very similar to that which one faces for cosmological claims. This seems to be the position of McMullin, as he includes this example in an essay on cosmology in order to advance his argument about the nature of cosmological evidence. If we may elaborate on McMullin's point, we see that the success of this astrophysical account of pulsars lies in not simply the predictive success of quantum theory (among other theories) in the discovery of new phenomena, the pulsars, that are predicted by the logical extension of the theory, but by a host of other phenomena that also take part in the explanation of pulsars, e.g., the remnants of supernova explosions and the gravitational influence of the dense neutron stars that act as pulsars.[2] Thus this sort of coherence is the origin of why the extension of physics determined locally accounts for pulsars "beautifully and convincingly."

McMullin identifies the key for such success in hypothetico-deductive inference, specifically through the retroduction that hypothetico-deductive inference makes possible.[3] According to McMullin, hypothetico-deductive inference, not inductive generalization, is what allows one to approach novel circumstances scientifically. While he recognizes that induction from specific cases to general cases is an act of extending

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[1] McMullin, Ernan. 1981. Pg. 179. Emphasis in original.

[2] The use of binary pulsars as evidence for the General Theory of Relativity is discussed in detail in Chapter 12 of Clifford M. Will. *Theory and Experiment in Gravitational Physics*. Rev. ed. Cambridge [England]: Cambridge University Press, 1993.

[3] McMullin, Ernan. 1981. Pg. 180.

concepts from known cases to unknown cases, McMullin does not see this as integral to providing warrant to claims about novel circumstances. For those cases where it is possible to investigate a physical system through a variety of means, McMullin identifies the warrant of a scientific claim in a novel circumstance in the ability of a hypothesis to explain features of that circumstance. Specifically, McMullin argues that such circumstances call for a hypothetical structure, "a set of constituent entities or processes and the relationships between them."[4] Structures do not merely dictate laws, they dictate the relationships between the constituents of physical systems and they are to be evaluated on their ability to provide a good account of the physical systems that they purport to explain. From this it follows that warrant is granted to the scientific claims that lay out a structure on the success of the structure in explaining a physical system, novel or otherwise. (We may identify this, using McMullin's nomenclature, as *hypothetico-structural* methodology.)[5] McMullin writes,

> The explanatory power of a structural theory is not just a matter of the successful prediction it enables one to formulate at some specified time. A good structural model will display resources for imaginative extension over a considerable period... The warrant for the retroductive claim that a particular structural theory is highly confirmed comes not just from the extent of its present predictive power but from the sequence of its past development and (to a lesser extent) from its promise for the future.[6]

Taken as a hypothetico-deductive account, we may summarize McMullin's position as follows: certain structures are warranted not simply by their ability to produce success through predictions, but by their ability to produce a host of coherent predictions about physical systems that derive from the nature of the physical system as given by the

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4 McMullin, Ernan. "Structural Explanation." American Philosophical Quarterly 15, no. 2 (April 1978): 139-147. Pg. 139.

5 Ibid., pg. 139.

6 Ibid., pg. 146.

structure. In the case of pulsars, the extension of quantum theory of terrestrial matter to this novel circumstance is done through the creation of a hypothetical structure, the neutron star, that can be the centre of predictions derived from the explanation this structure provides, e.g., that the remnants of a supernova should surround a young pulsar.

It is the purpose of this work to present an account of the coherence of recent cosmological investigations, and the use of these investigations to promote the inclusion of the *cosmological constant*, as a case study of what might be identified as Newtonian methodology, the use of agreeing measurements of theoretical parameters to advance empirical support for scientific claims. Such a claim is contrary to the position of McMullin, as he explicitly contrasts the methodology of cosmology, a methodology that he identifies as hypothetico-deductive (or hypothetico-structural), with Newton's account of scientific inference.[7] He writes,

> It is worth noting that this [coherence] is not mere induction, not the simple analogy of Nature that Newton postulated in his Third Rule of Reasoning whereby the qualities found "to belong to all bodies within the reach of our experiments are to be esteemed the universal qualities of all bodies whatsoever." Inductive generalization, which Newton wrongly believed to be the principal method of empirical science, can only postulate more of the same elsewhere and can be validated only by endless and uncertain sampling (unless one lays down risky *a priori* principles of homogeneity). Hypothetico-deductive inference (retroduction) can on the other hand establish the existence of structures and processes altogether different from any that lie within direct reach, and is limited only by the resources of the scientific imagination and by the richness of the causal connections between the postulated structures and the accessible world of our apparatus.[8]

Under McMullin's interpretation of Newton, Newton's methodology does not go far beyond inductive generalization. Recent work by William Harper and by George Smith

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[7] The term "hypothetico-structural" comes from the earlier McMullin work and is not used in the work on cosmology.

[8] McMullin, Ernan. 1981. Pp. 179-180.

suggests otherwise.[9] In this work, we will follow the characterization of Newtonian methodology given by Harper and Smith, which shows that Newton adopts an account of hypothetical structure not unlike that advocated by McMullin. Indeed, this Newtonian methodology goes beyond McMullin's hypothetico-structural account by addressing more directly what it means for a theoretical structure to represent a physical system in a way that ties this representation to the empirical success of a theory.

According to the work of Harper and of Smith, Newton's ideal of empirical success relies on creating theoretical extrapolations from existing data that could act as ongoing guides for research and that could deliver continued accurate and agreeing measurements from a number of independent phenomena. The focus of this ideal is not predictive success, though that obviously plays a role in empirical success, but on success in terms of robust measurements of both phenomena and theoretical parameters. One key element of this methodology is the definition of phenomena as regularities in existing data that are expected to continue into the future. The mathematical properties of phenomena are given by their theoretical description and this is used to transform the fit of these regularities to existing data into measurements of phenomena. Given such phenomena, Newton's methodology seeks to transform measurements of the phenomena into measurements of theoretical parameters through systematic dependencies between the phenomena and theory. In the ideal case, approximate measurements of the phenomena produce approximate measurements of the parameters of the theory.

This transformation of measurements of phenomena into measurements of

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[9] Harper, William. 1990. Harper, William. 2002. Harper, William. 2007. Smith, George E. 2001.Smith, George E. 2002.

theoretical parameters is another key element of the methodology. These transformations serve as the "resources for imaginative extension over a considerable period" that a good structural theory should provide. Theoretical parameters are those mathematical quantities associated with a theory that are used in constructing an explanation of the relationship of the elements of any physical system that the theory purports to explain. The empirical success of the theory is then governed by whether or not independent measurements of these parameters agree with one another.

Here we see an important addition to the hypothetico-structural account of McMullin: the hypothetico-structural account provides warrant based on the coherence of successful prediction based on the elements that arise from the explanation of a physical system provided by the structure, and the Newtonian account provides warrant not simply from this coherence but specifically from the coherence of measurement results. How well the theoretical structures accurately approximate the physical system can be determined by how well the parameters of the theory are measured from the physical system and how well measurements of other elements of the physical system back up these measurements, elements that are independent in the sense that they rely on different systematic relationships between the physical systems and the resulting measurements. Additionally, the use of such independent sources of measurement provides a robustness to these measurements of theoretical parameters, and to the theory underlying them, because it reduces the possibility of systematic error influencing measurement results: systematic error would have to be coordinated between the different systematic relationships used to provide the measurements of the theoretical parameters. Accordingly, this shows the theoretical parameters to be causally relevant to the accurate representation of the physical systems that the theory purports to explain as they are more likely to provide an account of the dynamics of the physical system than unknown factors. The focus on agreeing measurement results provides a natural way to distinguish, on empirical grounds, between different structural accounts that might provide an explanation for the same data that is not obviously available in McMullin's account. A commitment to agreeing measurements allows us to compare theories on not only the accuracy of their predictions but also on the extent to which each theory provides agreeing measurements of their theoretical parameters. A theory that fixes parameters from multiple independent sources has naturally met a higher standard of comparison with the available evidence.

Newton used this methodology to establish his theory of universal gravitation—the unification of terrestrial gravity with the forces keeping the planets in roughly circular motion.[10] In so doing, he made use of the demonstration that both terrestrial phenomena and celestial phenomena provide accurate agreeing measurements of the same force.

This use of phenomena to provide a unifying account of a single force addresses an important epistemic hurdle for astronomy and cosmology: identifying those physical laws that are causally relevant to the dynamics of remote physical systems and providing warrant for that identification. In this work we will be examining the attempt by cosmologists to identify the influence of the cosmological constant in distant physical systems and to provide justification for the use of the cosmological constant. These recent attempts appeal not simply to coherence but to the ability of investigations relying on different systematic relationships to produce accurate measurements of cosmological

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10 Newton, Isaac. 1999. See also George E. Smith (2002) and William Harper (2002).

parameters.

The cosmological constant, Λ, is a parameter of the General Theory of Relativity.[11] Though not present in the earliest forms of the theory, Λ arises as a simple generalization of the Einstein Field Equation, the equation that relates the behaviour of the geometry of spacetime to its contents.[12] If positive, the natural role of Λ is a measure of the strength of a metaphorical anti-gravity force driving distant objects apart. Given its potential to balance out the pull of gravity, Einstein introduced the parameter into his theory in order to gain an additional degree of freedom that would allow him to create a static, essentially unchanging model of the universe. Such a model would match what Einstein took, at that time, to be the likely structure of the universe. When, under pressure form empirical results and theoretical challenges, Einstein's initial model seemed untenable, Einstein abandoned the constant and urged others to reject its use. In the words of John Earman from his review of the history of Λ, this began "the most checkered history of any constant in physics."[13] Following Einstein's use of Λ, many cosmologists over the years have used Λ to fit a model to meet some cosmological restriction[14]. Often these same cosmologists abandoned Λ when some new observation or theoretical concept provided the means around the restriction and made the use of Λ extraneous. The rise of quantum field theory also lead to problems for Λ. It is possible to represent Λ as a measurement of the energy density associated with the vacuum of empty space—which according to quantum theory must be not truly empty but a roiling sea of particles that flash into and out of existence. As a measurement of this vacuum energy, Λ is often referred to as "dark

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[11] Will, Clifford M. 1993.

[12] Earman, John. 2001.

[13] Earman, John. 2001. Pg. 215.

[14] Examples of this are found throughout John Earman, 2001.

energy". Unfortunately, estimates for the density of energy in the vacuum from quantum theory differed wildly from those estimates from astronomy.[15] While the theoretical predictions derived from quantum theory were not definitive, the difference in the possible values of the parameter certainly discouraged many from including the parameter in cosmological theory. For these and other reasons, the inclusion of the cosmological constant was not widely accepted in the cosmological community.

When recent results strongly favoured a positive cosmological constant, the cosmologists producing those results noted the extra burden that they faced in presenting those results. For example, in their report of their results in 1999, the authors of the Supernova Cosmology Project write,

> Given the potentially revolutionary nature of [the conclusion that $\Lambda > 0$], it is important to reexamine the evidence carefully to find possible loopholes. None of the identified sources of statistical and systematic uncertainty described in the previous sections could account for the data in a $\Lambda = 0$ universe. If the universe does in fact have zero cosmological constant, then some additional physical effect or "conspiracy" of statistical effects must be operative—and must make the high-redshift supernovae appear almost 0.15 mag (~15% in flux) fainter than the low-redshift supernovae. At this stage in the study of SNe Ia, we consider this unlikely but not impossible.[16]

The authors identified the radical nature of their conclusion and the need to address the audience about the possibility for error or alternative explanation. According to a historical account of the supernova measurements written by Robert Kirshner, a member of rival group the High-*z* Supernova Search Team, both teams resisted publishing their results based on the evidence requiring a cosmological constant for at least a year.[17]

However, by 2003, the cosmological constant had become widely accepted in the

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[15] Carroll, Sean M. , William H. Press, and Edwin L. Turner. 1992.

[16] Perlmutter et al. 1999. Pp. 581-582.

[17] Kirshner, Robert P. 2004.

cosmological community. Kirshner illustrates this acceptance with an anecdote:

> "We've done these calculations in a standard Λ-cold dark matter universe." The energetic young speaker at the front of the Philips Auditorium at the Center for Astrophysics, Kathryn Johnson, a professor from Wesleyan, was setting the stage for presenting her new results on galaxy cannibalism. There were 100 people in the room for the Thursday Astronomy colloquium, Kathryn had a lot of new results to share, and she wasn't wasting any of her time or theirs by justifying the cosmology she had assumed.
>
> Nobody blinked. Nobody asked a question. But my mind, always unreliable after 4 p.m. in a darkened room, started immediately to drift into speculation. How could a "Λ" universe, two thirds dark energy and one third dark matter be the "standard" picture in the autumn of 2003? Just 5 years earlier, cosmic acceleration had seemed unbelievable, and dark energy, in its guise as the cosmological constant, had been a notoriously bad idea, personally banished by Albert Einstein. What had changed?[18]

According to the picture painted by Kirshner, the cosmological constant went from disrepute to acceptability in the space of a few years. Kirshner does not cite increased accuracy or elimination of systematic error within the supernova results as the main reason, even though he notes that there had been such improvement in the results. Kirshner attributes the success of Λ in the cosmological community to "a sudden convergence of many independent lines of research on the very same values for the contents and age of the universe, weaving a web of evidence."[19] Like McMullin, Kirshner emphasizes the coherence of the evidence rather than its amount or quality and, like Newton, Kirshner highlights the convergence of measurements of parameter values.

While Kirshner discusses a few different cosmological projects, he identifies the primary cause of the change in attitude within the cosmological community as the scientific results of the Wilkinson Microwave Anisotropy Probe and the agreement

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[18] Kirshner, Robert P. 2004. Pg. 262

[19] Kirshner, Robert P. 2004. Pg. 264

between the results it produced and the earlier results. This satellite makes detailed observations of the background radiation of the universe in order to produce measurements of cosmological parameters. Of the agreement between the measurements, he writes,

> Even though the [background radiation] measurements don't detect cosmic acceleration directly, as the supernova measurements do, taken together, they point with good precision to a universe with both dark matter and dark energy. Things were fitting together–and the better you measured them the better they fit. Quantitative agreement is the ring of truth. This is the reason why, by the autumn of 2003, our colloquium speaker didn't bother to make the case that a Λ dominated universe was the right picture.[20]

This use of accurate agreeing measurements as the ultimate test of a theory evokes the rich notion of empirical success pursued by Newton. This work is an attempt to provide a meaningful exploration of Kirshner's comments by using this case study to discuss how combining accurate agreeing measurements from multiple sources can add to the support of a theory.

Newton's Methodology

According to Harper's account of Newtonian methodology, there are three key differences in which the methodology of Newton surpasses the pursuit of predictive success associated with a simple hypothetico-deductive methodology.[21] The first is the use of measurements of the phenomena of the physical systems that the theory explains to measure the parameters of the theory. The second is the use of theory mediated measurements to answer theoretical questions. The third is the use of theoretical propositions as guides to future research. The first and third of these differences are what primarily concern us in this work.

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20 Kirshner, Robert P. 2004. Pg, 265.

21 Harper, William. 2007.

The first key feature of the methodology of interest to us is that theory is used not simply to predict phenomena but to get accurate measurements of theoretical parameters from accurate measurements of phenomena.[22] In the Newtonian methodology, the key to achieving empirical success is using the theory to identify those systematic dependencies in the theory that allow us to identify phenomena, in the sense of ongoing regularities in the data that we expect to continue, the measurement of which would count as measurements of the theoretical parameters on which the phenomena depend. In this case, the measurement of phenomena is provided by the best fit of these phenomena to the available data and the measurement of the theoretical parameters is the constraints on the possible values of these parameters allowed given the measurements of the phenomena and the systematic dependencies between these phenomena and the theoretical parameters. As in McMullin's account, these phenomena are the result of a theoretical structure that specifies the relationships between elements of physical systems. Moreover, the success of this identification of phenomena in a physical system is dependent not simply on its direct application, but in the ability of the theoretical structure to deliver in multiple tests of different aspects of the physical system.

In the Newtonian methodology, the restriction to accurate parameter measurements accomplishes two things in addition to the hypothetico-structural account of McMullin. First, by turning parameter measurements into measurements of theoretical parameters, the methodology exhorts us to look for tests of the theoretical structure wherever the theoretical parameters should play a role, not simply in a particular physical system. Second, by assessing the phenomena and the theoretical structure that identifies

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[22] Harper, 2007

the phenomena on the basis of agreeing measurement, the methodology provides a means to restrict the range of tests that count as successful confirmation of the theoretical structure: measurements that restrict theoretical parameters to one range exclude a wide range of theoretical possibilities.

An example of the identification of phenomena as expected regularities can be seen in Ole Römer's derivation of the speed of light.[23] Römer accomplished his measurement of the speed of light by carefully examining the data on the orbit of the moon Io of Jupiter, primarily through observations of when the planet eclipsed the moon. The data shows that the timing of the eclipse is not uniform and that there is a correlation between the time of the eclipse and the position of the Earth relative to Jupiter. Using the assumption that the orbits of the moons of Jupiter were approximately undisturbed circles and that the motion of the moons along these paths were approximately constant, Römer was able to use the difference in the time of the observed event that was correlated to the relative position of Jupiter and the Earth to measure the speed of light. The hypothesis that the speed of light is constant, a theoretical commitment, allows the identification of two phenomena. The first is the expected regularity of the orbit of the moons of Jupiter. That this expected regularity is not exact in the data produces yet another regularity in the data, namely the coordination between the time when an eclipse should be observed and the time when it is actually observed. These two phenomena provide a means of measuring the speed of light because of the systematic dependency between the difference in the time of the eclipse and the difference in distance between Jupiter and the Earth at the time of the event. The measurement of the temporal displacement of the

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[23] Harper, William. 1990.

eclipse provides a measurement of the speed of light. (This example is similar to many in cosmology, in which we are interested in more than simply phenomena that explain the nature of a distant object, we are also interested in phenomena that explain the space between the distant object and ourselves.)

The second key feature of the methodology of interest to us is a commitment to treat supported theory as provisionally accepted for the purposes of future research.[24] This is a two-fold commitment. On the one hand, it demands that the phenomena previously established be used as the basis for future research and investigation. Thus we see the creation of *second-order phenomena* from the data in a manner similar to the way in which Römer identified the discrepancy in the observation of the eclipses of Jupiter's moon above.[25] One other hand, this is a commitment to abandon theory established by the method only in the face of equally well-supported theory. A theory may provide a better fit to the data, something which could count as predictive success, but it cannot supplant existing theory unless it too can recapture the same or similar systematic measurements of its theoretical parameters from the phenomena. Phenomena are of necessity approximations to the data and their measurements provide similarly approximate measurements of the theoretical parameters. The goal of the methodology is to create as accurate an account of the physical systems under investigation as is possible. This means that we continue to support the identification of the phenomena, in the sense that we continue to use them as ongoing regularities in the data, as long as this can be supported by the evidence, including the continued creation of second-order phenomena. It also

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[24] Harper, William. 2007.

[25] The term *second-order phenomenon* taken from George Smith (2002).

means that we abandon our theory when we find better phenomena that more accurately describe the physical system and are supported by theory with better support, or that we abandon theory in favour of a newer theory that has better systematic dependencies with existing theory. Until such time, however, we continue to use our theory as a guide to research in order to produce better successive approximations to the physical systems that we investigate, either through better measurements of the phenomena or the use of the phenomena to identify second-order phenomena that can be used to better measure theoretical parameters.

Newton's Rules for the Study of Natural Philosophy

Rule 1	No more causes of natural things should be admitted than are both true and sufficient to explain their phenomena.
Rule 2	Therefore, the causes assigned to natural effects of the same kind must be, so far as possible, the same.
Rule 3	Those qualities of bodies that cannot be intended and remitted [i.e., qualities that cannot be increased and diminished] and that belong to all bodies on which experiments can be made should be taken as qualities of all bodies universally.
Rule 4	In experimental philosophy, propositions gathered from phenomena by induction should be considered either exactly true or very nearly exactly true notwithstanding any contrary hypotheses, until yet other phenomena make such propositions either more exact or liable to exceptions.

Table 1.1: Newton's rules of reasoning. From Isaac Newton (1999). Translator's clarification included.

One expression of Newton's commitment to provisional acceptance of theory is Rule 3 and Rule 4 of his *Rules of the Study of Natural Philosophy,* often called *Newton's* *rules of reasoning* (these rules are listed in Table 1.1). Newton writes of Rule 4 that, “This rule should be followed so that arguments based on induction may not be nullified by hypotheses.”[26] By extending the theory to new areas, we test it and measure theoretical parameters in new ways and, in a sense, force the issue on whether or not the theoretical constructions that we use to describe and predict the behaviour of physical systems do actually explain these systems. Contrary to McMullin's interpretation of Newton, this is neither validation by “endless and uncertain sampling” or validation by “risky *a priori* principles of homogeneity”; this is a commitment to respect the warrant granted by the agreeing measurements provided by the evidence until greater warrant is given to reject or replace the theoretical structure explaining the relevant physical systems.

Malcolm Forster has investigated similar aspects of this methodology through his examination of William Whewell's philosophy of scientific discovery.[27] According to Whewell, scientific discovery takes place through induction, in a process called *the colligation of facts*, and scientific theories receive empirical support through both predictive success in new areas and through what Whewell calls *the consilience of inductions*.[28] The colligation of facts consists in identifying a phenomena, as a theoretical construction, in a physical system and using the statistical data about that system to fix the parameters of the mathematical equation or equations governing that theoretical construction. As Forster points out, there are two reasons why this process cannot be said to determine the mathematical construction or its parameters.[29] The first reason is that this rpocess necessarily goes beyond the available data, fitting to finite data one of many

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[26] Newton, Isaac. 1999. Pg. 796

[27] Forster, Malcolm R. 1988.

[28] Whewell, William. 1968.

[29] Forster, Malcolm R. 1988. Pp. 70-71.

possible mathematical constructions. The second reason is that identifying a particular formula to express the behaviour of the phenomena involved, regardless of how well this describes the physical system, must be compared to data with some error, whether this error is the result of observational error or the result of other systematic influences on the physical system involved. It is only at the later stage, through the prediction of new cases and, especially, through the consilience of inductions that empirical support is granted to the construction and its parameters. The consilience of inductions is the demonstration that the coefficients measured in a given induction are measured independently in other inductions. That is, empirical support for the applicability of a theoretical construction comes when independent applications of the construction produce measurements of the parameters of the construction that match those of other measurements. This leads to simplicity in the theory, in the sense that one explanation serves for two otherwise independent cases, but this simplicity is the result of the discovery of the identification of common cause, not a criterion applied to chose one theory over another.

One key difference between this methodology and that of McMullin's hypothetico-structural approach is that this methodology ties theory construction more tightly to generating empirical support for the theory. It is not a virtue that hypotheses are novel generations, created from whole cloth to stand against a collection of data. Rather, hypotheses in the form of theoretical constructions, regardless of their origin, stand or fall based on how well they provide the same explanation for a number of cases and this is evaluated by how well the explanation provides agreeing measurements of the theoretical parameters. Because this explanation is tied to the measurement of the parameters of the theoretical construction, this is not risky *a priori* reasoning, but the discovery of phenomena as regularities within the data from the evidence rather than the attribution of these regularities. It is possible to make the hypothesis that two elements of a physical system are explained by the same structure and produce a predictive, or retroductive, success with this hypothesis. Demanding that the hypothesis of structure not merely predict, or retroduce, a relationship but that the hypothesis of structure support a systematic relationship between the elements explained and the nature of the structure is more difficult for the hypothesis to sustain. However, the hypothesis can be sustained by the ability of the elements explained to produce agreeing measurements of the parameters of the theoretical structure. In the process, we can support the claim that there is evidence supporting the underlying theoretical structure not merely because we can fit predictions to the data, but because we can appeal to agreeing measurements through which we can discover in the data the theoretical structure at work. This does not supply certainty, but it does supply what we need to treat the results at least as working hypotheses for future research, results on which we can rely in order to turn data into evidence.[30]

Cosmological Investigations

Over the course of this work, we will be examining two cosmological investigations, what we will call the *supernova investigation* and the *background radiation investigation*. Each of these investigations is the result of a series of projects, papers, and teams (though we will only focus on one team in our discussion of the background radiation investigation), but we identify them in the singular in order to more easily divide the two more-or-less independent sets of investigation. Each investigation proceeds by identifying phenomena in the physical systems of the cosmos that provide measurements of the

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30 Smith, George E. 2001.

parameters of the *standard cosmological model*. The standard cosmological model, which popular science writers often refer to as the Big Bang theory, has as its primary features the global expansion of the universe, the slowing down or acceleration of that expansion at different cosmological eras, and the density of matter and energy on which the behaviour of the expansion depends, including that energy associated with Λ.[31] We will examine this theory in chapter two. Within each investigation, the results produced are obviously dependent on existing cosmological theory; however, cosmologists attempt to offset this dependence through reliance on independent measurements of the parameters of their theory. As such, these two investigations are certainly amenable to presentation as a case study for this Newtonian methodology at work.

The use of accurate agreeing measurement within this methodology addresses how to provide support for theory-mediated measurements in such a way as to avoid the possibility of what Smith calls a "garden path."[32] Such paths are created when the use of theory about phenomena generate, through systematic error or through the design of the theory, positive support for the theory where the theory does not apply. Smith characterizes the worry as follows,

> The main risk is a discovery that would falsify [a particular] law in a way that nullifies all or part of the evidential reasoning that has been predicated on it.[33]

Finding support from a number of independent sources lessens the chance that systematic error is the source of the agreement upon which we have based our research.

The worry of the garden path is the worry of the cosmological skeptic: that the

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[31] Peebles, P.J.E. 1993. Rich, James. 2001.

[32] Smith, George E. 2002. Pg. 162.

[33] Smith, George E. 2002. Pg. 162.

application of physical principles derived locally, or indeed some other cosmological speculation used to create a framework for investigation, creates falsely positive results. As P.J.E. Peebles wrote in 1971,

> It should be apparent from this list that the expansion postulate, while strong, does not enjoy the overwhelming weight of evidence of, say, the quantum principle. What is needed is a more tightly woven web of interconnected results, and one of the major goals of cosmology is still to build this web. Following the almost exclusive practice in cosmology the expansion of the Universe will be adopted below as a convenient reasonable and fertile working hypothesis, but it is well to bear in mind that it is still an hypothesis."[34]

Cosmologists took the need to make theory-mediated measurements, and the fear that they may lead to garden paths, quite seriously. As Peebles indicates, within cosmology there was also the position that avoiding a garden path relied on good evidence from a number of independent sources.

The need for such a methodology within cosmology is one driven by a history of missteps based upon observations riddled with error. The role of these errors can be found in most histories of cosmology and it is discussed in the context of the role that theory plays in determining observations by Helge Kragh.[35] In particular, Kragh points out that it is not merely that the reports of observation are mistaken, it is that they are believed too confidently. One example Kragh chose of this cleaving to tightly to the reports of observations is that of the early determinations of the Hubble constant. He writes,

> Hubble's value of the expansion parameter, wrong by a factor of seven or so, was accepted as unproblematically [*sic*] correct for more than two decades. The small value of the Hubble time caused problems for cosmologies of the Big Bang type, which might have been received more positively had astronomers not taken Hubble's result to be so

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[34] Peebles, P.J.E. 1971. Pg. 27.

[35] Kragh, Helge. 2007.

authoritative.[36]

In this case, the determination of the expansion rate of the universe placed limits on the possible age of the visible universe and galactic development that, while still fairly broad, were in conflict with the results of geology on the age of the Earth in addition to astrophysical theories about the age of the stars. Thus that cosmologists accepted the value of the expansion parameter, and indeed that they accepted the parameter itself, was problematic. The origin of this problem is that an expected unification was not realizable: if taken seriously, the cosmological phenomena would establish an upper bound for the age of the Earth significantly younger than the lower bound for the age of the Earth established by the phenomena of geology.[37] If we assume that the geological limits were well established, this would be an indication that adopting the theoretical framework of cosmological expansion, or the phenomena used to investigate it, were problematic. However, Hubble's determination of the expansion parameter was beset by conspiring systematic errors in determining the distances to the galaxies he observed, thus his results led cosmologists on a sort of garden path. It was only with the ability of other astronomers to discover and publish agreeing measurements of the galaxies that Hubble observed that allowed cosmologists to move to a more secure understanding of the visible universe. We will discuss this example in more detail in the next chapter.

In 1971, well after the correction of Hubble's results and well before the contemporary investigations we will be discussing, Peebles expressed the position that the cosmology of that time had little evidence in relation to the speculation that was used to generate theoretical approaches. However, he notes that there was the opportunity for

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[36] Kragh, Helge. 2007. Pg. 246.

[37] McCrea, W.H. 1953.

improvement and his description for this opportunity is in line with the Newtonian ideal of empirical success. He writes,

> In cosmology the reliance on physical simplicity, pure thought and revealed knowledge is carried well beyond the fringe because we have so little else to go on. By this desperate course we have arrived at a few simple pictures of what the Universe may be like. The great goal now is to become more familiar with the Universe, to learn whether any of these pictures may be a reasonable approximation, and if so how the approximation may be improved. The great excitement in cosmology is that the prospects for doing this seem to be excellent. On one front we have some explicit questions, like the shapes of the redshift-magnitude relation and the redshift-angular size relation, and the values of some elementary parameters like Hubble's constant and the mean mass density. Probably we will only know for sure whether these questions are clever after we understand the answers, but at least we can see how available technological understanding can be turned into powerful new attacks on them. A second front is the search for new phenomena that may or may not interconnect in a pleasant way with accepted ideas. Of course we have no plan for finding these nuggets, only the expectation based on past form that as techniques of observation develop and extend our view we will stumble upon them.[38]

This passage reads in a manner similar to the use of regularities in the data (the redshift-magnitude relation and the redshift-angular size relation), along with established parameter values (Hubble's constant and the mean mass density), to measure theoretical parameters and form the basis for further research. It is interesting to note that while Peebles was perhaps not wholly convinced of the standard cosmological model by 1993, he had elevated it from being part of a "desperate course". He defines a scenario as, "a promising or otherwise sensible set of ideas, perhaps even with some observational basis, but one that is not yet definite enough to yield testable predictions by which the scheme might be falsified," but he is clear that the standard cosmological model is more than a scenario, even if he cannot commit to exact values of certain parameters.[39] Peebles'

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[38] Peebles, P.J.E. 1971. Pp. vii-viii.

[39] Peebles, P.J.E. 1993. Pg. xvi.

assessment of the standard cosmological model at the time is perhaps summarized by the following, “That is, we are seeing in cosmology a developing network of interconnected results. This network is what suggests that we really are on the path to a believable approximation to reality.”[40]

In the next chapter, we will examine the standard cosmological model which the two investigations support. Chapters Three and Four will discuss the supernova investigation and the background radiation investigation respectively, along with the systematic dependencies that they rely upon. Chapter Five will discuss the combination of the two investigations and the benefit for the standard cosmological model in the combination.

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[40] Peebles, P.J.E. 1993. Pg. 5.

Chapter Two: The Foundations of the Standard Cosmological Model

In this chapter, we review some of the fundamentals of the standard cosmological model in order to understand what the model is and the relationship of the cosmological constant to the other features of the model. In pursuit of this goal, we will examine what cosmologists have identified as the key elements of the theory, the way that these elements form a picture of the universe, and some of how cosmologists have marshalled evidence in support of the theory.

Cosmology, as a science, must be about the contents and dynamics of the universe at the largest scales that we can describe the universe. It is primarily a part of physics and explains how physical laws are operating at the largest scales. In ancient times, cosmology was effectively limited to a description of the solar system, with a rough account of the stars, due to the limitations of our observations. With the increase in technology and theoretical advances, primarily in gravitational physics, cosmology has grown both in scope and in the ability to produce detailed and accurate descriptions of astronomical phenomena of interest to cosmology. While many have speculated, and continue to speculate, about the origin of the contents of the universe, the progress on these elements has remained elusive.

The standard cosmological model, commonly called the Big Bang theory, is primarily a theory of the dynamics of the universe.[41] According to the theory, the universe is, on the average, homogeneous and the distance between galaxies is increasing over time. The homogeneity of the universe is usually expressed as the Cosmological Principle: (on a large enough scale) the universe is homogeneous and isotropic (i.e., it

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[41] Peebles, P.J.E. 1993. Rich, James. 2001.

appears the same in every direction one investigates). Accordingly, the universe of the standard cosmological model is a uniform soup of matter and radiation that becomes, as a whole, more or less dense over time. The general history of this change in density is governed by the expansion distances in space. Given this expansion, the theory commits to a dense early period in the existence of the universe. If we simply extrapolate backwards in cosmological time to the extreme, then the standard cosmological model has a point in the finite past that is infinitely dense, a point that many identify with the beginning of the universe and its contents. However, this extrapolation is not truly supported by cosmologists, as the physical properties of the universe when it is very dense are effectively unknown. Thus the dynamics of the universe in the most remote times of the distant past are usually judged to be a matter of speculation beyond the standard cosmological model.[42]

For roughly the first half of the Twentieth Century, the chief rival of the standard cosmological model was the Steady State theory.[43] This theory held that the universe was essentially unchanging and that, just as spacial differences are smoothed out over large amounts of space, the evolution of areas of the universe are smoothed out over time. The picture of the universe within the Steady State theory is that of an expanding universe with small pockets of matter and energy creation that work to keep the average density of the universe constant. The Steady State theory holds to the Perfect Cosmological Principle: (on a large enough scale) the universe is homogeneous, isotropic and it appears the same at any time.[44]

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[42] Peebles, P.J.E. 1993.

[43] Kragh, Helge. 1996.

[44] McCrea, W.H., 1953. Kragh, Helge. 1996.

With the increasing evidence of cosmological evolution, almost all of the proponents of the Steady State theory eventually abandoned the theory.[45] Some of these proponents have adopted the theoretical framework underlying the Steady State theory to form a modified theory, Quasi-Steady State Cosmology (QSSC). QSSC makes use of many of the hypothetical physical laws that were developed to explain a steady state universe but applies them to a model that incorporated the evidence for cosmological evolution over time. According to QSSC, the universe goes through cycles of expansion and contraction that get bigger with each successive cycle.[46]

However, it is difficult today to identify any true rivals to the standard cosmological model. As in the case of QSSC, theories that might replace the standard cosmological model remain very speculative. Unlike QSSC, most potential replacements are very close to the standard cosmological model and may even be thought to preserve the standard cosmological model as a sort of approximation or limiting case of their theory.[47]

The picture of the universe found in the standard cosmological model is put together in part through extrapolation from the physical laws that we observe locally and in part from what might be called educated guesses about what is adequate to describe the behaviour of the universe as a physical system at the largest scales. These educated guesses are often about certain initial conditions, not about a complete origin of the universe, but about what the contents of the universe must have been, roughly, at an early cosmological era. These conditions, initial or otherwise, can be quite broad. One such

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[45] Kragh, Helge. 1996. Hoyle, F., Burbidge, G., Narlikar, J. 2005. Arp et al. 1990.
[46] Hoyle, F., Burbidge, G., Narlikar, J. 2005.
[47] Kragh, Helge. 2007.

broad condition is the commitment to homogeneity of the average density throughout the universe.

The Fundamentals of the Standard Cosmological Model

In order to be meaningful and functional as a theory of the universe at the largest scales, any cosmological theory must address, to some extent, concerns in three areas: the space and time of the universe, the contents of the universe, the change, thermodynamic or otherwise, of the contents of the universe.

Cosmological theories must address concerns of space and time as discussions of the universe at the largest scales requires, at least, a container for the events of the universe. It became apparent that more than simply a container is required in our cosmological theories following the development of the General Theory of Relativity and other metrical theories of spacetime.[48] These theories connect the behaviour of space and time, through the geometrical rules governing measurements, to the contents of space and time. Within contemporary cosmological theories, such concerns of space and time are usually covered by a specific theory of gravitation.

As the universe as we know it obviously has contents, and these contents are the basis for all astronomical, and thus cosmological, observations, cosmological theories must address at least some of the contents of the universe and pick out which contents provide the basis for observations of the universe at the largest scale. Having identified the relevant contents, a cosmological theory should provide an account of the change of these contents of interest to cosmological behaviour or observations. Some of the changes of these contents may simply be kinematic changes. That is, these changes will be

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[48] Kragh, Helge. 1996. Jammer, M. 1954.

concerned only with the motion or relative position of the contents. In contemporary theories, these changes are likely to be governed by the theory governing space and time and gravity incorporated into a cosmological theory.

For simplicity, we may call the remaining cosmological concerns of the contents of the universe to be thermodynamic concerns, as they will involve some change of the state of the energy of the contents. One such change is the change in the interaction between photons and baryons in the early universe: at some point, the temperature of these components became low enough relative to their density that they would no longer interact with significant frequency relative to their previous interactions.

How specific a given cosmological theory is on any one of these elements depends on the theory itself and the demands of the available evidence: without some cosmological account, we will have no reason to suppose that a particular observation is relevant to cosmology. This will be the case even though the theory itself may not account for and may still be falsified by potential observations. One can see an example of this interaction in the development of cosmology before and after the time of Newton. Before Newton, cosmology could be and often was essentially free from the concerns of terrestrial gravity, whereas after Newton there was at least a *prima facie* case that gravitation as observed on Earth was active in causing or otherwise influencing behaviour at the cosmological scale.

That this determination of what is important is bound up with cosmological theory is a challenge for cosmology because the assumptions used in beginning cosmological investigations may unreasonably influence the results gained through investigation. As P.J.E. Peebles says of the commitment to homogeneity of the standard cosmological model,

> Since a homogeneous mass distribution is easy to characterize, and it is not so difficult to deal with departures from a mean distribution, it may not be surprising that some progress is feasible within this picture. It is reasonable to ask whether the progress might be circular, whether some cosmologists have only invented a problem that is easy to solve."[49]

Peebles identifies the only means to address this challenge as the use of evidence in an indirect manner, though he is quick to point out that such indirect inference is successful in many scientific fields. His example of such indirect inference is from particle physics:

> No one has yet seen a quark, yet the weight of evidence from high-energy physics compels belief in these particular objects as a useful working approximation to reality. The weight of evidence in cosmology is not nearly as great, but... far from negligible.[50]

It seems clear from the text that Peebles' "indirect inference" is the use of "a developing network of interconnected results," to provide empirical support to cosmological theory.[51] It is worth noting the similarity between this approach and the following passage from Smith about Newtonian methodology:

> Newton recognized that measures invariably involve theoretical assumptions, and hence remain provisional... He also seems to have appreciated that, because measurements in physics involve physical procedures and assumptions, a distinctive feature of this science is that it cannot help but include within itself its own empirically revisable theory of measurement. This insight might explain why Newton was so quick to view success in measurement as a form of evidence in its own right; here success includes (1) stability of values as a measure is repeated in varying circumstances... and (2) convergence of values when the same quantity is determined through different measures involving different assumptions... Achieving success of this sort in determining values is almost certainly what Newton had in mind with the Cryptic remark at the end of the Scholium of space and time about the book explaining "how to determine the true motions from their causes, effects, and apparent differences."[52]

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[49] Peebles, P.J.E. 1993. Pg. 4.
[50] Peebles, P.J.E. 1993. Pg. 4.
[51] Peebles, P.J.E. 1993. Pg.5.
[52] Smith, 2002, pg. 145-146

The use of agreeing measurements from independent sources, that is, sources that make use of different assumptions and methods about how each source produces measurements and thus rely on different systematic means of producing measurements of theoretical parameters, allows us to have greater trust in the assumptions and methods of each source.

Given the need to address these areas of concerns as outlined above, we may consider a cosmological theory to be a set of key elements that address or coordinate these issues using a set of theoretical constructions that purport to model the behaviour of the universe at the largest scale and a set of boundaries on these parameters, ideally through systematic dependencies between theoretical parameters and phenomena. Such a theory will determine, to an approximate extent, the nature of spacetime at cosmological scales, the contents relevant to cosmological dynamics and observation, and the thermodynamics of the contents of the universe at cosmological scales. Additionally, while cosmological theories may depend upon theories of astrophysics, these theories need not be considered part of the cosmological model. For example, while a cosmological theory must allow that there are stars, the particular physical operation of stars need not be an important part of the theory. Exception must be made when there are special global effects of cosmological observations closely tied to such theories. For example, Quasi-Steady State Cosmology relies on the presence of a particular kind of dust in the space between galaxies in order to produce a number of observations on cosmological scales, so this will be an important element of the theory itself.[53] In general, the elements of a cosmological theory will be those elements that serve to provide an

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[53] Hoyle, F., Burbidge, G., Narlikar, J. 2005.

explanatory framework for behaviour and observations at the cosmological scale rather than elements that explain specific astronomical observations.

This definition of cosmological theory seeks to address the usage of “model” as used in cosmology and provide a context for understanding that we can rely on later. To some extent, this definition originates in Peebles' discussion of the use of the word “model” in his preface to *Principles of Physical Cosmology*, his 1993 review of cosmology.[54] Peebles also writes that in the use of the appellation “standard cosmological model”, the word “model” is appropriate because the theory is “known to be an incomplete approximation to what is really happening, and there certainly is the chance that there is something very wrong with the picture.”[55] At least in the mind of the cosmologist, the use of the word “model” addresses the hypothetical origin of many of these cosmological theories and also seeks to address the use of the theories to provide incomplete approximations that address the nature of available observations but leave some room for future accounts that can be more specific. Similarly, in our definition, a cosmological model provides an approximate account and a range of parameters that can be used to produce an account of physical systems at the largest scale that remains sensitive to future improvements, e.g., to provide a better approximation, through either a more restricted range of parameters or by appealing to better theories about particular observations.

Peebles also writes of potential confusion surrounding the use of “model” through the common use of the word to refer to both full cosmological theories, which may allow

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[54] Peebles, P.J.E. 1993.

[55] Peebles, P.J.E. 1993. Pg. xvi

for a wide range of parameters, and specific idealizations of the universe with specific parameter values.[56] Given this ambiguity, it may be more correct to think of cosmological theories, including the standard cosmological model as a family of models or as a global model.[57] In order to produce greater restrictions on the parameters of a theory, the theory will need greater support from the evidence, though there may still be significant room to improve the approximation of the theory.

The standard cosmological model is founded on four core elements that address or coordinate cosmological concerns. These elements are as follows: the universe is close to homogeneous and isotropic; the universe is globally expanding; the dynamics of the universe are determined by the General Theory of Relativity; and in the distant past the universe was extremely hot and dense. These core elements are intended to create approximations that will explain the behaviour of physical systems at cosmological scales. The model is a framework for describing the kinematics of the universe in terms of parameters that can be tied to theoretical parameters that are causally relevant to these kinematics. The standard cosmological model identifies the kinematics as the global expansion of the universe and the causally relevant parameters providing the dynamics are the mass-energy densities of the contents of the universe. These parameters are established, within the model, as causally relevant by the General Theory of Relativity, which provides a systematic dependency between these parameters and the kinematic parameters that can, in principle, be measured through observation. More details on this are explained later in this chapter.

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[56] Peebles, P.J.E. 1993. Pg. xvi.

[57] Cf. discussion of model *vs.* family of models in W. Myrvold and W. Harper (2002) and the discussion of global models in K. P. Burnham and D. R. Anderson (1998).

The identification of these core elements is remarkably stable among different authors over the latter decades of the Twentieth century. A paradigm example is found in *Principles of Physical Cosmology*, where Peebles lays out these core elements as follows:

> 1. The mass distribution is close to homogeneous in the large-scale average. …
> 2. The universe is expanding, in the sense that the mean distance l between conserved particles is increasing with time at the rate
> $$\frac{dl}{dt} = H_0 l. \quad \ldots$$
> 3. The dynamics of the expanding universe are described by Einstein's general relativity theory… With general relativity theory, we are assuming local physics is the same everywhere and at all times. As will be discussed here and in later sections, that has to be wrong at early enough epochs, because the standard expanding world picture extrapolates back to a singular state in which conventional physics becomes undefined. …
> 4. The universe expanded from a hot dense state where its mass was dominated by thermal blackbody radiation.[58]

Similarly, Peter Coles and George F.R. Ellis, in their 1997 review of cosmological evidence, describe the core of the standard model using the following core principles:

> a)expansion of the universe,
> b)from a hot big bang,
> c)where nucleosynthesis of the light elements took place,
> d)resulting in the CMB as relic radiation.[59]

Coles and Ellis use "CMB" to refer to the cosmic microwave background radiation. While Coles and Ellis do not explicitly refer to the General Theory of Relativity in the above list, it is present as the context for their discussion of these core principles. Similarly, homogeneity and isotropy, as we shall see, are prerequisite to the expansion of the universe as considered by Peebles, Coles and Ellis, and other cosmologists working on the Standard Cosmological Model. Peebles' earlier works on cosmology also contain

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[58] Peebles, P.J.E. 1993. Pp. 5-6.
[59] Coles P., Ellis, G.F.R. 1997. Pg. 206.

these core principles, though not quite so explicitly. In *The Large-Scale Structure of the Universe*, Peebles takes the model as described above as a backdrop and "deals with departures from an ideal homogeneous and isotropic Friedmann-Lemaître cosmological model [the standard model of contemporary relativity following the General Theory of Relativity]."[60] Peebles' 1971 publication *Physical Cosmology* is an early work investigating and explaining the model as outlined above.[61]

Within the standard cosmological model, the spacetime structure of the universe, and issues regarding it, are subsumed under the General Theory of Relativity and limited in scope by the commitment to homogeneity and isotropy. According to the General Theory of Relativity, there is a specific structure to spacetime that is determined by the nature of the mass and energy of the contents of that spacetime. In the theory, the contents and the spacetime influence each other, leading to the physical behaviours that we identify as gravitational. This behaviour is mediated by the Einstein Field Equation and solutions to this equation provide the basis for models (or families of models) of spacetime.[62] The particular solutions to the Einstein Field Equation of interest to us are those determined by the commitment to homogeneity and isotropy. These solutions are the Friedmann-Robertson-Walker (FRW) models in the case of a zero cosmological constant and the Friedmann-Lemaître-Robertson-Walker (FLRW) models in the case of a non-zero cosmological constant.[63]

Einstein introduced the cosmological constant in order to expand the space of

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[60] Peebles, P.J.E. 1980. Pg. 395.
[61] This characterisation of the earlier work is given in preface to P.J.E. Peebles (1993).
[62] Rich, James. 2001.
[63] Rich, James. 2001.

solutions to the field equation governing the General Theory of Relativity in order to produce a model that Einstein considered likely to best fit the universe. As a theoretical parameter of gravitational theory, the cosmological constant can operate in a manner opposite to the influence of other parameters of the theory and thus can be used to fit solutions of the Einstein Field Equation to a greater range of possible dynamics. In particular, Einstein turned to the parameter as a means of cancelling out the influence of matter, which would act to contract space as a whole, in order to produce an essentially unchanging spacetime. When this model proved to be unappealing to Einstein on several grounds, he advocated the rejection of the cosmological constant as a parameter.[64] Though the parameter appeared to play effectively no role in solar system dynamics, many cosmologists continued to consider the parameter, even if only to state their assumption that it be set to zero.[65] This work examines the contemporary evidence in favour of the inclusion of the cosmological constant.

The commitment to homogeneity and isotropy provides an important foundation for cosmological theories, regardless of whether or not one adopts the General Theory of Relativity. One of the lessons of the development of relativity theory is that one can chose an arbitrary system of coordinates to describe physical systems and that there is no intrinsic distance or temporal scale that we must adopt *a priori* to any physical investigation.[66] However, there is a naturally arising determination of time and distance for a spacetime with contents that are distributed homogeneously. A prerequisite to homogeneity is Weyl's postulate, which states that the galaxies of the universe can be

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64 Earman, John. 2001.
65 Earman, John. 2001.
66 Jammer, M. 1954.

considered such that their worldlines, their paths in spacetime, form a collection of non-intersecting line with each worldline perpendicular to a collection of hypersurfaces representing three-dimensional spaces arranged by time, each hypersurface representing a different moment of the universe. This idealization allows us to consider cosmological time as that time carried along with each galaxy.[67] It is in the context of Weyl's postulate, and the hypersurfaces it identifies, that we can describe the universe to be homogeneous. Thus a more explicit definition of the Cosmological Principle is, "All space-like hypersurfaces have a homogeneous and isotropic distribution of their contents."

Using the Cosmological Principle, we can model the spacetime of the universe using the Robertson-Walker metric. The equation for the metric is as follows:

$$ds^2 = c^2 dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta \, d\phi^2\right)\right) \qquad (2.1)^{68}$$

This equation provides a means of defining the fundamental measurement of distance, ds^2, between two points of the spacetime identified by their time coordinate, t, and their spatial coordinates (given here in spherical coordinates), r, θ, φ. Weyl's postulate allows us to consider measurements of time, dt^2, separately from spacial measurements. The additional factor in the measurement of time, c, representing the speed of light, enters into the metric as the metric does require a commitment to that postulate of the Special Theory of Relativity that every observer measure the speed of light in a vacuum as the same value. While this restriction from the Special Theory of Relativity is part of the Robertson-Walker metric, the full General Theory of Relativity is not required for its use

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[67] Kragh, Helge. 1996. In many publications, authors use "epoch" to refer to this cosmological time, but this work will continue to use "cosmological time" throughout.

[68] Rich, James. 2001.

and thus the commitment to homogeneity and isotropy is truly separate from the assumption of the General Theory of Relativity.

While measurements of distance are determined, within any given hypersurface, independently of time, time still plays a role in the relationship between distances considered in different hypersurfaces. In the metric, the measurement of spatial distance is multiplied by a scale factor, $a(t)$. The result is that the Robertson-Walker metric is essentially the metric for a spherically symmetric space, for each moment of time associated with a hypersurface according to Weyl's postulate, where the dynamics of the ideal points of the space is determined by a scale factor that changes with time, globally increasing or decreasing the mean distance between these points. An additional factor, k, is used to represent whether or not the global curvature of the hypersurfaces is Euclidean, hyperbolic, or spherical; these circumstances are usually referred to as flat, open, or closed respectively. In hyperbolic surfaces, parallel lines can diverge and in spherical surfaces parallel lines can converge.

It is common to represent the action of the scale factor in terms of two other parameters: the Hubble parameter and the deceleration parameter. The Hubble parameter, $H(t)$, is the derivative of the scale factor divided by the value of the scale factor at a certain time, as such, it represents a sort of speed of the expansion (or contraction) of the scale factor. In cosmological publications, authors often refer to the present value of the Hubble parameter as the Hubble constant, H_0. Usually given in units of kilometres per second per megaparsec, the Hubble constant is often represented through the value h, where $H_0 = 100h$ km s^{-1} Mpc^{-1} or through some other value, h_x, where the subscript x

indicates the number to multiply with h_x in order to produce the value of H_0. The other parameter, the deceleration parameter, is a product of the second derivative of the scale factor. As it contains the second derivative, the deceleration factor represents a sort of acceleration of the scale factor; it earns the "deceleration" label as early cosmologists expected the parameter to indicate the influence of matter in slowing the expansion. Accordingly, acceleration of the scale factor is represented by a positive value of the second derivative and a negative value of the deceleration parameter. Thus the expectation within FRW models is that the deceleration parameter will always be positive, leading to a slower expansion of the universe and perhaps an eventual reversal producing contraction. However because of the inclusion of a cosmological constant or algebraically equivalent vacuum energy density within FLRW models, these models allow the deceleration parameter to be negative and thus allow the expansion of the universe to accelerate.

The Hubble parameter has its origins in Edwin Hubble's discovery of the linear relationship between redshift and distance in (what were then) relatively distant galaxies.[69] The derivative of the scale factor leads, in the case of an expanding universe, to a shift in the wavelength of light travelling cosmological distances such that, though all wavelengths are effected. Light in the visible part of the spectrum would move towards the red end of the spectrum. In the case of a contracting universe, this shift would be toward the blue end of the spectrum. This effect of the scale factor was first noted in 1917 by Willem de Sitter and that this redshift increases uniformly with distance (in galaxies

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[69] Kragh, Helge. 1996.

out to a certain point) was noted by Hermann Weyl in 1923.[70] The linear nature of the relationship between redshift and distance noted by Hubble prompted him to posit that the relationship he noted was that of "the de Sitter effect."[71]

Given the importance of redshift, cosmologists often report many calculations and results involving other quantities as a function of redshift rather than as a function of time. Given the finite speed of light, any observation at a distance is also an observation of the past; this makes redshift, which is correlated to distance, also something tied to the past. Given that redshift represents a cosmological effect that is readily observable and that interacts with cosmological parameters in predictable ways, giving cosmological equations in terms of redshift makes a certain amount of sense. Redshift is usually represented as z, a function of the ratio between the observed wavelength of a photon and the emitted wavelength of the photon, where $\lambda_{\text{Observed}} / \lambda_{\text{Emitted}} \equiv 1 + z$.[72]

The Hubble relation of redshift to distance is something that any cosmological theory should address. In the standard cosmological model, the relation has a natural place as a regularity of the data that provides information about a parameter of the theory. That is, the Hubble constant is produced by the change in the scale factor and thus redshift measurements provide information about the rate of expansion and, as we will discuss, information about the density of matter, radiation, and the value of the cosmological constant. Some alternative cosmological models account for this redshift in another way, either through so-called "tired light", which naturally shifts with distance or through some fundamental change with the source of light, perhaps a form of evolution of

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[70] de Sitter, W. 1917. Weyl, H. 2009.
[71] Hubble, E. 1929.
[72] Rich, James. 2001.

the thermodynamics of the universe over cosmological time. As the Hubble relation is, given our best observations, a feature of the universe at the largest scales, it would seem an obvious source of evidence for a cosmological theory. This does not force every cosmological theory to account for the Hubble relation, but we may justifiably place a greater burden on a theory that does not provide such an account to produce evidence from other sources. Such theories will be ignoring a host of data, and the evidence that can conceivably be produced from that data, of which other cosmological theories will make use.

The Friedmann equation, or the Friedmann-Lemaître equation, governs the relationship between scale factor and the contents of the universe in the Standard Cosmological Model. The basic form of the equation is,

$$\left(\frac{\dot{a}}{a}\right)^2+\frac{k}{a^2}=\left(\frac{8\pi G\rho}{3}\right) \qquad (2.2)^{73}$$

where G is the constant of gravitation and ρ is the overall density of mass and energy in the universe. This establishes a basic relationship between the scale factor and the overall density. However, this simple presentation of the equation hides the change in the density over time (if there is such change) and the difference between the changes in different types of mass-energy densities (if there are such differences). We will examine a version of the equation that includes these details shortly.

An important term that arises from the simple form of the equation above is the critical density, ρ_c, which is that current value of the total energy density such that the

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[73] Rich, James. 2001.

geometry of the universe is flat, and thus k=0, and

$$\rho_c = \frac{3}{8\pi G}\left(\frac{\dot{a}}{a_0}\right)^2 \qquad (2.3)^{74}$$

In this definition above, the subscript "0" indicates, as is common for cosmology, the current time. The current value of cosmological density parameters are often reported as fractions of the critical density using the upper case Greek letter Ω and a subscript to indicate a particular density. Accordingly if $\Omega_{\text{Total}} = 1$, the universe is at the critical density and thus the spacetime is flat, if $\Omega_{\text{Total}} > 1$, the spacetime is closed, and if $\Omega_{\text{Total}} < 1$, the spacetime is open.[75]

Because of these relationships, within the standard cosmological model information about the mass-energy densities in the universe can be gathered through two means. The first of these means is more or less direct observation. For example, through galaxy counts and assumptions about the relationship between visible light and matter, one can attempt to measure the amount of matter present in a given volume in the universe at the present cosmological era. Additionally, the density of photons in the universe can be estimated directly from the observation of the background radiation. The second means of gathering information about the mass-energy densities is through observations of the geometry of the universe. This geometry should change over time, and the change is dependent upon the mass-energy densities. Additionally, the overall geometry of the universe is dependent on the overall mass-energy density of the universe. These different means provide the potential for the theory to gain evidence through its

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[74] Rich, James. 2001.
[75] Rich, James. 2001.

ability to unify a number of otherwise independent observations.

A more complete presentation of the Friedman Equation, or rather the Friedmann-Lemaître equation that includes the possibility of a non-zero cosmological constant addresses the change in density over cosmological time, *t*, (or according to redshift, *z*) and thus the change in the effect that the density has on the scale factor over cosmological time. This, in turn, shows how information about the behaviour of the scale factor over time ties in to information about the cosmological parameters. Such a more detailed formulation of the Friedmann-Lemaître equation is the following:

$$\left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\Omega_M\left(\frac{a}{a_0}\right)^{-3} + \Omega_R\left(\frac{a}{a_0}\right)^{-4} + \Omega_\Lambda + \left(1-\Omega_{Total}\right)\left(\frac{a}{a_0}\right)^{-2}\right] \qquad (2.4)^{76}$$

This equation contains the differential effect that each density parameter has on the scale factor over cosmological time. The effects are given in terms of the critical density and the current values of the scale factor, a_0, and the Hubble constant, H_0, which reports the current value of the derivative of the scale factor. Ω_M represents the density of all matter, Ω_R represents the density of radiation, Ω_Λ represents the density associated with the cosmological constant, and Ω_{Total} represents the total density, the sum of all of these other densities. While it is possible that the cosmological constant is not the result of an energy density but is a constant of the equation governing the equation of gravity, the constant will still provide the algebraic equivalent of an energy density, albeit one that does not dilute with cosmological expansion as others do, and thus properly finds its place in this presentation of the Friedmann-Lemaître equation.

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[76] A modification of the equation taken from James Rich (2001), pg. 28.

When we look at the behaviour of this equation going back in time, given the restriction from the standard cosmological model that the universe is expanding, then we expect that the scale factor a will decrease relative to a_0. As a/a_0. shrinks towards to past, the negative powers assigned to this factor indicate that the influence of Ω_M, Ω_R, and the total density get larger. Thus, if these were the only operative factors in the equation, we expect that they would have a greater effect in slowing the expansion in the past, telling us that the expansion was must faster in the past. This makes a certain amount of sense, as we can think of the gravitational attraction of the contents of the universe as a sort of drag pulling the galaxies back together as they fly away from each other. The drag would have been much greater in the past, thus the expansion would have had to be much greater in the distant past in order to be reduced to the present value. Thus measurements of the behaviour of the scale factor over time measure values of these density parameters.

The above picture is complicated somewhat by the presence of a non-zero cosmological constant. The action of the cosmological constant is opposite that of the mass-energy densities above: a positive value of the constant accelerates expansion rather than decelerating it.[77] This was the purpose for which Einstein initially introduced the constant.[78] In order to model an essentially unchanging universe, Einstein required something in his theory of gravitation that would counteract the influence of matter that might otherwise cause a universe to collapse in on itself. Such a model is one of many models that can make use of the cosmological constant, as its action expands the behaviour that the scale factor can exhibit, given the relationship of mass-energy densities

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[77] Rich, James. 2001.
[78] Earman, John. 2001.

to the scale factor. With the cosmological constant, the scale factor can undergo periods of acceleration and thus measurements of the behaviour of the scale factor place limits on the relative values of the cosmological constant and the mass-energy densities.

A key difference visible in the more detailed version of the Friedmann-Lemaître equation is the different effects that different densities have over cosmological time. The influence of the density of matter decreases according to the cube of the scale factor because this represents the increase in the volume proportional to the scale factor that the existing density must thin out to cover. The influence of the density of radiation decreases according to the fourth power because in addition to an increase in volume, radiation undergoes redshift which decreases its energy proportional to the increase in the scale factor. Looking at the behaviour of the scale factor over time thus gives us information on the relative values of these parameters relative to this differential effect over cosmological time.

This difference in density over time can also be seen in other aspects of cosmological investigation, particularly in regards to another core element of the standard cosmological model: the commitment to a hot, dense early universe. The heat of the early universe is tied closely to the overall density of radiations, primarily in the form of photons and neutrinos, and to the ratio of photons to ordinary matter.[79] The difference in the densities of matter and radiation over time indicates that there should be a time in the history of the universe where the density of radiation dominated the dynamics of the universe. The details of this radiation-dominated era will place limits on the formation of

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[79] Peebles, P.J.E. et al. 1991. Olive, S. et al. 1980. Yang et al. 1984.

light elements, an important part of this core element of the standard cosmological model highlighted in the Coles and Ellis quotation above.

While the Friedmann-Lemaître equation provides the core means of addressing cosmological concerns of the contents of the universe within the standard cosmological model, most of such concerns are also addressed in conjunction with the commitment to the hot, dense early universe. This commitment is one not simply of high temperature and density, it is also, as mentioned above, a commitment to a relatively high density of radiation relative to matter. Additionally, the standard cosmological model commits to the early universe being an effective blackbody; that is, the matter and radiation of the universe were in thermal equilibrium. The result of this interaction is that the early universe becomes the site of *primordial nucleosynthesis*, the formation of the light atomic elements that would later form the basis for the atomic make-up of the universe (with heavier elements produced mainly within stars).[80] The end result of this era of primordial nucleosynthesis is the relative abundances of a number of light elements, primarily hydrogen, deuterium, helium (of atomic weight 3 and 4) and lithium, and background radiation. The background radiation of the universe is formed when the universe lost enough matter and radiation density such that baryons could form atomic nuclei and capture electrons; the result of this was that photons did not almost immediately interact with matter and thus were free to stream off into the universe.[81] After this era, the expansion of the universe reduces the temperature of the radiation, and its energy density, in such a way as to preserve the characteristic blackbody spectrum of the radiation.

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[80] Olive, S. et al. 1980. Yang et al. 1984.

[81] Rich, James. 2001.

Additionally, the expansion preserved a great deal of the isotropy of the radiation.

The relative abundances of elements produced at the end of the period of primordial nucleosynthesis depend on the periods of interactions that can be sustained in the early universe and the likelihood of specific interactions; this will depend on mass-energy densities.[82] A high overall mass-energy density will end up limiting the amount of time available for nucleosynthesis, because it will have produced significant drag in the past to slow down the scale factor. Conversely, a low over-all mass energy density will end up increasing the amount of time for primordial nucleosynthesis. As the density of radiation is much more significant in this period, the amount of photons and the amount of neutrinos is a significant factor on nucleosynthesis. Of course, the density of baryons, the particles involved in nuclear processes, is important as well. To some extent, the density of baryonic matter is more important to primordial nucleosynthesis than the overall density of matter, as any additional matter is presumably not taking part in nucleosynthesis, even though this matter may have interacted with baryons in a much earlier era of the universe. Thus we find that primordial nucleosynthesis constraints on cosmological parameters tend to place their constraints on photon density, neutrino density, and baryonic matter density more than other parameters. It should be added that this commitment to a period of primordial nucleosynthesis depends not only on the explicit cosmological commitments, but also on the assumption that the nuclear processes that we observe in the lab or deduce from other sources act as expected in the distant locations and times involved.

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[82] Olive, S. et al. 1980. Yang et al. 1984.

In accordance with our Newtonian methodology, the standard cosmological model is thus a commitment to a theoretical construction of the relationship between spacetime and its contents. As this relationship is mediated by the Friedmann-Lemaître equation, this construction is able to produce systematic dependencies between its main parameters, those of mass-energy densities, and the kinematic parameters of the behaviour of the scale factor. The key kinematic parameters are the Hubble constant and the deceleration parameters, though other parameters representing higher-order derivatives of the scale factor over cosmological time might be of use. Because the behaviour of different mass-energy densities is distinguishable over cosmological time, the values of the kinematic parameters can provide information about the values of the mass-energy densities. Investigation into these mass-energy density parameters is carried out through the extension of local physical principles to distant regions as licensed by Newton's Rule 3. This allows us to attempt to discover physical principles at work in distant regions and discover associated phenomena within the data produced by research that can be used to measure cosmological parameters. The main parameters of the standard cosmological model, at present, are listed in table 2.1.

Parameter	**Symbol**
Hubble Parameter	$H(t)$ or $H(z)$
Hubble Constant (present value of $H(t)$)	$H_0 = 100\ h$ km s^{-1} Mpc^{-1}
Density parameters:	
Total	Ω_{Total} or Ω_0
Matter (the sum of other matter terms)	Ω_M
Baryonic Matter	Ω_b
Dark Matter	Ω_{CDM}
Radiation (photons)	Ω_r
Neutrinos	Ω_ν
Dark energy (mass-energy density associated with the cosmological constant)	Ω_Λ

Table 2.1. Parameters of the Standard Cosmological Model

Evidence for the Standard Cosmological Model

Given the rough outline of the standard cosmological model above, we now turn to the sources of evidence, outside of those of interest later in this paper, that support the theory. There are essentially three pillars of support for the theory: the strength of the redshift-distance relationship, the observation of light element abundances, and the presence of background radiation. Additional observations of cosmological evolution are also evidence in favour of the standard cosmological model over the Steady-State model, but not of interest for this work.

The security of our belief in the redshift-distance relationship is of importance as it provides a means of testing homogeneity and isotropy and of providing information about mass-energy densities. To some extent, the security of our belief in the relationship is also a test of the General Theory of Relativity, as establishing that the redshift is truly a feature of distance and not intrinsic to the objects observed is a point in favour of the correct use of the Robertson-Walker metric and thus metrical theories of spacetime in general. If the redshift were due to some other cause, then this could, depending on the mechanism of the redshift, require a modification of General Relativity at cosmological distances.

The challenge for producing the redshift-distance relationship is producing a robust measurement of distance. Given the impossibility of travel to and from the astronomical objects that we observe, every determination of distance will rely on identifying some feature of a distant object and using this as the basis for the determination of distance. The standard astronomical means to determine distance are part of the *cosmological distance ladder.*[83] The cosmological distance ladder is a series of reference techniques that are built upon one another, providing a means to extend the confidence of one distance determination technique to another. This is possible as the ranges of applicability of the techniques tend to overlap.

One of the first rungs of the distance ladder is parallax.[84] This is a simple geometrical technique relying upon the mathematical relationships of a triangle to determine the distance to an unknown point from two sites of observation of known distance apart. Distance determinations due to parallax are essentially limited to within very local regions of our Galaxy. However, in theory one may also use a similar process to determine the distance to an object of known size from a single point of observation, based upon the angular diameter of this object. However, in both of these cases, two factors work against the observer. The most important one is the angular resolution that the equipment used to determine parallax. Distant objects require greater precision of measurement or greater known separation in order to determine distance to the same

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[83] Rowan-Robinson, Michael. 1985.
[84] Rowan-Robinson, Michael. 1985.

degree of accuracy. In the case of determinations of size from angular diameter, the problem is determining the actual size of a distant object. This technique falls prey to an additional difficulty that the change in scale factor introduces a further complication. As the scale factor changes over time, at some point more distant objects actually begin to grow in angular diameter.[85] This is due to the fact that they were closer when their light was emitted than those objects that emitted light a later time. The weight of such complications makes parallax and angular diameter unsuitable for determinations of the largest distances, especially in the absence of exact determinations of the cosmological parameters that effect the scale factor. However, for objects of known size, this distortion of angular size can be used to provide information about the geometry of the universe that produces such distortion. This relationship between angular size and geometry forms the basis of some of the parameter determination used in the investigation of the background radiation, and we will discuss it in later chapters.

A primary extragalactic rung of the distance ladder is determinations of distance based directly on the assumed luminosity of Cepheid variable stars (or Cepheids).[86] These stars are known to have a relationship between the period of their fluctuation of luminosity and their maximum emitted luminosity. Thus a determination of their period reveals their maximum luminosity. This intrinsic luminosity can be compared with the observed brightness to determine the amount that distance has diminished the light reaching the observer. This method of determination is successful to the extent that the nature of Cepheids is understood and to the degree that the nature of dust within our

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[85] Rich, James. 2001.
[86] Rowan-Robinson, Michael. 1985.

Galaxy, dust within other galaxies, and whatever dust there might be in the space between galaxies, all of which might decrease apparent luminosity, is properly taken into account.

Edwin Hubble used Cepheids, along with two other techniques, in his unfortunately incorrect determinations of the value of the Hubble constant.[87] Hubble's observations were plagued with an unknown source of systematic error in making his determinations: he was unaware that there were two different types of Cepheids, each with a different relationship between period and luminosity. In addition, Hubble relied as a cross-check for his determination of distance on methods regarding the assumed intrinsic brightness of the brightest stars in the galaxies he was observing; unknowingly, he had misidentified regions of gas heated by starlight as stars.[88] These two conspiring sources of error lead him to determinations of distance that were significantly incorrect and produced measurements of the Hubble constant that differ from current measurements by a factor of 7.[89]

The results stemming from the systematic error in the use of Cepheids led to significant problems for the standard cosmological model. The value of the Hubble constant, representing as it does the derivative of the scale factor and the expansion of the universe in terms of the mean distance between ideal points, places limits on the past history of the universe. It is common to write of the Hubble time, H^1, which is the characteristic timescale of the universe in the sense that it is roughly about that long ago in the past that the mean distance between ideal points was zero. While near to this point in time the conditions for describing the universe break down, in the context of the

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87 Hubble, Edwin. 1929. Baade, W. 1956.
88 Sandage, Allan. 1958. Kirshner, Robert P. 2002.
89 Baade, W. 1956. Rowan-Robinson, Michael. 1985. Kragh, Helge. 1996. Earman, John. 2001.

standard cosmological model this limit nonetheless places boundaries on how long there is in the history of the universe for galaxies, solar systems, stars, and planets to form. The value of the Hubble constant based on the assumptions used by Hubble and others in the mid-1930s placed the Hubble time at approximately two billion years.[90] This conflicted with determinations of the age of the solar system, which were reported to be on the order of four billion years.

This problem is exacerbated when one considers that the presence of mass-energy densities greater than zero decreases what is effectively the age of the universe, T_0, a function of H^{1}. The presence of a positive mass-energy density in the universe, coupled to the scale factor through the Friedmann equation, means that in the past the expansion must have been faster, reducing the time needed to expand the average distance between points to its current distance. Some cosmologists turned to the cosmological constant to solve this apparent age of the universe problem, as the action of the cosmological constant to accelerate the scale factor could be used to indefinitely extend T_0. Some other cosmologists rejected, to a greater or lesser extent, the applicability of the standard cosmological model to the universe as a whole, in some cases arguing that the theory was correct to some extent but that the timescale of the universe as a whole was something too abstract to apply to local physical systems.[91]

The dramatic revision of the value of the Hubble constant began in the early 1950s, with significant public motivation for the revision of extragalactic distance measurements beginning with a 1952 presentation by W. Baade, who suggested that many

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90 McCrea, W. 1953. Kragh, Helge. 1996. Earman, John. 2001.
91 Kragh, Helge. 1996.

such distances needed to be doubled.[92] Though Albert Behr had published a paper calling for a doubling of extragalactic distance determinations the year previously, Baade's presentation appeared to have more impact at the time.[93] Baade's presentation made enough of an impact that W.H. McCrea includes the results of the presentation in an appendix to his 1953 review of cosmology. McCrea includes the results, even though the results had not been published at the time and he refrains from including Baade's name in print because of this, because of its potential impact and because other astronomers present when Baade presented his results seemed to be prepared to accept the results.[94] McCrea notes, however, "The observational results [of Hubble and others]... have stood for the past fifteen years or more. It is certainly disconcerting to learn that such a drastic revision may be required at a single stroke."[95]

Baade eventually summarized the problems with earlier Cepheid work in a 1956 paper.[96] In going over the development of the use of Cepheids, he shows that one of the arguments in favour of their identification as one type of star with one period-luminosity relationship is the agreeing measurements of this relationship that different investigators were able to produce between different samples of Cepheids. This is an important point to consider, as in this work we want to consider the extent to which agreeing measurements build justified confidence in the value of a parameter. As Kirshner notes in his discussion of systematic error, "Just because your measurements agree with one another is not a guarantee you're doing things right."[97] Hubble's mistaken estimate of the value of the

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[92] Kragh, Helge. 1996.
[93] Kragh, Helge. 1996..
[94] McCrea, W.H. 1953.
[95] McCrea, W.H. 1953. Pg. 361.
[96] Baade, W. 1956.
[97] Kirshner Robert P. 2004. Pg. 95.

Hubble constant is an example of one produced with determinations deriving from agreeing measurements from different sources, ones with conspiring systematic errors.

Baade's argument in favour of two populations of Cepheids, each with their own period-luminosity relationship, relies not only on the results of accurate observations, but also, and crucially, on the ability of this hypothesis to unify a number of otherwise unconnected astronomical results. This unification is found not merely in a qualitative agreement of shared explanation, but in the agreeing measurement of distance produced from the observations of different phenomena of the Andromeda nebula. Baade goes beyond merely hypothetico-structural explanation to make the agreement of measurement from phenomena that we would otherwise identify as independent do the work of establishing the scientific claim he is putting forward.

Baade notes that the initial impetus for his investigation into the Cepheids was due to the fact that, based on their use in determining distance to the Andromeda nebula, the upper limits for the magnitudes of the globular clusters in the nebula are 1.5 magnitudes fainter than those in our galaxy.[98] Globular clusters are spherical collections of stars in orbit within and around galaxies; if their formation in the Andromeda nebula is similar to those in our Galaxy then the upper limit of the brightness of these collections should be similar. Conversely, if there is a significant difference in their formation then this difference in composition could be the part of the cause of the observed difference in luminosity. The determination of the distance to the Andromeda nebula was based on the Cepheids found within the globular clusters in the Andromeda nebula, and if this distance is incorrect then the discrepancy of brightness of these globular clusters could be caused

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[98] Baade, W. 1956.

entirely by the mistake in the calibration of the Cepheids. Assuming in addition that the Cepheids in globular clusters are of a different sort than other Cepheids, and that the maximum luminosity of the globular clusters in the Andromeda nebula is the same as that for our galaxy, allows one to perform a measurement of the period-luminosity relationship of this second class of Cepheids.

Baade also acknowledges that there were good reasons to identify the Cepheids in globular clusters as different from the Cepheids found elsewhere.[99] Astronomers had begun to divide stars into two populations based on their spectrum and magnitude, Population I and Population II. According to Baade, "the color-magnitude diagrams leave no doubt that in the two cases we are dealing with stars in different physical states."[100] Globular clusters are mainly comprised of population II stars. Additionally, those Cepheids found with Population II stars show spectral characteristics, in the form of emission lines, not found in Cepheids found with Population I stars. That these documented difference could be associated with a difference in the period-luminosity relationship seemed natural to Baade, yet this and the globular cluster luminosity discrepancies did not convince him that there was a serious challenge to the use of the Cepheids. He writes, "I felt that in the end the results from the Cepheid program would be more convincing."[101]

Further research with the one of the largest telescopes available at the time revealed another means of measuring the discrepancy in the two populations of Cepheids.[102] Using the 200 inch telescope at the Palomar observatory, Baade was able to

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[99] Baade, W.H. 1956.
[100] Baade, W.H. 1956. Pg. 9.
[101] Baade, W.H. 1956. Pg. 10.
[102] Baade, W.H. 1956.

demonstrate that, if one relies on the distance determination provided by the Cepheids, the brightest stars of Population II in the the Andromeda nebula were also 1.5 magnitudes fainter than similar stars in our galaxy.

Thus that there are two different populations of Cepheids with two different period-luminosity relationships, something that continues to be borne out by astronomical investigation, united three different, otherwise independent astronomical observations: that one can identify two different types of Cepheids by their spectra and the stars that surround them; the maximum brightness of globular clusters in our galaxy and the Andromeda nebula; and the maximum brightness of Population II stars in our galaxy and the Andromeda nebula. These last two observations produce agreeing measurements of the difference between the period-luminosity relationship of the two types of Cepheids. Given this difference, there is no luminosity difference between these objects that we would otherwise expect to be governed by the same physical laws and situations, eliminating the need for other explanation. While more results were needed to confirm the difference (and indeed show that the extragalactic distance measurements needed more adjusting than Baade suspected), the essential argument remained the same: the identification of the two classes is warranted because of the the ability of this identification to produce the unification of a number of observations and better accuracy within the observations due to the agreeing measurements this identification produced.

Until at least the middle of the 1980s, there remained significant controversy surrounding the further reaches of the cosmological distance ladder and thus the value of the Hubble constant.[103] One group working on the distance ladder, lead by Allan Sandage

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[103] Rowan-Robinson, Michael. 1985.

and Gustav Tammann produced measurements of the Hubble constant with $h \approx 0.5$. (Current determinations of the Hubble constant place the value almost directly in between the values determined by the two groups.) A rival group, lead by Gérard de Vaucouleurs, produced measurements such that $h \approx 1$. Michael Rowan-Robinson, author of a book reviewing the cosmological distance ladder reports, "when I asked the protagonists what was the range outside which they could not imagine the Hubble constant lying, these ranges did not even overlap."[104] In his book, Rowan-Robinson attempts to assign what he finds more reasonable weights and estimations of systematic error on the rungs of the distance ladder. He suggests that the origin of the disparity between the two parties rests on excessive correction due to dust by de Vaucouleurs, the underestimation of extinction by Sandage and Tammann (along with some inconsistencies in their treatment of a particular group of galaxies), and "a general tendency to overestimate the accuracy of extragalactic distance indicators."

Even with the existing disparity and the caveat about the accuracy of the distance ladder, Rowan-Robinson does not present this as a serious blow for the standard cosmological model. One reason for his confidence in the standard cosmological model is the support that the theory receives from the results of primordial nucleosynthesis, which is not very sensitive to the exact value of the Hubble constant and whose results can be reported using h as a factor.

The results of primordial nucleosynthesis in the form of observed relative element abundances was definitely a more convincing set of observations than the redshift-distance relationship. In their 1984 review of the theories and observations related to

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[104] Rowan-Robinson, Michael. 1985. Pg. 102.

primordial nucleosynthesis, Yang et al. write, “The almost universal acceptance of the standard (i.e., simplest) hot big-bang model (Friedmann-Robertson-Walker cosmology) rests, in large part, on the success of this model in accounting for the abundances of the light elements, particularly helium-4 and deuterium.”[105] In an earlier review, Olive et al. single out helium-4 abundance as cosmological evidence for four reasons: it is present in large enough quantities that its origin is likely to be mostly cosmological in origin; in the standard cosmological model, it is produced in large enough quantities that it could only be destroyed in the production of excessive amounts of heavier elements; and within the framework of the standard cosmological model, helium-4 abundance is the least sensitive abundance to the cosmological parameter with the poorest constraint: the ratio of photons to baryons, η.[106] As both reviews cover, the element abundances provide differential measurements of the parameters involved, thus the determination of the abundances of all these elements places tighter constraints on the theory than might otherwise be the case.

The success of these tight constraints is the agreeing measurements that the relative element abundance places on the cosmological parameter of the mass-energy density of baryonic matter. In their 1991 review of the state of the standard cosmological model, Peebles et al. adapt a figure from Yang et al. to demonstrate the convergence of element abundance measurements.[107] Peebles et al. add a band to indicate the region allowed by observed abundances, a band that they point out is in agreement with measurements of baryon density from other means. Thus not only is there agreeing measurements of the mass-energy density of baryons from the relative abundance of a

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105 Yang J. et al. 1984. Pg. 493.
106 Olive K.A. et al. 1981. Pg. 557
107 Peebles P.J.E. et al. 1991. Figure 2, pg. 772.

number of different elements, this measurement agrees with independent measurements of the parameter. Even though these observations do not fix other parameters, such as the mass-energy densities of all matter, dark energy, or the total mass-energy density, these agreeing measurement results were taken, as Yang et al. note, as convincing.

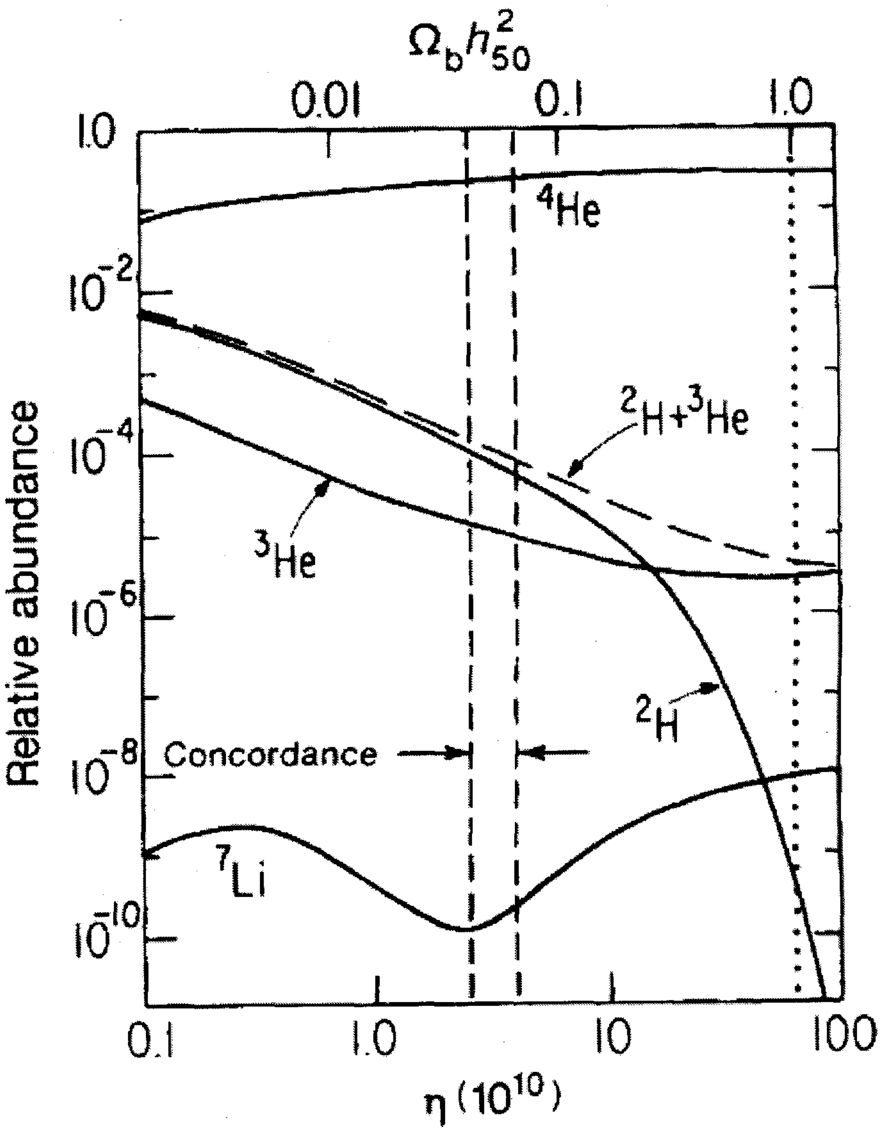

Figure 2.1: Measuring the density of baryons from element abundance. The systematic dependencies of the relative abundance of the light elements and the mass-energy density of baryons in the standard cosmological model (equivalent to the ratio of baryons to photons in the background radiation). The band labelled "Concordance" indicates the region that fits the observed element abundances. From Peebles et al. 1991.

Another significant success of the standard cosmological model that originates in theories of primordial nucleosynthesis is the prediction of the number of neutrino families, N_υ.[108] Due to the great influence of radiation density in this early period, a great number of neutrino families would significantly increase the overall mass-energy density of the early universe. Similarly, too few would radically decrease the density. The evidence from element abundances placed the number of neutrino families at three, a number later found in particle physics tests.[109] This convergence of results on the same value from the different sources, especially given the temporally prior restraint from cosmology, built confidence in the applicability of theories of particle physics to these regions of the universe distant in time and in space.

Just using element abundances alone, the standard cosmological model is able to unite a number of different observations under a series of fairly loose constraints. As Yang et al. write, these results build confidence in the “simplest” version of the standard cosmological model, presumably indicating both that the confidence is built outside of the need to include the cosmological constant and that while the results constrain some parameters, others remain relatively unconstrained.[110] This is, to some extent, one aspect of the power of these observations, as fairly weak constraints on many cosmological parameters can generate detailed information about the theory. As Peebles et al. describe the results:

> To summarize, the standard model makes specific and successful predictions for light element abundances and N_υ. Any proposed alternative cosmology must face the particularly difficult questions of what (other than the Big Bang) could have produced the observed abundance of deuterium,

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[108] Peebles, P.J.E. et al. 1991.
[109] Olive K.A. et al. 1981.Yang J. et al. 1984.
[110] Yang J. et al. 1984.

> an isotope readily destroyed in stars and not easily produced, and the remarkably uniform abundance of helium in galaxies.[111]

Thus even if alternative cosmological theories provide better accounts relevant to some parameters of the standard cosmological model, these alternative theories must also account for the ability of the standard cosmological model to provide tight constraints unifying these diverse aspects of the universe.

The cosmic microwave background radiation (CMB), is yet another observation significantly dependent upon the early period of heat and high density. It is pervasive in the universe, it is of extragalactic origin, and it is remarkable isotropic and homogeneous (to approximately one part in one hundred thousand). That it has a blackbody spectrum, or rather one that appears to be highly redshifted, is exactly what one predicts will be the outcome of primordial nucleosynthesis. The discovery of this radiation in 1965 provided significant support for the standard cosmological model over its prominent rival, the Steady State theory, which had not predicted such a background.[112] Even though later attempts were made to account for such background radiation through the action of specially shaped and constituted dust in the space between galaxies, many of these theories could not capture the blackbody nature of the radiation.[113] The later Quasi-Steady State Cosmology makes use of the same dust, but with additional factors that are not consistent with the Steady State theory.[114]

This review of some of the evidence for the standard cosmological model before the investigations of interest to this work shows even in this early work some use of the

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[111] Peebles P.J.E. et al. 1991. Pg. 771.
[112] Kragh, Helge. 1996.
[113] Peebles P.J.E. et al. 1991.
[114] Hoyle, F., Burbidge, G., Narlikar, J. 2005.

systematic dependencies between theoretical parameters and the results of observation in order to build more secure theories based on agreeing measurements. This is what we will build upon in the remaining chapters to establish that the recent addition of the cosmological constant is not a significant departure from the methodology providing support for the standard cosmological model prior to the addition.

Chapter Three: The Type Ia Supernova Investigation

We begin our case study of the combination of independent investigations with the type Ia supernova investigation. While a number of different research teams have undertaken this investigation, in this work we will primarily focus on the work of the High-*z* Supernova Search Team (HSST) and the Supernova Cosmology Project, (SCP). These two teams operated independently, though they often used data derived from the other team when the data was available and when the data met the standards set by the team prior to analysis.

Cosmologists greeted the recent supernovae investigation as an excellent source of cosmological observations in general and specifically for the measurement of two key parameters of the standard cosmological model: the mass-energy densities of matter and of the cosmological constant. Currently, such observations place their strongest constraints on the relative values of these parameters. Additional constraints adopted from other cosmological investigations place the values of these parameters, as fractions of Ω, the so-called critical density for a flat universe, at approximately $\Omega_M = 0.287$ for matter and $\Omega_\Lambda = 0.713$ for the cosmological constant.[115]

Part of the focus for our review of this investigation is the means by which the investigation uses observations to produce reliability in not only their results, but in the assumptions that they use in producing these results. We need to discover to what extent these observations go beyond the "desperate course" that Peebles identified in early cosmology.[116] That is, we wish to discover the extent to which the methodology of the

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[115] Kowalski, M. et al. 2008.

[116] Peebles P.J.E. 1971. Pg. vii

investigations go beyond relying on simplicity in order to create hypotheses and produce results and establish whether the incorporation of the cosmological constant into the standard cosmological model produces “a path to a believable approximation”.[117] This task will be taken up again ultimately in Chapter Five, where we review the power of combining the measurements from the supernova investigation with the measurements from the background radiation investigation. In this chapter, we will look at the way that the investigation relies upon the theoretical constructions made available by the standard cosmological model to produce observations that measure the parameters of the standard cosmological model. We will also see how this methodology works in the specific case of justifying the relationship that forms the basis of this investigation: the relationship between the relative brightness of the type Ia supernovae events over their lifetime to the peak brightness of these events.

Supernovae Observations and the FLRW Model

Supernovae are events of increased brightness in a small region of the sky; the standard scientific position on these events is that they are the results of the explosion of a star.[118] Such explosions eject and heat gases that remain visible for some time after the initial explosion. Astronomers divide these events into types by the qualities of the event's spectrum and the relative brightness of the events over time. As they are quite bright relative to stars and can be expected to exceed the brightness of their host galaxy, supernovae provide an excellent opportunity for astronomical observation. As discussed in some detail below, certain features of Type Ia Supernovae (SNe Ia) make them

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117 Peebles, P.J.E. 1993. Pg. 5.
118 Kirshner, Robert P. 2004.

particularly useful for observations as these events betray a regularity that can be used to determine their distances.[119]

The basic procedure of this cosmological investigation involves two major components. The first component of the project is an effort to determine the nature of SNe Ia as *standard candles*.[120] Standard candles are objects with known brightness that can be used to determine distance based on the difference between the intrinsic brightness of the source and the brightness recorded by an observer. The second component of the overall project is an effort to locate SNe Ia over a wide range of distances, and thus over a wide range of times, in order to generate accurate observations of the behaviour of the expansion of the universe. Such change over cosmological time, and the pace of that change, are systematically linked to the parameters of the standard cosmological model through the General Theory of Relativity. Within General Relativity, the Friedmann-Lemaître equation ties the values of the mass-energy density parameters to the behaviour of the scale factor over cosmological time and this is tied to the observations of SNe Ia over a range of distances.

The Friedmann-Lemaître-Robertson-Walker model (FLRW model) provides a straightforward account of the homogeneity and isotropy of the universe and, accordingly, an account of space and time within the model. Homogeneity in the model is possible as the Robertson-Walker metric effectively separates the spacetime of the model into a foliation of spatial hypersurfaces arranged along a time parameter independent of position on a hypersurface. These hypersurfaces and the time parameter provide the geometrical

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[119] In some publications, authors refer to type Ia supernovae through the use of "SN Ias" or "SN Ia's".
[120] Rowan-Robinson, Michael. 1985.

context in which the contents of the cosmological model can be described to be homogeneous. Additionally, the model allows for a descriptions of its dynamics according to the time parameter, the so-called expansion and contraction of space, that preserves this homogeneity. In spherical coordinates, the metric is represented using the following equation for the proper distance, ds^2:

$$ds^2 = dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right). \quad (3.1)$$ [121]

In this equation, all points in space are assigned the standard spatial coordinates of a spherical space. That the space is divided up into such spherical hypersurfaces presupposes that there is a synchronization between ideal clocks embedded in these hyperplanes such that they all follow the time coordinate, *t*, which we can identify as a cosmological time. The metric also introduces a deviation in the purely spatial part of the metric in the form of a scale factor, $a(t)$. The change in this scale factor over cosmological time is the result of the influence of the relevant mass-energy densities of the contents of the universe, described by the Friedmann equation (later modified by Lemaître to include the action of the cosmological constant). The change in the scale factor over time produces a shift in the spectrum of light that travels significant distance, producing a redshift, *z*.

The action of the scale factor introduces a complication for determining distances in cosmological contexts. For a slow enough expansion, there should be an area close to our position where distance determinations are not significantly influenced by expansion.

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121 Rich, James. 2001. In this equation, the speed of light has been set to a dimensionless c=1 for convenience.

For this region, we may with some safely extrapolate from those methods of determining distance within our galaxies to determine distances to other galaxies. This may be the case even for the determination of distance to those galaxies we observe to be redshifted, at least out to a small redshift, z. However, the action of the scale factor will produce a significant impact on the determination of distance to objects at greater distance.[122] The distance where the expansion becomes significant depends upon the rate of expansion.

Over the large distances of interest to cosmology, a preferred approach to measuring distance is through the use of luminosity distance.[123] Luminosity distance is a distance determination that depends upon the relationship between the amount of light one observes to the amount of light emitted by a source. This serves as a determination of distance because this relationship will depend upon the geometry of the space between source and observer. In the case of the FLRW model, the influence of the scale factor on luminosity distance is significant at great distance and is usually a quantity that one wishes to measure in one's observations.

The case of Euclidean space provides the most straightforward example of luminosity distance at work. In a three-dimensional Euclidean space, the light from a source spreads out to form a sphere around the source. At the time that light reaches an observer, the sphere will have expanded to a radius, d, equal to the distance between the source and the observer. The flux, F, that the observer records will depend upon that radius, the geometry of a sphere, and the luminosity of the source, L. This relationship is represented in the equation,

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122Rich, James. 2001.

123 Rich, James. 2001. Schutz, Bernard F. 1985.

$$L = 4\pi d^2 F \qquad (3.2)^{124}$$

Accordingly, we can then identify the luminosity distance, d_L, based on the relationship between flux and luminosity as follows:

$$d_L = (L/4\pi F)^{1/2} \qquad (3.3)$$

Thus in the case of the Euclidean space, luminosity distance is simply coordinate distance.

It is fairly straightforward to adapt luminosity distance to the case of the spherically symmetric spacetime of the Robertson-Walker metric. The surface area of a sphere of radius r_0 in the metric must take into account the scale factor, a, and is given by the following:

$$A = 4\pi\,(a_0 r_0)^2 \qquad (3.4)^{125}$$

As the photons observed will have been redshifted, by z, the observed flux will be altered accordingly, relative to the intrinsic luminosity; this produces the following equation:

$$F = L/A(1+z)^2 \qquad (3.5)^{126}$$

Accordingly, the luminosity distance is,

$$d_L = (1+z)a_0 r_0 \qquad (3.6)$$

Provided we can establish the intrinsic luminosity of a distant source, this provides us with an account of distance that relates directly and systematically to the light that we record in an observation. Specifically, the flux is an observed quantity that can be established by our measuring devices. Accordingly, if we know the intrinsic luminosity of

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[124] Schutz, Bernard F. 1985.
[125] Schutz, Bernard F. 1985.
[126] Schutz, Bernard F. 1985.

a source, then the ratio of flux to intrinsic luminosity can be established and this quantity provides information on the geometry that is of interest to our investigation.

Luminosity distance and redshift provide the basis for one set of systematic dependencies upon which the SNe Ia investigation relies. In the data that we collect on distant sources, the theory tells us to expect that there is a regularity in this data: a relationship between luminosity and redshift. As the redshift is a product of the change of the scale factor, this relationship provides information about the scale factor and, in turn, measurements of the parameters that influence the scale factor.

The primary use of redshift and luminosity distance in cosmology is its use in the determination of the Hubble parameter, a parameter representing the change in the scale factor over time. Given H_0 as the present value of the Hubble parameter, the following rough equality holds:

$$H_0 d_L = z + (1 - q_0) z^2 + \ldots \quad (3.7)^{127}$$

Here H_0 is the current value of the Hubble parameter (a product of the first derivative of the scale factor and thus a measure of the rate of expansion), q_0 is the *deceleration parameter*, (a product of the second derivative of the scale factor and thus a measure of the change of the rate of expansion). For objects relatively close to our position as observers, only the first term need be considered. Thus a measurement of the observed flux of an object of known luminosity, along with a measurement of redshift, provides a measurement of the current value of the Hubble parameter. In practice, a collection of objects is used to produce a measurement of H_0. The first observations in support of relativistic cosmology were those Hubble carried out that indicated, through the use of

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127 Schutz, Bernard F. 1985.

Cepheid variable stars as standard candles, that the eponymous relationship held for a range of galaxies.[128] For more distant objects, the current value of q_0 may be significant enough to consider and thus an observation of a more distant object can potentially provide information about both parameters.

The Hubble parameter and the deceleration parameter are *kinematic* parameters, in that they merely describe the action of the scale factor over cosmological time, along with the bodies carried with the scale factor, analogous to describing the motion of bodies in kinematics without reference to their causes. A purely kinematic analysis does not rely on a specific theory of gravity, thus it does not generate the further information without the use of some theory of cosmological dynamics.[129] Any cosmological theory that uses a metric theory of gravity, like general relativity, and has a commitment to the large-scale average homogeneity and isotropy of the universe will make use of these parameters as theoretical constructions that may, or may not, measure parameters of the gravitational theory. In the case of the standard cosmological model, the behaviour of the scale factor, and thus these kinematic parameters, are systematically dependent on the mass-energy densities of the universe.

Additional considerations may come into play in observations making use of luminosity distance as there are additional factors influencing what light one observes such as the opacity of intervening media and the peculiarities of the instruments used to observe the flux. Additionally, as cosmological observations depend on identifying redshift, other influences on redshift such as peculiar motion and the presence of

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[128] Kragh, Helge. 1996.

[129] Turner, Michael & Riess, Adam G. 2002.

intervening dust may influence the observation of individual events or objects. In order to combat the possibility of the undue influence of such complicating factors, measurements based on luminosity distance are done through curve-fitting to a collection of such observations even though individual observations could technically provide such information on their own.

While establishing the flux of an event or object is the (usually simple) matter of recording an observation, establishing the intrinsic luminosity of a distant event or object, establishing it as a standard candle, is the key to using luminosity distance and is the result of inference. The use of a standard candle is one of the extension of properties from known cases to those of (relatively) unknown cases. One must identify some type of event or object with measurable properties and then identify that event or object in future observations and identify in the object of that observation the same properties as one finds in the known of that type. Accordingly, the epistemic strength of observations using standard candles relies on the strength of the correct identification of a type in general and the identification of that type in observations.

Additionally, standard candles need not necessarily be identified as events or objects with a single fixed intrinsic luminosity, they can be of use if there is a dispersion of luminosities within a range. One can consider such standard candles to be better or worse in the sense that there may be a narrower or wider range of intrinsic brightness in the type. While a type of event or object with a single value for its intrinsic brightness would be an ideal standard candle, it is likely that any method of identifying a standard candle would at best identify a range of dispersion of the brightness of that standard candle. This intrinsic dispersion of luminosity, if low enough, would make the object or event a serviceable standard candle for establishing boundaries on distance measurements. Making repeated such observations can increase the accuracy of measuring parameters related to distance through placing tighter and tighter bounds.

Type Ia supernovae serve as standard candles not simply because they have a low dispersion within a range of intrinsic luminosities, but because where a SN Ia falls in the range of luminosities is determined to a large degree by the shape of the curve of its brightness plotted over time.[130] Calibrating the relationship between peak brightness and light curve shape allows astronomers to effectively reduce the dispersion in the luminosities of these events so that they are better standard candles than they would otherwise be. Alternatively, one could say that the relationship enables astronomers to treat SNe Ia as a family of standard candles identifiable by their common characteristics and specified by the length of their light curve.

It is worth noting that while there is some theoretical speculation about the underlying cause of SNe Ia that would produce homogeneity in brightness of the events, this is not part of the reasoning used in the cosmological observations. The consensus on the underlying nature of these events is that they are the result of a white dwarf gathering enough mass, from an orbiting companion body or from some other external source, to initiate gravitational collapse.[131] A white dwarf is composed of material that resists the contraction of gravity through pressure that derives from electron degeneracy pressure. This pressure can only support so much mass, the Chandrasekhar limit, that should be the same amount for every white dwarf star. Much of the speculation about these events may

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130 Phillips, M. M. 1993. Riess, Adam G. et al. 1998. Perlmutter, S. et al. 1999.
131 Perlmutter, S., Schmidt, B. P. 2003.

be considered a fairly straightforward extrapolation of astrophysics; yet these models seem to be regarded as still speculative by cosmologists and none of the supernova cosmology teams referenced in this work make use of this speculation. The support for the homogeneity of SNe Ia is based on observations of the events and the identifiable relationships between these events. While these remain theoretical constructions that the evidence must support in some way, they do rely less on assumptions of astrophysical principles than they otherwise would if their homogeneity as a type of event was based upon a causal account of the physics of white dwarf stars.

SNe Ia are identified by their spectral characteristics and by the shape of their light curve, the graph of their brightness in any given band of the spectrum over the time of the event.[132] In general, the light curve for a given band of one SN Ia is quite similar to that of another, once corrected for the effects of distance and intervening dust. The brightness of these events rises over about twenty days, peaks, and then declines for about sixty to one hundred days; the decline in the first thirty days after peak brightness is at a faster pace than the remainder of the decline. The chief differences is these light curves are the length of the event before and after the period of peak brightness and the slope of the declining brightness after the peak. Contemporary SN Ia research in cosmology relies on the relationship between light curve shape and peak brightness: broader light curves correspond to brighter peaks and one can use this knowledge to estimate the intrinsic brightness of these events. Early proposals to relate peak brightness to light curve shape proposed that the point on the curve at which the light curve began to flatten out should be the identifiable characteristic of light curve shape that should be used to determine a

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[132] Phillips, M. M. 1993. Riess, Adam G. et al. 1998. Perlmutter, S. et al. 1999.

relationship.[133] This proposal was abandoned due to the difficulty in measuring this point and astronomers turned primarily to a relationship between the peak brightness of the events (usually in the blue, *B*, band) and the overall decrease in brightness for a relatively short period in the immediate phase of decline from peak brightness.[134]

One representative example of a particular method of relating peak brightness to light curve shape is the fifteen-day blue band method (the $\Delta m_{15}(B)$ method); this method was developed by Mark Phillips (1993) and formed the basis for methods developed subsequently. The $\Delta m_{15}(B)$ method does not make use of the change in slope of the declining light curve, but rather rests on the ability of observers to accurately determine the time of peak luminosity and the luminosity at peak and for fifteen days in the rest frame of the event. Observers record the brightness over time and determine the change in brightness in the blue band over the fifteen days from peak brightness, $\Delta m_{15}(B)$. The blue band seems to be the band in the visual spectrum for which there is the most dramatic range in luminosity and the steepest line for the relationship between peak brightness and light curve shape. Using their now canonical catalogue of well-observed, relatively nearby SNe Ia of relatively well-known distance, the Calán/Tololo survey, Hamuy et al. (1996a, 1996b, 1996c) used a weighted, linear, least-squares fit to their data in order to more firmly establish the $\Delta m_{15}(B)$ relationship. Using a preferred sub-sample of twenty-six events chosen for their demonstrably low extinction, the amount of flux was lowered due to the presence of dust, Hamuy *et al.* measured the linear relationship between $\Delta m_{15}(B)$ and peak brightness in the *B* band to be $M_{\mathrm{PEAK}} = a + b(\Delta m_{15}(B) - 1.1)$, with the

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[133] Pskovskii, Iu. 1977. Pskovskii, Yu. 1984. While this is the same author, the spelling of the name varies in these publications.

[134] Phillips, M. M. 1993. Riess, Adam G. et al. 1998. Perlmutter, S. et al. 1999.

specific values of a = -19.258 ± 0.048, b = 0.784 ± 0.182, and σ(mag) = 0.17.[135] To use this relationship with newly discovered SNe Ia in order to determine their luminosity in the B band, one measures $\Delta m_{15}(B)$ of the SN Ia and uses the parameter values and the equation as determined by Hamuy et al. above to generate the luminosity (with the given range of accuracy). According to Hamuy et al., this procedure effectively reduces the dispersion of magnitudes for these events to a range of 0.17 mag from a range of 0.26 mag. They write, "The reduction of σ by approximately a factor of 2 permits SNe Ia to be used as excellent distance indicators (with precisions in relative distances of ~ 7% [to] 10%)."[136]

Later developments by the High-z Supernovae Search Team and the Supernova Cosmology Project expand on the basic technique outlined by Phillips and Hamuy et al.[137] The High-z Supernova Search Team used a method that tracks intensities of colour in different bands over time, using an algorithm to compare the intensities in these colour over time to the expectation of peak magnitude in the colour.[138] This is the *multicolor light-curve shapes* (MLCS) method. The Supernova Cosmology Project used an ideal light curve that must be stretched to fit the light curve in the rest-frame of an observed event.[139] The amount of this stretch is used similarly to the $\Delta m_{15}(B)$ method in determining the expected maximum luminosity. This is the *stretch factor parametrization* method. Both of these techniques are used in conjunction with procedures to check for the effects of dust in changing the relative intensity of the flux in different bands of the

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135 Hamuy et al. 1996a, p. 2394.
136 Hamuy et al. 1996a, p. 2396.
137 Riess, Adam G. et al. 1998. Perlmutter, S. et al. 1999.
138 Riess, Adam G., Press, William H., Kirschner, Robert P. 1996.
139 Perlmutter, S. et al. 1999.

events; in the case of the MLCS method, this check is incorporated into the method itself.

Given that SNe Ia function as standard candles, they can be used to determine the value of the cosmological parameters using the appropriate equation relating luminosity distance to these parameters. A rough approximation to the basic parameters in terms of the Robertson-Walker metric alone can be done with equation (3.7). However, only for relatively close SNe Ia outside of our local group of galaxies, could (3.7) be used for determinations of the Hubble parameter. Such SNe Ia would usually have their distance determined through other methods as well and thus these observations would be expected to add a robustness to the determination of the Hubble parameter through these other means. For SNe Ia at greater distances, equation (3.7) is sufficient for only a rough approximation of the deceleration parameter, though in general the cosmological teams mentioned above turn to a more complicated relationship between luminosity distance and the cosmological parameters. Perlmutter and Schmidt (2003) describe the underlying relationship between luminosity distance and cosmological parameters to which the SCP and HSST appeal through the following equation:

$$D_L = \frac{c}{H_0}(1+z)\kappa_0^{-1/2} S\left\{\kappa_0^{1/2}\int_0^z dz'\left[\sum_i \Omega_i (1+z')^{3+3w_i} - \kappa_0 (1+z')^2\right]^{-1/2}\right\} \quad (3.8)^{140}$$

Within this equation, $S(x)$ is defined based on the general curvature of the model, with $S(x)$ defined as sin (x), x, or sinh (x) for closed, flat, or hyperbolic curvature. The term κ_0 also represents general curvature; $\kappa_0 = \Sigma_i \Omega_i - 1$. In (3.8), each relevant mass-energy density, Ω_i, is considered with its associated equation of state, w_i, though in practice only the mass-energy densities for matter and that associated with the cosmological constant

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[140] Perlmutter, S. , and Schmidt, B.P. 2003. Pg. 200.

are considered as other densities play little role in the current cosmological era.

While equation 3.8 omits reference to the kinematic parameters, save for the identification of H_0, the systematic dependencies upon which it relies include these parameters. The kinematic parameters are the origin of the geometrical difference that makes the relative values of brightness carry systematic information on distance. Additionally, the kinematic parameters are the description of the relative position of points in the systems involved at the largest scales and this is reflected in the measurement of redshift. However, while it is possible to merely fit the luminosity distance data to the kinematic parameters, one can simply omit the reference to kinematic parameters because the kinematic parameters are systematically dependent on the mass-energy densities and thus produce a fit of these parameters more-or-less directly to the data.

One can still report a fit directly to the kinematic parameters and some authors do report such a fit. One benefit of addressing the kinematic parameters is that because they are not dependent on a particular theory of gravity, the results reported in terms of the kinematic parameters can be used by those investigating alternative theories and these results can be expected to be more likely to survive serious theory change in the future, thus potentially giving observational results more use. Another advantage is that the kinematic parameters can be used to illustrate the independence of the assumption of homogeneity and isotropy and the assumption of global expansion of the universe from the assumption of a hot, dense early universe. The kinematic parameters can help establish, even without the full assumption of the General Theory of Relativity, that there was an era in the past that was far denser than it is today. The drawback of such a fit to the kinematic parameters alone is that not all cosmological investigations measure the kinematic parameters. Thus one cannot look to accurate agreeing measurements of these parameters in combination with other cosmological investigations.

From the above details of the SNe Ia investigations, we can identify a set of assumptions used by supernovae investigators to produce their results. One assumption is the assumption of the FLRW model, along with some degree of homogeneity and isotropy. This allows investigators to produce luminosity distances and the relationship between luminosity distances to cosmological parameters. Associated with this last assumption is the specific assumption of a particular value of the Hubble parameter for use in calculations. While the identification of the nature of SNe Ia rest on a set of observations, the greater cosmological investigation rests on the assumption that the distant SNe Ia are of the same nature, in relevant ways, as those relatively close to us. We may consider this to be part of a more general assumption that the physics of the distant regions that we observe is the same in the relevant areas as the physics that we examine in closer regions and that we examine in the laboratory.

These assumptions work together to form the theoretical constructions that are used to turn the data into observations supporting the theory. In the determination of redshift, the basic physics of the spectrum allow us to identify the deviation in that spectrum. This, together with the observed brightness, provides information on the kinematic parameters only in the context of certain cosmological theories and provides information on the density parameters only in the context of the standard cosmological model (or a similar theory that includes similar relationships). These theoretical constructions are not used in order to make or verify predictions, but to produce a measurement of the parameters of the theory. The theory gains support by how well we can demonstrate that we are actually getting an accurate measurement of these parameters. Given the systematic relationship between redshift, distance, the scale factor and the mass-energy density parameters, not every set of data is guaranteed to produce a measurement. Thus that any measurement is possible at all is at least one successful test of the theory. As we will address more fully in Chapter Five, the agreeing measurement of these parameters from independent investigations can provide significant support for the reality of the measurements and thus for the theory used to produce them.

In order to address, within their investigation, the impact of these assumptions and the potential for systematic error and alternative hypotheses to address the results of investigation, investigators turn to cross-checks between different identifiable sets of observations to verify that the results that they are getting are robust when potentially significant differences are taken into account. This is somewhat similar to what we will examine later in comparing the results of investigations between independent investigations that return the same measurements of the parameters of a theory.

Cross-Checks and the Development of SN Ia Usefulness

Supernova investigators use cross-checks between different sets of data, sets with a significant difference or that are independent on some grounds in order to provide greater security for the inferences from the type Ia supernova observations. This methodology begins with the contemporary use of SN Ia as standard candles and thus we will examine this contemporary development before examining the cross-checks in general.

The contemporary use of SNe Ia as standard candles begins with a paper by M. Phillips (1993) that established a greater range of intrinsic brightness in these events than previously identified.[141] Using the data available at the time, Phillips establishes the both the dispersion of the type Ia supernova and a relationship between this dispersion and other observable features of these events; Hamuy et al. later expanded this work using their catalogue of the Calán/Tololo supernovae observations.[142] Additionally, the work of Hamuy et al. forms the basis of the relatively near sample of SNe Ia that are combined with more distant events to develop a range of observations sufficient to note the change in expansion represented by the deceleration parameter, q_0.

One of the primary hurdles to the introduction of a light curve to peak brightness relationship was the quality of photometry prior to the use of charge-coupled devices to record the flux of the observed light. Concern over the photometry of early SN Ia observations was a general concern at the time Phillips wrote his paper on SN Ia luminosity dispersion, as noted in review articles such as Branch and Tammann (1992) and the catalogue of type I supernova light curves by Leibundgut et al. (1991). The motivation for this concern was increased when Hamuy et al. (1990) demonstrated that significant differences in the observations of SN 1987A at different locations were due to the the different systems of photometry used. The poor photometry turned out to be particularly troubling for proposals that the light curve shape bore a special relationship to peak brightness. Though Pskovskii (1977, 1984) presented evidence for such a relationship, Boisseau and Wheeler (1991) demonstrated that systematic errors due to poor photometry could introduce such a relationship to the data. For example, in cases where the light from the host galaxy is not sufficiently removed from the photometry, this

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[141] Phillips, M.M. 1993.

[142] Phillips, M.M. 1993., Hamuy, Mario et al. 1996a, 1996b, 1996c.

contaminating light can flatten out the light curve of the event while adding to the observed flux, mimicking the relationship between light curve and peak luminosity. Boisseau and Wheeler also pointed out that the weakness in the photometry of the recorded supernova was almost certainly a source of systematic error leading to an apparent relationship between light curve shape and distance.[143]

That accurate photometry should be a limitation to the study of these events is not surprising, given the requirements of making detailed observations of these events. As the location of these events cannot be predicted, it is difficult, if not impossible, to book time in advance at the best telescopes in order to study these events as soon as they occur. This challenge was surmounted when SN Ia search teams began a project of booking telescope time in advance and conducting searches for supernovae on less suitable, but more freely available telescopes immediately prior to their scheduled time on more suitable telescopes.[144]

In order to reduce the systematic error associated with the identification of SNe Ia, Phillips relied on three criteria: supernovae must be recorded with a certain standard of photometry, the light curve of the events must be *well-sampled*, and the relative distance to the events must be established with one of a set of methods.[145]

Phillips' first criterion, accurate photometry, requires that the photometry used to record a supernova can rule out significant influence from the host galaxy. This accuracy removes the key systematic error for the light curve to peak brightness relationship identified by Boisseau and Wheeler. Given this criterion, all the observations save one

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[143] Boisseau, John R. and Wheeler J. Craig. 1991. Pg. 1283.
[144] Kirshner, Robert P. 2004.
[145] Phillips, M.M. 1993.

were performed using charge-coupled devices or photoelectric photometers. The only photographic data that Phillips used was that for SN 1971I where there were corroborating photoelectric data.

Phillips' second criterion, requiring a light curve to be well-sampled, restricts his sample to those supernova of which the photometric record of the supernova begins before or at peak brightness. Additionally, the photometric record must extend for at least twenty days past peak brightness and the decline rate of the light curve must be available for direct measurement, and not calculated from bracketing data.

Phillips' third criterion, accurate relative distance, requires that distances to the host galaxies of the supernovae admitted into the sample be produced from either the Tully-Fisher method or the Surface Brightness Fluctuations method. Both of these methods have a zero-point that is consistent: they seem to determine galaxies to be the same distance away.

The use of these three criteria serve to reduce potential sources of error, though of course they limit the sample size; Phillips is left with only nine events in his sample. Later work by Hamuy et al. (1995, 1996a, 1996b, 1996c) built up a larger sample, the Calán/Tololo sample of nearby SNe Ia that contemporary projects use for comparison to farther samples.

Another way that Phillips improves the light curve to peak brightness relationship is to use $\Delta m_{15}(B)$ rather than the relationship identified in Pskovskii's work. Pskovskii used the slope, β, of the light curve in the B band, or blue band, from peak brightness to the bend in the light curve where the curve begins to flatten out.[146] Identifying both the

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[146] Pskovskii, Iu. 1977. Pskovskii, Yu. 1984.

slope and the point of the bend is more difficult than identifying the total change in magnitude, thus Phillips, and later techniques using similar methods, reduced the potential error in these identifications. in Phillips words, the switch to $\Delta m_{15}(B)$ provides "a simpler and more robust procedure."[147] According to Phillips, the fifteen day period was arrived at after experimentation, presumably with the data from the available sample, to determine which interval provided the greatest discrimination.

The use of $\Delta m_{15}(B)$ to parametrize SNe Ia allowed Phillips to provide a new determination of whether an event was "peculiar" or not. One of the supernova accepted into his sample is SN1991bg, one noted to lie outside of the assumed range of scatter and within the same galaxy as another SN Ia. Branch and Tammann (1992) identify this event as peculiar as it was "intrinsically red and intrinsically subluminous"and had some aspects of its spectra that were also "peculiar." However, this event has a place in the observations used by Phillips and sits close to the best-fit line through the data points for a linear relationship between $\Delta m_{15}(B)$ and peak brightness in the *B* band (the line does pass through the error bounds for the observation).[148] This determination of what is and is not typical can have a significant impact on results, as Phillips notes,

> The large dispersion in the absolute *B* magnitudes implied in Figure 1 is in apparent conflict with the results of B&M [Branch and Miller, 1993], who derived $\sigma(M_B) \leq 0.36$ mag for a larger sample of SN Ia's. However, B&M eliminated SN 1971I, SN 1986G, and SN 1991bg from their sample due to their "peculiar" nature... B&M noted that more than half of the supernovae in their sample occurred at large distances where intrinsically fainter events such as SN 1971I and SN 1991bg would not have been detected. If we limit the B&M sample to supernovae at the distances of the Virgo and Fornax clusters or closer, and include the two events that were clearly intrinsically faint (SN 1971I and SN 1991bg), a dispersion of $\sigma(M_B) \sim 0.7$

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[147] Phillips, M.M. 1993. Pg. L106.
[148] Phillips, M.M. 1993. Pg. L107.

> mag results. Hence the large dispersion derived in the present *Letter* are likely to be more representative of the SN Ia class *as a whole*."[149]

Phillips references two difficulties for determining dispersion here. One is that determining what is and is not typical, at least one that will not provide an operation to distinguish between typical observations and peculiar observations, may introduce systematic error. The second difficulty is due to Malmquist bias, the bias that arises because, due to the design of an observation program or to the capabilities of an instrument, certain faint objects or events are left out of a sample. If Malmquist bias plays a role, the subluminous SNe Ia are those most likely to be missed in the distant sample, thus they are the least likely to play a role in early determinations of the typical nature of an event and act as a source of systematic error. By sticking to operational definitions of typicality (the three criteria) and demonstrating the correlation of peak brightness to light curve, Phillips can successfully redefine typicality for these events. Following the development of Phillips work by Hamuy et al., the assumption of typicality for SNe Ia was not that of a supernova with small dispersion around a typical intrinsic brightness, but a smaller dispersion around a typical intrinsic brightness dependent on the shape of the light curve.

Though Phillips is working with a small sample, he does attempt to look to use the established relationship as a focus for the unification of measurements obtained from independent means. For example, Phillips uses the relationship in regards to the assumed reddening of two supernovae in the sample. In the sample, their are two pairs of supernovae that were identified as similar on grounds of their appearance, and a

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149 Phillips, M.M. 1993. Pg. L107. Emphasis in original.

correction to one of the pair was applied based on this similarity. Phillips writes,

> Absolute magnitudes in B, V, and I for the sample of nine SN Ia's are plotted versus the decline rate parameter $\Delta m_{15}(B)$ in Figure 1. The points for SN 1986 G and SN 1971I are joined by a dotted line to indicate that the reddening for SN 1986G was determined by assuming that its light curves and colors were a close match to those of SN 1971I; the points for SN 1989B and SN 1980N are similarly connected, although the lie so close in the figure that the dotted line is not apparent. The fact that the reddenings were derived in this fashion does *not* guarantee that the absolute magnitudes will be similar; hence, the close agreement seen in Figure 1 reinforces the idea that these pairs of supernovae closely resemble one another.[150]

Phillips is suggesting that there is support for the correction due to the assumption of reddening in the agreement of the position of the corrected supernovae with the linear relationship suggested by the overall data. Thus the assumption of the nature of these supernovae and the assumption of the relationship of peak brightness to light curve shape both lead to the same agreeing measurement of the light curve to peak brightness relationship; it is not merely that they both produce coherent results, but that they both produce agreeing measurements.

Another example of this sort of reasoning is in the simple argument that there is a significant dispersion in the peak brightness of SNe Ia. Phillips does not merely demonstrate that there is this dispersion in the chosen sample, but he points out the dispersion relative to the identified error bounds, the correlation of peak luminosity to $\Delta m_{15}(B)$, and that this correlation is found in all three bands examined. Phillips writes,

> The major implications of Figure 1 are obvious. First, and most important, the data provide striking evidence of a significant intrinsic dispersion in the absolute magnitudes of SN Ia's. The scatter in absolute magnitude amounts to ± 0.79 mag in the *B* bad, decreasing up ± 0.59 mag in *V* and ± 0.46 mag in *I*. Even in the *I* band, the dispersion is significantly greater than the

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150 Phillips, M.M. 1993. Pg. L106. Author's emphasis.

> combined errors associated with the photometry and host galaxy distances. This increased scatter could conceivably be due to inaccurate reddening corrections and/or relative distances, but this cannot explain the second major result of Figure 1—namely that the peak luminosities and initial decline rates of SN Ia's are highly correlated, with the slope of correlation being steepest in B and becoming progressively flatter in the *V* and *I* bands. Spearman rank-order correlation coefficients calculated for the *B* and *V* data are 0.980 and 0.992 respectively. Eliminating SN 1986G and SN 1989B from the sample on the grounds that the reddening corrections for these events are uncertain yields correlation coefficients in *B* and *V* of 0.961 and 0.984, consistent in both cases with rejection of the null hypothesis at the 1% level of significance.[151]

The reasoning here is not merely that the dispersion is something that can be observed, but that measuring where an event falls within the dispersion can be measured in two ways, both directly and through a measurement of the shape of the light curve. In this case, while systematic error that correlated these two observations is possible, because of the agreeing measurements Phillips has at least shown that any systematic error must itself be correlated with either the light curve of the supernovae or its brightness. This is something unlikely to be the case if the relationship between peak brightness and light curve shapes is not truly part of the nature of these events.

That Phillips definition of typicality can identify a distinct set of supernova events is not in itself interesting, but that given this definition, he is able to show that measuring one aspect of these events systematically constrains the value of another aspect of these events, an aspect that we would otherwise take to be unrelated to the first, speaks to the importance of his definition and that he is correct in making this identification. This agreement in measurement between brightness and light curve provides evidential support for both the reality of the dispersion and that the conception of typicality used by Phillips

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151 Phillips, M.M. 1993. Pp. L105-L106.

is superior to that used by other investigators who rely on other conceptions of typicality. That is, rather than assign an *a priori* definition of type Ia supernovae that will predict features of these events that will agree with the data to a certain extent, Phillips definition is one that we can discover to be true because of the agreeing measurements in the data. This success prevents us from continuing to advance the claim that type Ia supernovae have an intrinsic brightness hidden to us due to systematic error; such a claim can only be advanced if we can also demonstrate why the systematic error also produces the relationship Phillips discovers.

The data available to Phillips left open the question of whether or not SNe Ia, rather than being members of one class, were rather members of two subclasses divided by luminosity. The hypotheses that there are two subclasses is encouraged as the events in Phillips' sample do not cover the range of $1.33 < \Delta m_{15}(B) < 1.64$. If there were in fact two subclasses, the linear relationship derived by Phillips might be an artefact of the two distinct classes. Phillips offers two short arguments against this hypothesis. The first argument is again that of the "peculiar" supernova that nonetheless find themselves a place in the relationship. The close agreement shows the typicality is more likely to be true. The second argument is that the more luminous events show the linear relationship on their own, and thus it is unlikely that there are two subclasses, one which shows the relationship and another, separate subclass that happens to lie along the line determined by the relationship of the other.

The strategy of Phillip's second argument above is something that is followed in many later supernova papers: identify more-or-less independent subsets of the available data, check the measurements of parameters provided by a restriction to that subset, and finally compare the measurements produced by each subsets to each other and to the measurements produced by ranging over the entire data set. To the extent that these measurements agree, this provides evidence that the systematic differences between these subsets that are responsible for the parameter measurements are those of the object of investigation, not some systematic difference working in conspiracy to confuse the results. This is a particularly powerful approach if the subsets identified can be linked to suspected sources of systematic error. In Phillips' case, he addressed the concern that the linear relationship could be caused by two distinct groups, each with their own relationships. That the relationships of each group produced the same measurement is evidence that these groups are jointly explained by the relationship. In later supernova projects, researchers divide their samples by host galaxy morphology.[152] As supernova behaviour may be based on the age of the stellar populations of the host galaxy and galaxy age is related to morphology, that measurements based on dividing into subsets based on galaxy morphology show agreement with other measurements is a sign that the impact of host galaxy age is at least limited to what range of disagreement there is in the various measurements.

Though work on calibrating the light curve to peak luminosity relationship is ongoing, the largest step in this calibration before the beginning of the contemporary use of SNe Ia to measure the cosmological constant is the work of Hamuy et al.[153] In building a sample of relatively nearby SNe Is, they filled in the sample in the range absent in the work of Phillips, writing, “The inclusion of the remaining Calán/Tololo SNe has

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[152] Hamuy, Mario et al. 1996a. Perlmutter, S. et al. 1999.
[153] Hamuy, Mario et al. 1996a, 1996b.

significantly populated the absolute magnitude/decline rate diagram in the range $0.8 < \Delta m_{15}(B) < 1.7$, strongly confirming the reality of the magnitude-decline rate relationship."[154] The slope that Hamuy et al. derive for the relationship is somewhat smaller than that derived by Phillips. They attribute this difference to a rule they employ to keep excessively reddened events out of their sample. This rule, justified by the expectation that excessive reddening is caused by dust, dust that might also reduce the magnitude in other bands, eliminates three fairly dim supernovae.

After this addition to the range of recorded supernovae light curves, there remain a few grounds on which to challenge the SN Ia peak luminosity to light curve relationship. For the measurement of the slope of the relationship itself, Hamuy et al. identify two possible biases, presumably among many standard astronomical sources of possible error. The first possible bias is the possibility of a systematic difference between events with $\Delta m_{15}(B) < 1.2$ and those events with $\Delta m_{15}(B) > 1.2$. The latter events all had distances based on the use of Cepheid variable stars, while the former events all had distances determined with the surface brightness fluctuations test. This opens the door for a possible systematic difference between the tests to influence the measurement here. The second possible bias is the Malmquist bias, which limits the number of low luminosity events in the sample as a function of distance. As Hamuy et al. point out, however, the Malmquist bias is likely to be replicated in applications of the relationship to determine the Hubble constant at great distance.[155] Thus even if the Malmquist bias is significant, it is likely that the relationship would then represent a truer sample of the domain of

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[154] Hamuy, Mario et al. 1996a. Pg. 2394.

[155] Hamuy, Mario et al. 1996b.

application, which is likely to have the same bias.

The use of the relationship of the light curve shape to the peak brightness of the event makes SNe Ia into better standard candles. While the work of Phillips and Hamuy et al. cements a greater degree of dispersion in the peak brightness of the events than others had hoped to establish, it also provides another parameter, one that an observer can determine from observation, that can be used to reduce the effective dispersion. One is able to use the light curve shape, rather than merely the identification of the event as a SN Ia, to determine a smaller range for the dispersion of absolute magnitude. Thus one can be more confident in the use of SNe Ia as standard candles.

What we see beginning in the effort to establish the light curve to peak luminosity relationship and carrying through in later applications of SNe Ia as standard candles is the attempt to establish both that the relationship is something found in the observations that we can expect to find in the future and something that is representative of SNe Ia themselves, not of some error in their observation. One way to establish this robustness of the theoretical construction is to have astronomers extend the relationship found in observations to new areas of the data where the relationship has not been tested. An example of this is the work of Hamuy et al. in enlarging the sample of SNe Ia, and enlarging the range of that sample, and demonstrating that the relationship found by Phillips continues to hold. This is thus justification for their claim that the results of their work "strongly [confirm] the reality of the magnitude-decline rate relationship."

Another way to establish this robustness is to demonstrate the ability of the theoretical construction to unify the account of more-or-less independent sets of observations. An example of this is the second argument put forward by Phillips against the possibility of the two physically distinct classes of SNe Ia. Under the assumption that there are two independent classes, the relationship still seems to hold for both sets. Thus the assumption of independence leads to the conclusion that the same relationship in the data still holds for the two sets of observations. As both the results of Hamuy et al. and the argument put forward by Phillips are internal to the SN Ia observations, there is a limit to how independent we can take the relevant situations to be and this leaves open certain possibilities for systematic error. However, the incremental approach to establishing independent subsets within the data, to establishing a range of agreement between subsets of observations that are independent to lesser or greater degrees, does serve at least to establish limits on some sources of systematic error and shows what systematic error, or alternative theories of the observation, must account for. If a particular form of systematic error should show up in one subset to a greater extent than it should in another, then the degree of agreement between the measurements produced by analysis using individual subsets provides a limit on that form of systematic error. For an alternative hypothesis to succeed, it must also account for the agreement between the measurements produced by using the subsets of observations. The degree of independence one can establish between subsets of the data will add to how much support we take this agreement to add to our trust in the theoretical construction under investigation. Additionally, the greater the degree of agreement between these more-or-less independent subsets of the data, the more for which systematic error or an alternative theory will have to account, and the greater our expectation that the phenomenon in question is a true feature of the data.

In order to more fully understand the approach that the supernova investigation teams take towards systematic error, we must examine the types of systematic errors that they identify and their approach to these types of systematic error. This will enable us to see how the cross-checks are used to bolster support for the overall project and show us where some external or future research can bolster support for the results of the SN Ia investigations.

The systematic errors identified by the SCP and the HSST are almost identical and the errors are grouped similarly. In Perlmutter et al. 1999, the SCP identifies the following categories and addresses cross-checks when addressing these categories when possible: extragalactic extinction, Malmquist bias and other luminosity biases, gravitational lensing, and supernova evolution and progenitor environment evolution. In Riess et al. 1998, the HSST divides the systematic error into the following categories: evolution, extinction, selection bias, effect of a local void, weak gravitational lensing, light curve fitting method. Later papers by both teams tend to refer back to these earlier categories, elaborating on their specifics when required. In "Measuring Cosmology with Supernovae", written by a member of each team, Perlmutter and Schmidt (2003) break down the systematic error of SN Ia observations into the following categories: K-corrections, extinction, selection effects, gravitational lensing, and evolution. Below we will discuss systematic error in the SN Ia investigations according to the categories of extinction, Malmquist bias, gravitational lensing, observation methodology and procedures and evolution. In the following, we will primarily use Perlmutter et al. 1999 as the primary example.

Extinction is the dimming of the light relevant to an observation due to the action of dust that lies in the space between the position of an observer and the object or event emitting light. Such dust may absorb or scatter the light and, though not common, it may re-emit light at the wave lengths of interest for an observation. Whether or not the dust will interfere with the observation and the extent of this interference depends upon the specific composition, size, and shape of the intervening dust as well as its distribution. Additional complications for certain astronomical observations can come about as dust of certain shapes can introduce polarization into light that passes through the dust cloud if that cloud is under the influence of a significant magnetic field. Extragalactic dust resides in the space in between galaxies and galactic dust may reside in our own galaxy or in the host galaxy of an object or event.

There are a number of ways to account for the effect of extinction. Within our own galaxy, there are a number of established maps of dust that an astronomer can use to correct for extinction. However, there may still be unknown concentrations of dust surrounding our galaxy, present in the host galaxy, and present in extragalactic space. However, as the extinction characteristics of dust are often specific to particular wavelengths, observing objects or event over a range of wavelengths can give insight into the presence and amount of extinction. Typically, dust tends to extinguish bluer light more effectively than it extinguishes redder light, hence a method that tracks the overall colour of an observation can detect extinction, particularly when the expected intrinsic colour of an observation is known.

In Perlmutter et al. (1999), the SCP uses the expected reddening effect of dust as the basis for a cross-check within their observations. The SCP compare the colour of the distant supernovae in their sample against those of the Calán/Tololo set, the set that the SCP use as relatively close SNe Ia for the purposes of this comparison, the overall colour of the events is represented by colour excess, a quantity $E(B-V)$ representing the magnitude difference between the *B* band and the *V* band as it would appear to be in the rest frame of the event. This comparison is used to test for any difference that might arise from colour change due to extinction—a colour change that would also introduce dimming. Given that there is no significant difference in the distribution of colour excess in the distant sample and the colour excess in the relatively near sample, the SCP conclude that there is not significant extinction in their sample, or at least that there is not significant difference in extinction between the two samples. As the difference in luminosity is what drives the conclusions of the investigation, the difference in extinction is more important than the extinction itself as far as the results of this investigation and the possibility of systematic error is concerned.

This cross-check is also a test of the typicality of the SNe Ia model used to make observations in a similar manner to those used by Phillips. Demonstrating that the distribution of colour excesses for the near and distant samples is the same is a demonstration that the identification, using the prescribed model, of distant events with the near events produces agreeing measurements of relavant parameters and produces a unifying effect on the data. In this case, the measurement is the colour excess profile of the samples. This unification could be maintained by a conspiracy of the model, the features of near and distant SNe (including perhaps SNe Ia evolution) and extinction, but this cross-check, and others, help to establish just how precise such a conspiracy must be. In this way, a cross-check against systematic error can also add to the burden of evidence that an alternative hypothesis must address.

That the SCP take this cross-check seriously as a test of typicality is borne out in their use of the resulting distribution in determining the fit for their "primary analysis" in

Perlmutter et al. (1999). In identifying the colour excess of members of their overall sample, the team identifies two distant events that are outliers to the distribution; the two supernovae appear to be “very likely reddened.”[156] Accordingly, these outlying, atypical supernova are excluded from the fit that the team presents as their primary results. The team does present the results of fits that include these events, showing that the results are still close to those that they highlight.

Riess et al. (1998) perform a similar cross-check comparison in a test for potential SNe Ia evolution. In their cross-check comparison, they look to the difference in extinction correction as tied to galaxy type, identifying differing amounts of dust associated with different galaxy types. The agreement in the measurements of SNe in different galaxy types is taken as evidence against significant extinction not accounted for.

One additional cross-check performed by the SCP in Perlmutter et al. (1999) is a check on the determination of cosmological parameters using only the bluest SNe Ia of their distant sub-sample. The result of this test is the demonstration that, to within statistical error, the measurements of cosmological parameters agree. This warrants the conclusion that the measurements of cosmological parameters are not sensitive to reddening and thus not sensitive to extinction due to common dust.

These cross-checks against extinction rely on the difference in colour and thus cannot close off the possibility that of extinction from grey dust, that is, a dust that causes extinction over a range of wave lengths without discernible preference based on colour. Proponents of Quasi-Steady State Cosmology have appealed to such dust in order to

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[156] P99, 573.

compare their own model to the results of the SNe Ia data.[157] A few cosmologists had speculated that there might be dust with this property well before the SNe Ia investigations were complete.[158] Riess et al. (1998) reports that such dust is unlikely, as it would significantly increase the luminosity dispersion of the sample beyond that which was observed, however, they note that they cannot dismiss a role for such dust. We will return to the issue of dust again in the discussion of cosmological evolution in Chapter 5.

Selection bias due to luminosity is also of obvious importance to considerations of systematic error. Such a bias is most acute in these investigation when the bias is different for different ranges of supernovae, as it is the luminosity observed for supernovae at different ranges that provides the measurements of cosmological parameters. The expected selection bias in these investigations is Malmquist bias, a bias pervasive in astronomical observations. Malmquist bias is the introduction of a preference for higher luminosity objects and events in a sample at farther distances due to a lower end cut-off in the flux of an observation. Due to the finite abilities of observation and recording equipment, such a flux cut-off is effectively guaranteed for observations spanning a large enough range. This bias need not have a great impact on an investigation, however, and it is of limited impact in an investigation of objects or events of small intrinsic luminosity dispersion, like SNe Ia.

The specifics of the peak luminosity to light curve shape relationship works against Malmquist bias in the SNe Ia investigations. The most significant impact that the bias could have is to introduce more supernovae that are bright relative to their light curve

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157 Vishwakarma, R.G. and Narlikar, J.V. 2004.
158 Arp, H.C. et al. 1991.

shape. This would mean that the light curves would tend to be narrower than they would otherwise be at the lowest end of the scale. However, these already very narrow light curves would be such that they would also likely fall beneath the flux cut-off too soon to be entered into the sample as they would not be seen for a minimum amount of days. Thus this bias is likely to have the most dramatic effect on the fewest events. Both Perlmutter et al. (1999) and Riess et al. (1998) use Monte Carlo simulations to estimate the effect of the bias across the span of observations and use this to generate estimates of the effect of selection bias.

The greatest danger from selection bias arises when different samples have different degrees of bias. As later papers combine SNe Ia from a number of sources and tend to introduce SNe from greater distances made possible by better techniques, this could be a tricky problem to overcome. The variety of techniques and recorded information from different teams of investigators makes cross-checks for this bias difficult if not impossible. However, because this bias must still preferentially not only identify brighter supernovae, but supernovae that are brighter relative to the dispersion of their light curve shape, it is unlikely to have significant impact. For if the bias merely adds more representative supernovae to the sample, this should by definition not influence the results except to increase their overall accuracy. In order to make the determination of the peak brightness to light curve relationship less accurate, the bias must introduce events into the sample that would skew the relationship. These would have to be events that are bright relative to the intrinsic brightness to light curve relationship and they would be events that would otherwise be too dim to enter the sample. This means that only at one end of the relationship would there be a population of events not representative of the overall population and this would be unlikely to significantly change any determination of the relationship that was based on the entire sample.

Systematic error associated with gravitational lensing covers a number of different effects, though all arise from the actual inhomogeneities of the universe. If the SNe Ia observations are successful in supporting their conclusions, we expect that the standard cosmological model, based as it is upon an approximate homogeneity, can accurately describe the basic dynamics of the universe and can still provide a description, at some level, of the distribution of matter in the universe. However, matter below a certain scale is obviously not homogeneous and this may introduce difficulties into particular observations. Within the standard cosmological model, Birkoff's Theorem allows that slightly over-dense regions can collapse within the overall homogeneity, carving out a bubble within the larger spacetime that shares the average density but that has all or most of the mass in that bubble concentrated in a smaller volume.[159] Accordingly, Kantowski, Vaughan, and Branch (1995) and Kantowski (1998), develop more detailed models that investigate the effect of these bubbles on observations, creating a "Swiss-cheese" model for the purposes of determining the effect that these inhomogeneities have on light passing through them. These papers form, along with others, the basis for the consideration of the effect of gravitational lensing in Perlmutter et al. (1999) and Riess et al. (1998) (where the additional lensing effect of a local void around our galaxy cluster is also briefly considered) . Usually, one considers gravitational lensing in the form of a concentration of mass acting as a focus, increasing the apparent luminosity of an

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159 Rich, James. 2001.

observation. However, in the passage through an under-dense region, the same principles result in a dimming of the observed light as the path of the light is bent towards the denser regions. Most light from an observation will pass through under-dense regions and see slight dimming, the occasional observation will see more dramatic increase due to the chance placement of a lensing body, and over a large enough sample the effect of gravitational lensing should even out.

The influence of gravitational lensing increases with distance. Earlier SNe Ia papers report the error as being of minimal concern, though with better and farther observations, the concern was more significant by 2003. Perlmutter and Schmidt identify this systematic error as ultimately limiting the accuracy of SNe Ia observations out to a great distance unless a large enough sample size can be produced.[160] While alternative models for use in making parameter determinations in swiss-cheese scenarios are available, the SCP and the HSST use *filled-beam* models in their analysis, that is, they use standard models that treat matter as homogeneously distributed, and they treat gravitational lensing error as part of their error budget. One exception is Perlmutter et al. 1999, where two fits to the data using two different swiss-cheese models are presented, demonstrating that these modified models return measurements of the cosmological parameters that overlap the primary fit, assuming a flat universe, and that the alternative models still very strongly support the inclusion of a cosmological constant. That these models do not influence the measurements is important when comparing the measurements from the supernova investigation with those from other investigations.

Our next category of systematic error, that arising from the peculiarities of the

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160 Perlmutter S. and Schmidt B.P. 2003. Pg. 209

methodology and procedures of the technical aspects of making observations, can be difficult to gauge using methods internal to an investigation. Indeed, if a systematic effect introduced from the observation procedure could be determined internally, surely the investigators would directly adjust for this effect.[161] Once the results of other investigations come in and a team of investigators has some reason to believe that a set of results is more accurate or more representative than their own results, they may presumably identify some specific systematic effect in their observation techniques. Lacking such independent evidence, however, there is little if any justification for investigators to infer a systematic effect in order to produce a specific result.

Within the type Ia supernovae investigations, one method to remove unknown but suspected systematic error from the investigation is to raise the standard for inclusion of an event on the basis of the details of the photometry of the event. In his early work, Phillips 1993 uses the three criteria of precise optical photometry, well-sampled light curves, and accurate relative distance as the gateway for his investigation. Riess et al. (2004) use similar criteria, based on the photometric and spectroscopic records of supernovae, to divide their sample into a "gold set" and a "silver set", a division that they follow in later papers with slight variation. In the 2004 paper, fits to the data are shown for both the gold set and the complete set, indicating the potential for an overall systematic effect from the poorer photometry and spectroscopy associated with the silver set. Later HSST papers report only on the gold set.

One form of systematic error arising from observation technique that the supernovae investigators do specifically address is that associated with K-correction. A K-

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[161] We see just this in the WMAP work.

correction is a correction applied to the photometry in order to account for the fact that there is a redshift in the observed light and that this will change the light as observed and recorded in one bandpass relative to the light at the source. As light-curve shape differs from band to band and supernovae are classified, in part, due to their overall spectra, K-correction is especially important in these investigations. For type Ia supernovae observations, the K-correction must be specially calibrated for redshift and for the spectrum recorded.[162] Systematic error can thus enter the K-correction through the accuracy of the calibration or through the accuracy of spectrophotometry, and the accuracy of the determination particular spectral template of individual supernovae.[163] As there are subsets of type Ia supernova with specific spectral features, these features can interfere with the accuracy of K-correction if not accounted for. Estimates on the error relating to calibration and photometry can be established by tests of the observing equipment on well-studied objects. Estimates on the error associated with the spectral features of SNe Ia can only be constrained by larger samples of supernova spectra.

These errors of technique are seemingly only amenable to reduction through external investigations that rely on techniques importantly different from those used in the primary investigation. As a general astronomical example, in the case where the accuracy of the instrumentation is in some doubt, the success of the instrumentation in independent tests can be used to reduce this worry. This has a bearing on K-correction, though the remaining potential error for K-correction can only be addressed through continued expansion of the sample of type Ia supernova recorded. Similarly, concern that

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162Kim, Alex, Goobar, Ariel and Perlmutter, Saul. 1996.
163 Perlmutter S. and Schmidt B.P. 2003. Pg. 207.

supernovae from outside of the gold set reducing the accuracy of parameter measurements due to their poor photometry and spectrophotometry is lessened as the sample size grows.

While some questions of cosmological evolution are more properly addressed as alternative theories or models, some questions of evolution are fairly straightforwardly considered as systematic error and addressed through cross-checks. These latter problems are the possibility of the evolution of supernova progenitor galaxies, either through their influence on the peak brightness to light curve shape or through the change in extinction properties. As mentioned above, one cross-check against the evolution of supernovae and their environments is to compare the features of type Ia supernovae from different types of galaxies. As different types of galaxies are thought to be composed of stellar populations of different ages, different galaxies at the same redshift can mimic, at least to some extent, differences in galaxies across a range of redshifts. Assuming that it is the differences in the progenitor stars of type Ia supernovae that would introduce evolution into these events, a cross-check of this type can limit the potential for systematic error due to evolution of the supernovae and their host galaxies. Both the SCP and the HSST appeal to cross-checks of this sort in their work. These cross-checks cannot necessarily guard against an overall difference in the amount of elements heavier than carbon that may be present in the universe as a whole as a product of stellar evolution over cosmological time, as higher levels of these elements may be present at higher levels in younger galaxies at later cosmological times.

In addition to looking to how the type Ia supernova investigations deal with systematic error, it is informative to look at the way that they deal with alternative hypotheses that may explain their results outside of the FLRW framework of the concordance model. Two particular alternatives are of interest here: tired light models and gray dust models. In the first case, the use of type Ia supernova investigation to rule out so-called *tired light* models demonstrates one of the key elements found throughout their methodology: the way that the assumptions of the model in general and in the specific case of the nature of type Ia supernovae can, through the demonstration of their usefulness in producing agreeing results in a number of cases, provide support back to the more fundamental assumptions of the standard cosmological model. In the second case, the aspects of the investigation that may not rule out gray dust but place constraints on a gray dust model show how the ability of the investigation to create more detailed information beyond a certain level of approximation can put constraints on alternative theories even when not ruling out these theories. We will examine tired light and time dilation below and return to gray dust with a discussion of the quasi-steady state theory in a later chapter.

The evidence in favour of time dilation associated with redshift comes in the context of an attempt by the SCP to support their particular use of the peak brightness to light curve relationship. The SCP uses a stretch factor, s, that introduces a correction to the luminosity of a supernovae by stretching the rest-frame light curve of the event to match an arbitrary template. The best fit of the stretching determines the correction, rather than simply matching the peak brightness to the brightness fifteen days later as with $\Delta m_{15}(B)$.

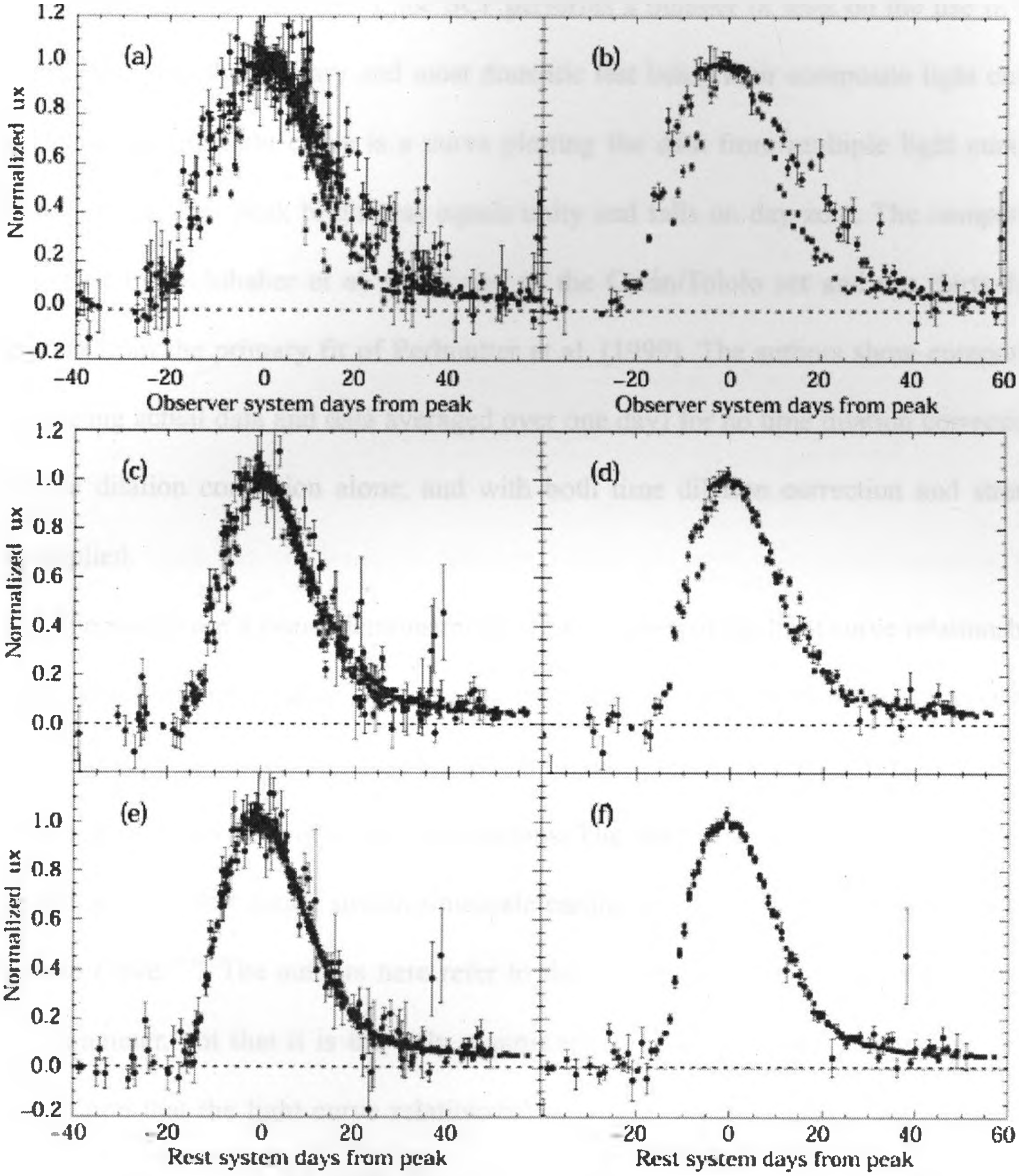

Figure 3.1: Light-curve and time dilation comparisons. The blue circles indicate results from the Calán/Tololo sample and the red circles indicate supernovae taken from the SCP sample. The curves have been normalized to a brightness of 1 for the purposes of comparison. (a) and (b) are not adjusted for time dilation or stretch factor. (c) and (d) have been adjusted for time dilation. (e) and (f) have been adjusted for time dilation and stretch factor. In (b), (d), and (f), the data has been averaged over 1-day intervals. (From Goldhaber et al. 2001)

In Goldhaber et al. (2001), the SCP performs a number of tests on the use of the stretch factor, with the primary and most dramatic test being their composite light curve test. The composite light curve is a curve plotting the data from multiple light curves, adjusted so that their peak brightness equals unity and falls on day zero. The composite curves used by Goldhaber et al. make use of the Calán/Tololo set and the thirty-five supernova from the primary fit of Perlmutter et al. (1999). The authors show composite curves (using actual data and data averaged over one day) for no time dilation correction, with time dilation correction alone, and with both time dilation correction and stretch factor applied.

The results are a visual demonstration for the power of the light curve relationship, together with the time dilation, to unify the data. The majority of the data points in the ultimate curve (with all adjustments) vary from no more than two-percent to four-percent, within the measurement error of the observations. The authors note that, "It is remarkable that application of this single stretch timescale parameter results in such a homogeneous composite curve."[164] The authors here refer to the fact that the stretch factor has only a single parameter, not that it is the only assumption. The result is still remarkable in its demonstration that the light curve relationship is able to produce such a unifying effect within the data, showing the same close results in the near and distant samples. This is dramatic evidence of the reality of the light curve relationship, at least in the range explored by the sample, because it shows the remarkable agreement in the relationship between the shape of the supernovae light curves and their peak brightness. The agreement of the curve shows that a measurement of redshift and a measurement of the

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164 Goldhaber. G. et al. 2001. Pg. 362.

light curve shape both provide agreeing measurements of the time delay of the event, as expected by General Relativity. In order to make the case that there is systematic error within these observations, one has to demonstrate how this systematic error can be so highly coordinated with peak brightness, light curve shape, redshift, and apparent time dilation. This raises the amount of evidence that an alternative theory has to raise in its own support in order to seriously challenge the standard interpretation of these events.

Goldhaber et al. also take the success of this unification to be evidence for the reality of time dilation.[165] We can understand that, though the assumptions of the standard cosmological model are required in order to make the supernova observations into a measurement of cosmological parameters, the assumptions used to make determinations of the luminosity of these events need not introduce so close an agreement in time dilation. Goldhaber et al. do additional analysis on their data, demonstrating that the stretch factor is not associated with redshift, while the overall width of the light curve, uncorrected by time dilation, is so associated. These results tie together the strength of the light curve relationship with tests of time dilation, so that independent tests of each can support the other. However, the association of light curve width with redshift may have a selection effects as a source of error. If the brightness of wide light curve events makes them more noticeable at greater redshift, this will introduce a similar relationship to that observed with light curve width, at least to some extent.

The HSST perform another, demonstrably independent test of time dilation using type Ia supernovae.[166] Blondin et al. rely on the determination that type Ia supernovae

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[165] Goldhaber. G. et al. 2001.

[166] Blondin, S. et al. 2008.

demonstrate very similar spectral characteristics on given days relative to their peak luminosity and that these characteristic spectra are accurate to within very few days and independent of the overall shape of the light curve. These features allow for observers to identify the age of type Ia supernovae with well recorded spectral characteristics. Using thirteen disant supernovae, Blondin et al. were able to find significant support for the presence of time dilation (significance >95%). They note that it is "no surprise" that they discover this result, but they stress two unique points of their paper.[167]

The first point they stress is that their observations, because they are not dependent on the brightness of the event observed, are free from selection bias, unlike those of the earlier paper. This is a demonstration of the independence of their results from the SCP time dilation results. This independence gives us more confidence in time dilation in general and hence in the reality of the light curve relationship, fundamental as time dilation is in generating the agreement amongst the supernova data in conjunction with the light curve relationship.

The second point that Blondin et al. stress is that their results not only provide evidence for time dilation, but they make the question of time dilation one of specifically measuring a parameter. Whereas the expected time dilation in a FLRW universe is $1/(1+z)^b$, where $b=1$, Blondin et al. find that $b=1$ is better supported than no time dilation, but that b may still vary slightly from 1. They thus look forward to a future series of tests where measuring this parameter may be possible. This looking forward to a more detailed and specific test in order to support what is an assumption for the fundamental tests of cosmology is an important feature of contemporary cosmological tests. This coincides

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[167] Blondin, S. et al. 2008. Pg. 733.

nicely with one of the important features of the Newtonian methodology noted in Chapter One: turning theoretical questions into questions of parameter measurement.

Methodological Notes

One thing that the supernova investigation demonstrates, as a case study for an overall methodology, is the evidential strength gained by looking for independent support for the theoretical parameters used in identifying phenomena in recorded data. By producing support for the theoretical parameters from samples that should have differing systematic errors, we bolster support for the techniques used to measure the phenomena to which the theoretical parameters are systematically dependent. Even in cases with smaller sample sizes and smaller differences between two samples, as with Phillips' identification of the typicality of a SN Ia, the demonstration that there would have to be different systematic error with identical effect in order to produce the same measurement of the theoretical parameter in two independent cases can be convincing. A more convincing case is demonstrated by work such as that by Goldhaber *et al.* (2001), which shows that the stretch-factor correction to the supernova light curves does substantially unify our understanding of these events.

There are additional strengths to be gained from this methodology in the development of successive approximations to the data. Ideally, according to the methodology for which we are developing the supernova investigation as a case study, we can use the physical principles of our theory to construct accounts of physical systems that at least approximate the dynamics of the systems to a high accuracy which we can then use to produce more detailed measurements and approximations. In the simple case, deviations from an early approximation can be used to get more detailed information about the theoretical parameters used in these hypotheses. This not only provides a more detailed physical account but, by its success in providing information, gives support to the claim that the original approximation was, to some degree of accuracy, correct in its application. In the case where there is independent use of these hypotheses to provide initial approximations that produce information, the independent observations provide more than the sum of their support. In the ideal case, these independent observations provide measurements that agree, thus further increasing the support for the initial hypotheses.

In the case of the supernovae observations, the primary cosmological approximation put to use is that of the redshift-distance relationship. That there is such a relationship in regards to those galaxies or galaxy clusters relatively near to our position is grounded in a plethora of cosmological observations. In the context of the standard cosmological model, this relationship is held to hold, as an approximation, for all galaxies or clusters of galaxies. We can identify it as a phenomenon identified in the data: a regularity that is expected to hold exactly in some cases but that has differences in particular cases due to the limits of observational techniques or peculiarities in the physical systems that indicate some other physical forces or phenomena at work. It is this latter property that is put to use in the supernovae observations, where a deviation from the linear relationship at great distances is used to provide information on the parameters of the standard cosmological model. In these observations, the difference over distance (and thus time) gives a measurement of the mass-energy densities associated with matter and the cosmological constant.

Specifically, the deviations in the data from the linear redshift-distance relationship are systematic in the way that we expect to see from values of the cosmological parameters in question. That is, the deviations from the primary phenomenon identified in the investigations allow us to identify secondary phenomena. These secondary phenomena are other regularities in the data that appear only after considering the primary phenomena, the measurements of which provide the information on additional theoretical parameters.

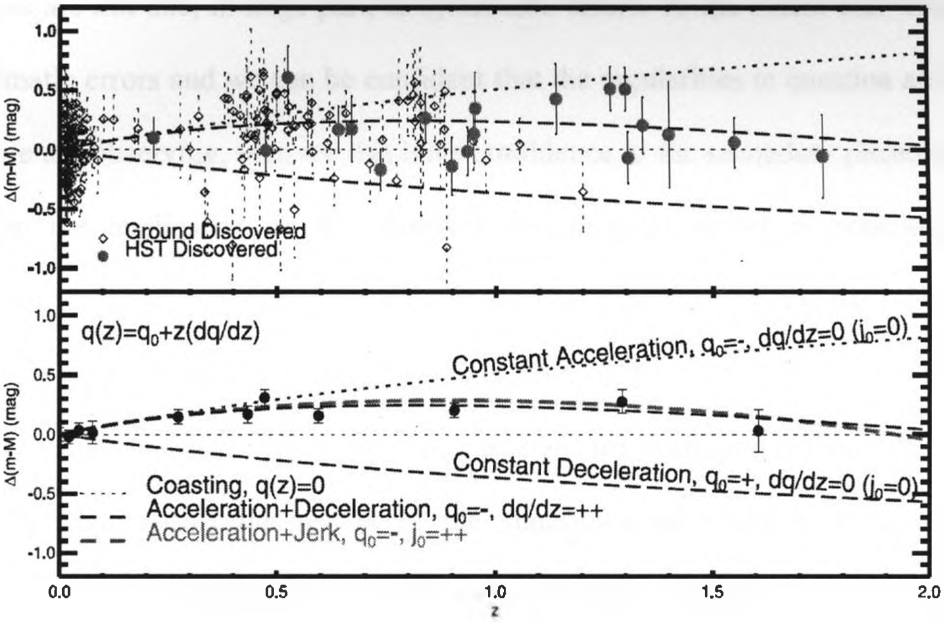

Figure 3.2: Kinematic parameters from SNe Ia. This shows the residual in the kinematic parameters relative to coasting universe. The bottom figure graph has data points represented by weighted averages for the purposes of illustration. (From Riess *et al.* 2004. Pg. 676)

This systematic relationship is illustrated nicely in Figure 3.2, taken from Riess *et al.* (2004). In the figure, the authors identify the observational results produced if the phenomenon of the local redshift-distance relationship holds throughout the universe for all cosmological time as a flat line in the middle of the graph. The authors also show a number of other potential curves for the systematic deviation of the relationship given certain cosmological constraints. In the graph in question, a positive slope to a curve indicates a period where the expansion of the universe is accelerating (or where dust mimics this effect) and a negative slope indicates where the expansion of the universe is slowing.

To have confidence in the results of these supernovae experiments, we must be confident that we are getting results of systematic regularities at work and that these regularities are not due, in large part, to systematic errors. To the extent that we can rule out systematic errors and we can be confident that the regularities in question are at work in what we are observing, then we can have confidence in the secondary phenomena that arise from the application of the standard cosmological model in generating these measurements. This figure addresses only the kinematic parameters, and part of the power in combining the results of the supernova investigation with other cosmological investigations, through the parameters of the standard cosmological model, is that it reduces the chance that the results of the supernova investigation is plagued with systematic errors. Through this we can then be more confident in these kinematic parameters.

The success of the supernovae observations in producing measurements bolsters support not merely for the claims that there are particular values for these cosmological parameters, but also in more fundamental claims. The information derived from these observations comes from the identification of the phenomenon of the redshift-distance relationship as a core element of the standard cosmological model. The success of the application of this theoretical construction to produce the supernovae observations supports that it was a good approximation to the universe and that in turn supports the hypotheses that create this phenomenon in the data. Similarly, the failure of these supernovae tests to provide information would undermine support for the identification of the redshift-distance relationship and the underlying hypotheses. For example, if the results of the supernovae tests had revealed an overly noisy and unusable data set then the core element of expansion and perhaps also that of relative isotropy and homogeneity would have been in jeopardy.

Chapter Four: The Background Radiation Investigation

The second investigation providing support for a positive value of the cosmological constant that we will investigate is the investigation into the background radiation, specifically into the signs of large-scale structure that can be seen in this radiation. The Wilkinson Microwave Anisotropy Probe (WMAP), a key instrument in this investigation, has produced a measurement of the mass-energy density associated with the cosmological constant of approximately $\Omega_\Lambda = 0.742$, not far from the 0.713 determined from the supernova investigation.[168] Essentially, this investigation uses the standard cosmological model, theories of particle physics, and theories of fluid dynamics to create a framework for determining the way that inhomogeneities in the early universe develop over time. At the *era of decoupling*, when the close interaction of photons and matter comes to a halt, the majority of photons stream away and many reach us as the background radiation.[169] Those photons bear the imprint of the relative density of the matter in their regions of origin. Assuming that our theories of particle physics and fluid dynamics are adequate to describe the universe at this early era, the inhomogeneity at the time of the emission of the background radiation is dependent on initial conditions and the homogeneous parameters of the standard cosmological model, as these control the ability of inhomogeneity at different scales to survive, grow, or shrink. Given the surviving inhomogeneities and their scales, the size that the scales appear to us is then determined by the overall geometry of the universe, which includes a contribution from the cosmological constant.

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168 Peebles, P.J.E., Page, L.A., Partridge, R.B. 2009. Pg. 467 Their work references a preprint version of Dunkley et al. (2008) and Kowalski et al. (2008).

169 Rich, James. 2001.

As discussed in Chapter Two, the background radiation originates in the distant past and it is closely linked to our theories of the origin of light elements in the universe. As such, an investigation into the details of the background radiation gives us an opportunity to compare the dynamics and contents of the universe at that cosmological era to the dynamics and contents of the universe at the present era. Additionally, as the mass-energy density of radiation played the dominant role in the dynamics of the universe in that era, an investigation into the background radiation provides an opportunity to measure the parameters of the cosmological theory in a different setting than they are now.

The aim of this chapter is to investigate the general methodology of the background radiation investigation, the assumptions that are used in the investigation and the systematic dependencies on which the investigation relies. The focus in this chapter will be mostly on the WMAP team and their efforts and results. Additionally, this chapter will discuss the possible systematic error that the WMAP team identifies in order to show some of the potential for leading the measurement of cosmological parameters astray that are specific to this investigation.

Large-Scale Structure Investigations

Large-scale structure investigations seek to use our knowledge of the physical laws that promote or disperse inhomogeneities in order to measure cosmological parameters.[170] While it is possible to use investigations of large-scale structures in truly inhomogeneous cosmological models, our interest is the role that their investigations play in the attempt to measure the parameters of cosmological models that rely on the Cosmological Principle,

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[170] Peebles, P.J.E. 1980.

that the universe is homogeneous and isotropic on some large-scale average. The larger-scale homogeneity provides the context for specific volumes where some matter is distributed more densely in some areas and less densely in others.

The tension between the tendency of matter to clump in the centre of relative voids of matter and the overall expansion of the universe is the primary interaction of use in large-scale structure investigations.[171] Some regions that are denser than the universal average will be able to withstand the general trend of expansion, while others will not. The result is that the action of the expansion of the universe will erase inhomogeneity at some degrees of relative density and will leave untouched inhomogeneity at other degrees of relative density. Given a knowledge of the present distribution of matter and of the behaviour of the scale factor at different times, we can extrapolate back to the inhomogeneities of the universe at an earlier time. Similarly, if we have the knowledge of the conditions of the inhomogeneities of the universe at two different times, we can use this information to determine the parameters that favour the evolution of the earlier distribution into the later distribution. In practice, the earlier conditions are not often known in large-scale structure observations, though they may be reasonably constrained to within a usable range.

The Sloan Digital Sky Survey (SDSS) and the 2 Degree Field Redshift Survey (2dF) are two examples of large-scale structure investigations.[172] Both investigations seek to map out a number of objects at cosmological distances, galaxies and quasars in the SDSS and galaxies alone in the 2dF. By charting the distribution of the mass in the

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171 Peebles, P.J.E. 1980. Rich, James. 2001.
172 Castander, F.J. 1998. Peacock, J.A. et al. 2001.

universe in the regions that they are able to survey and by using the position of these objects as a guide, these surveys seek to track the large-scale structure of the universe and extrapolate the possible parameter values from this distribution. In both cases, the information on inhomogeneities that they discover can be taken back to initial conditions of the nature of inhomogeneity in the universe present before the era of decoupling. However, some of their results can be thought of as merely an observation of how the influence of the mass of the objects that they can see acts against the average density of matter. (Those SDSS and 2dF results that rely on pre-decoupling dynamics, like those of the WMAP, are significantly more complicated.)

To determine the factors that may be at work influencing the evolution from one time to another in the contemporary cosmological era, one need only rely on the determination of the Hubble constant, as it represents the current rate of expansion, the observed mass, and the mass-energy density of matter, both from ordinary, or baryonic, matter and from dark matter. These are our primary concerns as the dynamics of the systems in question are governed almost entirely by gravity. For an inhomogeneity to grow into a sustained structure, it must have enough mass in enough of a volume to overcome the expansion of the universe that would otherwise effectively carry away the matter present in the region. As the matter around the region in question is homogeneously distributed, it effectively plays no role in the region that we are considering, and we can consider each region to be, in a way, analogous to its own little universe. If the density inside a region is significantly greater than the critical density, then the region will pull away from the global expansion of the universe and collapse into its own structure.[173] Depending on the specific volume and distribution that we are considering, this structure may be anything from a star to a galaxy cluster to even larger structures. However, it is worth noting that while we define the critical density a for the current time, given the current rate of expansion, structure formation takes place over a range of times where the rate of expansion was different and thus the critical density for a region of space was different. Thus structure formation will change over time and with the behaviour of the rate of expansion. If we know the distribution of the scale of inhomogeneities at one period, we should know the distribution of the scale of inhomogeneities in the future, as some will have grown predictably and some will have dispersed.

In this simple scenario, there are a number of systematic dependencies at work. The observations can establish what inhomogeneities, of what density, develop over time. The way that inhomogeneities develop and at what rate gives us information about the parameters of the standard cosmological model. In a universe where matter is the dominant mass-energy density, the overall density of matter determines what inhomogeneities develop and the rate at which they must develop. In a cosmological model where the mass-energy density of matter equal to the critical density and where matter is the only significant density, then inhomogeneities only have to be slightly over the critical density to pull away from the overall expansion of the universe. In a universe where the mass-energy density of matter is greater than the critical density, regions that are only slightly overly dense will not have time to form into structures before the collapse of the universe. In a universe with a mass-energy density of matter that is lower

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[173] Rich, James. 2001.

than the critical density, the difference in the density between a region where structure forms and the average density will be more pronounced. Such regions will expand along with the rest of the universe for a time until they begin to turn around and collapse inwards. The relative expansion of a region is going to be controlled by its density and by the rate of change of the scale factor over time. Over a long enough period, the second derivative of the scale factor becomes important, and this is controlled, through the Friedmann-Lemaître equation, by the mass-energy densities of the standard cosmological model. In a model with a cosmological constant, the cosmological constant plays little role while the mass-energy density of matter is dominant in the universe, but it eventually acts to slow and then stop structure formation when it is significantly dominant over the mass-energy density of matter. Changing the values of these mass-energy density parameters changes the rate at which overly dense regions will expand and then form structures or whether they will form structures at all.

The systematic effect that the total mass-energy density and that the distribution of mass within a region have on the development of inhomogeneities allows for mutual support of the measurements of the cosmological parameters and the methods used to determine the ratio of light observed in a region to the mass of that region. As determinations of the mass in a given region that are mistaken will give mistaken measurements of cosmological parameters, if we become more confident in the measurement results than we were in the determination of the ratio of mass to the light we observed, then this additional confidence can be passed on to this determination of the ratio, at least to the extent that some other method of determining the ratio would provide some different measurement of cosmological parameters.

In the era before decoupling, the era of interest to the WMAP project, there are complications to the scenario above where interaction between regions is mediated only by gravitation.[174] During this extremely hot and dense era, baryons matter and photons continually interact, forming a single fluid. Thus the action of gravity that would cause inhomogeneities to develop must not only work against the expansion of the universe, it must also work against the pressure of the fluid, which is the pressure of the photons interacting with baryons and each other. An additional complication is that the mass-energy density of the photons themselves is much more significant to the dynamics of the universe in this era than the other mass-energy density parameters. The former complication is addressed in large-scale structure investigations by turning to fluid dynamics to model the behaviour of the baryon and photon plasma of this era. The pressure of the plasma works in a manner analogous to sound waves or to waves in water, leading to fluctuations of over-dense regions and under-dense regions at different scales like overlapping ripples in water. These baryon acoustic oscillations are overlaid on the dynamics discussed above, where the propagation or diminution of inhomogeneities at certain scales is based on the relationship between the density of a region and the rate of expansion of the universe.[175] The density of the baryons as a whole plays a role as well, as this density will determine the speed at which these fluctuations oscillate.

At the decoupling of baryonic matter and photons, the combination of baryons into stable atomic nuclei means that the universe is effectively transparent to the photons

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[174] Kolb, Edward A. and Turner, Michael S. 1990.

[175] In some sources, "Baryon Acoustic Oscillations" or "BAO" is used to refer to projects that measure background radiation anisotropies at high angular scale. However, the basic physics is the same, with baryon acoustic oscillations being dominant over gravitational interaction at the larger angular scales and gravitation being dominant at lower angular scales. Some BAO data is generated from observations of the ultimate effect of these oscillations in galaxy clustering.

and they stream away to become the background radiation. These photons contain information about the *surface of last scattering*, the baryons with which the photons of the background radiation last interacted. There will be temperature differences in the photons that are dependent upon the density of the baryons in the region where the photons left. These temperature differences, which can be read in the background radiation, thus provide information about density fluctuations of the baryons at that time. Thus a large-scale structure investigation of the background radiation will look to the anisotropy of the background radiation, the difference in the radiation when looking in different directions, when looking at different regions of varying size as determined by an angle on the visible sky, and use this as a measurement of the inhomogeneity in the surface of last scattering. In practice this is usually represented by a quantity angular scale, *ell*, where the angular scale indicates that we are comparing regions on the sky with a width of about *π/ell* radians.[176]

The relationship between temperature fluctuations in the background radiation and density fluctuations in the surface of last scattering is complicated by the presence of (non-baryonic) dark matter.[177] Dark matter, which according to the consensus model is present in a far greater amount than baryonic matter, does not interact through electromagnetism. Thus it is free to form over-dense regions around the era of decoupling without being subject to the pressure of photons. To some extent, the pressure of the photons has some effect as the dark matter will interact gravitationally with the baryons that the photons effect directly. Ultimately, the presence of dark matter means that regions

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176 Spergel, D.N. et al. 2003.
177 Kolb, Edward A. and Turner, Michael S. 1990. Spergel, D.N. et al. 2003.

of over-density in the surface of last scattering could be significantly denser than the temperature difference in the background radiation would otherwise indicate.

The cosmological parameters of photon mass-energy density, baryon mass-energy density, and cold dark matter mass-energy density not only control the dynamics of density fluctuations, but also how much time these fluctuations have until the only interaction between regions is through gravitation.[178] At some point, the universe is transparent to photons and thus the pressure from photons that influences fluctuations is no longer at work. The timing of this event is controlled by the action of the scale factor and, at the era of decoupling, the dynamics of the scale factor is controlled almost entirely by the mass-energy density of radiation, with the mass-energy density of cold dark matter and the mass-energy density of baryons playing secondary roles. Thus the final power spectrum of fluctuations imprinted upon the background radiation depends upon the initial power spectrum of fluctuations and how the dynamics of the early universe allowed those fluctuations do grow or decay until the release of the background radiation.

Once the power spectrum of fluctuations has been frozen into the background radiation, there are additional influences on the power spectrum as we record it that must be taken into account.[179] The primary influence on the power spectrum is that the overall geometry of the universe can distort the apparent size of a fluctuation, thus appearing to shift the entire power spectrum along the axis of the angular size of the fluctuations. This breaks parameter measurements based on this investigation into two parts. The first part uses the parameters that are most influential at the era of decoupling to match the overall

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178 Kolb, Edward A. and Turner, Michael S. 1990. Spergel, D.N. et al. 2003.
179 Spergel, D.N. et al. 2003.

shape of the power spectrum. The second part uses the shape of the power spectrum relative to where that spectrum should appear in a flat, matter dominated universe to measure the overall geometry of the universe, represented by the values of the total mass-energy density and the value of the mass-energy density associated with the cosmological constant. This determination relies on the effect that the overall geometry of the universe has on the angular size of distant objects. Once the overall shape of the power spectrum is determined, this determines the angular size of fluctuations at a certain scale. The angular size that these fluctuations seem to be will depend upon the overall geometry of the universe, thus the difference between intrinsic size and observed size is a measurement of overall geometry. This in turn provides a measurement of the total mass-energy density of the universe.

A large-scale structure investigation into the background radiation can be summarized as the attempt to accomplish two tasks: 1) the accurate observation and recording of the background radiation, specifically the observation and recording of the anisotropy of the background radiation at different angular scales, 2) using this account to measure cosmological parameters. This last task may be broken down into two subtasks: 2a) generate the measurements of the parameters that determine the fluctuations at various scales, 2b) use the difference between the size of a fluctuation in itself to how it appears to us to determine other cosmological parameters. In contemporary cosmology, these tasks are accomplished through the use of the standard cosmological model to generate theoretical constructions that are used to identify regularities in the data. What counts as an accurate observation of the background radiation is dependent upon the idea that the power spectrum of anisotropies in the background radiation carries information about the inhomogeneities of the matter density at the surface of last scattering. For the second task, the overall shape of the power spectrum of inhomogeneities in the density of baryons is dependent upon a number of cosmological parameters, primarily the mass-energy density of photons and the mass-energy density of baryonic matter and cold dark matter. Following the determination of what combination of parameters matches the pattern of the power spectrum, the last subtask of the investigation uses the difference between the intrinsic size of these fluctuations and their apparent size to measure additional cosmological parameters.

Assumptions of the Background Radiation Investigation

The assumptions used in the background radiation investigations are primarily those of the standard cosmological model with the addition of some assumptions specific to large-scale structure investigations and some assumptions specific to the background radiation investigation alone. The standard cosmological model assumptions that are at work are the applicability of the General Theory of Relativity to a homogeneous distribution, that the matter and energy present is homogeneously distributed on some large scale, that the universe is expanding according to the behaviour of the scale factor in the Robertson-Walker metric, and that the very early eras of the universe were dense and hot. More particular assumptions are that matter density is dominated by cold dark matter, that the initial departures from homogeneity that produced the inhomogeneity observed in the investigation were scale-invariant departures and were adiabatic departures. Early work on the background radiation investigation did not seriously include the use of the cosmological constant, though by the time of the WMAP project, the parameter was included in the set of possible parameters or measurement. The use of cold dark matter and scale-invariant, adiabatic initial fluctuations in fitting the power spectrum of inhomogeneities are not without some justification, and we will address this below.

The assumption that the initial inhomogeneities of the universe, at least those which produce the traces seen in the background radiation, are adiabatic is based on the need for initial fluctuations to provide density inhomogeneities that will grow into the structures that we observe today.[180] Adiabatic inhomogeneities are defined as those which are not differences in composition, but are differences in density that could be created through the slow squeezing of some regions of the universe. By assuming that observed fluctuations are of this type, one ensures the most straightforward relationship between density and temperature. Isocurvature fluctuations are defined as those fluctuations in inhomogeneity based on content, not simply density, and as such cannot provide the basis for significant density increases in some areas that would eventually form the galaxies and galaxy clusters that we see today. The overall power spectrum of initial fluctuations is constrained as an initial condition as well on the basis that initial conditions cannot have density fluctuations that are too severe, otherwise a great many black holes would form in the early universe, creating a significant pattern to the development of density inhomogeneities that cosmologists have not observed.

Cold dark matter is used as a parameter in this investigation as it also solves some problems associated with structure formation in later eras.[181] The anisotropy in the background radiation is about three parts in one hundred thousand, which is not enough of a difference to account for the amount of inhomogeneity we see in large-scale

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180 Spergel, D.N. et al. 2003.
181 Spergel, D.N. et al. 2003.

structures of the recent era. This encourages the use of a dark matter parameter representing a matter that interacts gravitationally but not with photons. The reference to "cold" and "hot" in the nomenclature of dark matter is a reference to the relative velocity dispersion of the matter: hot dark matter has a high velocity dispersion, as we expect from neutrinos, while cold dark matter has a low relative velocity dispersion, and thus such matter would be like baryonic matter but not interact through electromagnetism. Hot dark matter, in the form of massive neutrinos, was considered as a possible parameter in some theoretical work on the early universe. However, as work on the dynamics of the early universe progressed in the early 1980s, it because apparent that neutrinos were both not likely to be massive enough to act as dark matter and that neutrinos were unlikely to produce viable accounts of large-scale structure formation in the era after decoupling. While there is still a role for the mass-energy density of neutrinos to play, this role is significantly smaller than that required to match the speculation that the mass-energy density of neutrinos can account for a significant fraction of the mass-energy density more strictly associated with matter. While it is possible to have warm dark matter, dark matter with a wide range of velocity dispersion still less than that of neutrinos, modelling cold dark matter is a much simpler procedure than modelling warm dark matter. This, along with the evidence that dark matter seems to be currently clumped with baryonic matter and is thus likely to be cold, encouraged the adoption of cold dark matter as the parameter of use in the investigation rather than a more complicated parameter representing a warm dark matter that developed to be cold later.

Of interest to our analysis of this cosmological investigation is the position that the use of cold dark matter to fit the curve is something initially justified on investigative grounds due to its simplicity and the facility with which it can be applied to modelling physical systems and later justified because of the success of the parameter. This is the position of the Peebles, Page and Partridge, themselves cosmologists, in their history of background radiation investigations. They write,

> The CDM [cold dark matter] postulate was not forced by a systematic evaluation of viable alternatives; it was adopted as a working hypothesis, in part because it is a conceptually simple way to reconcile the smooth distribution of the CMBR [cosmic microwave background radiation]with the lumpy distribution of matter, and in part because it is relatively easy to analyze the gravitational growth of clustering of CDM. The postulate was validated by passing searching tests, but that happened much later.[182]

According to this history, the cold dark matter hypothesis is adopted because it provides a clear and obvious way to relate the observed dynamics of a system to a parameter. Thus the hypothesis is adopted because it serves as a guide to research, given the theoretically established relationship between the cold dark matter and gravity. Such a research guiding hypothesis is to be justified based partially on the success that the research guide has in allowing the model to fit the data but primarily on the long-term ability of the overall model in producing measurements from a number of tests that continue to agree.

On this note, it is worth noting that Peebles, Page, and Partridge are explicit in their identification of the two main lessons of the history of the theory behind the large-scale structure background radiation investigation. The first lesson is that the theory was essentially constructive, in that it required a creative act to present a hypothesis to capture the available data. The second lesson is that the construction of the theory involved the presentation of a theoretical account of available data, so that the parameters of the theory matched the measurements available. They also add that the adoption of theory lies not in

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182 Peebles, P.J.E., Page, L.A., Partridge, R.B. 2009. Pg. 440.

the ability of the theory to produce results from the early matches, but in the ability of the theory to agree with a number of tests. They write,

> First, the theory was not wholly a product of logical thinking. That certainly was a factor, but there were also inspired guesses and the occasional denial of inconvenient evidence. Second, the theory was chosen to agree with early indications from the observations: the early fit of the theory and measurement is hardly surprising. The theory became a believable approximation to reality because it passed the subsequent development of a tight network of tests.[183]

The "tight-network of tests" to which the authors refer is not simply the multiple projects investigating the background radiation, but a number of tests that independently measure parameters measured in the background radiation investigation. The authors represent tightness by appealing to the error measurements produced by these tests and the boundaries of the error bars of these tests. We will return to this analysis in the next chapter.

The WMAP Project

Though there is a significant history of work on the background radiation investigation and a number of teams currently doing this work, in the interests of brevity we will focus our attention on the work of the Wilkinson Microwave Anisotropy Probe (WMAP) team.[184] While this does limit the scope of our attention, the WMAP team is likely one of the teams producing the most accurate observations of the background radiation, is likely one of the teams producing the highest volumes of papers, and it references and is referenced by other cosmological investigations in attempts to generate more secure parameter measurements through the combination of the results of different investigations.

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[183] Peebles, P.J.E., Page, L.A., Partridge, R.B. 2009. Pg. 435.

[184] Spergel, D.N. et al. 2003, 2007. Dunkley, J. et al. 2009. Komatsu, E. et al. 2009.

Following Page, Peebles, and Partridge (2009), we will adopt a reference model as the results of the WMAP investigation. This reference model represents not the best fit to all available data, but the best fit that the WMAP team can produce in a manner as independently as possible from other cosmological investigations. The results are not wholly independent, for as we will discuss below, the results of the WMAP project in measuring the cosmological constant due depend in some ways on these other tests because they help establish that the overall geometry of the universe is flat. The parameters of the reference model is given in Table 4.1.

Parameter	**Reference Value**
Distance scale ($H_0 = 100h$ km s^{-1} Mpc^{-1})	$h = 0.72$
Expansion time	$t_0 = 13.9$ Gyr
Density parameters	
Dark energy	$\Omega_\Lambda = 0.74$
Dark matter	$\Omega_{CDM} = 0.21$
Baryons	$\Omega_b = 0.044$
Neutrinos	$\Omega_\nu < 0.02$
Radiation	$\Omega_r = 10^{-4.33}$
Space Curvature	$\Omega_k = 0$
Primeval Mass Fluctuations	
Amplitude	$\sigma_8 = 0.80$
Spectral Index	$n_s = 0.96$
Opacity after decoupling	$\tau = 0.09$

Table 4.1: WMAP Reference Model. The reference cosmological model adopted by Peebles, Page, and Partridge (2009) from the results of the WMAP project. The mass-energy density of matter, Ω_M, is $\Omega_{CDM} + \Omega_b = 0.254$.

The parameters in this investigation that were not previously noted in Chapter 2 are the parameters of the primeval mass fluctuations and the parameter of opacity after decoupling. The parameters of the primeval mass fluctuations represent the initial condition of the fluctuations that developed into those imprinted on the background radiation. The amplitude parameter gives the expected value of a fluctuation from the overall average for a randomly selected region that today has a size of $8h^{-1} \approx 11$ Mpc. The spectral index represents the variation of the fluctuations based on the scale of fluctuations; for scale invariant fluctuations, $n_s = 1$. The opacity after decoupling is a measure of the optical depth of the universe, a measurement of how much the free electrons in the universe scatter the background radiation. While the full set of parameters reported by the WMAP team is list of over twenty parameters, the cosmological fit to the data that the WMAP team produces uses only a restricted set of parameters. These additional parameters are primarily used in fits to the data with a more complicated model to see if they allow for a better fit.

In what follows we will primarily be concerned with the temperature-to-temperature measurements of anisotropy in the cosmic background radiation. The WMAP team is able to produce additional information from the cosmic background radiation by looking at the polarisation of the cosmic background radiation. The use of the polarization data allows the WMAP team to break some of the parameter degeneracy that showed up in their earlier analysis. That is, the use of polarization data works to fix the values of specific parameters where the temperature-to-temperature data only allows the team to fix the combined values of these parameters. These degeneracies were not particularly strong in the two parameters that we are most concerned with in this work, Ω_M and Ω_Λ.

The WMAP instrument itself is a satellite-mounted temperature sensor designed to be able to measure the extremely small differences in the temperature of the background radiation with a minimum of noise. These differences are on the order of one part in one-hundred thousand or smaller. In order to carry out its task, the satellite has a number of radiometers shielded from the microwaves of the Sun and the Earth by a large disc at one end of the device. In order to reduce mechanical noise, all temperature control is accomplished through passive means. For the purposes of stable observations, the instrument spins in place at one of the Earth-Moon Lagrange points. In addition to observations of the background radiation, twice a year the instrument surveys Jupiter for the purposes of calibration and characterising beam response.

In order to produce a measurement, the WMAP team must take in a time-ordered string of data points, transform them in to a sky map, and then compare that map to hypothetical models of structure formation scenarios.[185] Identified foreground sources of microwave radiation are omitted from the map. The map produced by the time series of data is itself analysed to produce a power spectrum of the anisotropies in the map, and it is truly this that is compared to produce an account of which models of structure formation produce the best fit.

The cosmological parameter measurements are produced through the consideration of what models produce the best fit to the observed power spectrum. The mathematical structure of the power spectrum is the object of observation, not the background radiation itself, and the characteristics of this power spectrum provide the measurements of the parameters of the cosmological theory, through the best fit model. The consideration of the parameters space is dictated, in part, by the context of the results of other investigations. For example, the WMAP team performs the majority of their fits either with a different range of parameters or with certain fixed values with other parameters, with the assumption that the universe is flat, that $\Omega_{\text{Total}} = 1$.

By considering a number of key alternative models (or alternatively, by

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[185] Spergel, D.N. 2003.

considering key ranges of parameter values within the Friedmann-Lemaître-Robertson-Walker models), the WMAP team attempts to produce a more reliable overall measurement of the parameters involved. Three methods are used for such considerations: a $\Delta\chi^2$ test, a comparison of the requirements of alternative models with regards to other cosmological investigations, and a comparison of the fits of different models to characteristics peaks of the power spectrum.

The WMAP team uses a statistical formula to test what they refer to as "the relative goodness of fit" of the alternative models to their best-fit model. This formula produces a measure of goodness of fit based on calculated likelihoods:

$$\Delta X^2_{eff} \equiv -\Delta(2 \ln \boldsymbol{L}) = 2 \ln \boldsymbol{L}(\Lambda CDM) - 2\boldsymbol{L}(model) \qquad (4.1).$$[186]

Here a positive value indicates that the fit of the model is not as good as the fit of the WMAP's values for the standard model and a negative value indicates that the model has a better fit than the WMAP's values. On this test alone, an alternative model with no dark matter, even with a cosmological constant, does far worse than the WMAP suggested model, scoring $\Delta\chi^2_{\text{eff}} = 248$. This model even adds an additional parameter by not requiring a flat cosmology, thus it should be expected to be better able to fit the available data. Doing somewhat better than the WMAP suggested model is a model that abandons the restriction that the universe is flat. Dropping this restriction provides $\Delta\chi^2_{\text{eff}} = -2$ with the addition of only one additional parameter. However, the WMAP team suggest the flat model as their best fit as they cannot produce a best fit to the recorded power spectrum without committing to values of cosmological parameters that are inconsistent with those produced by other investigations

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186 Spergel,D.N. et al. 2007. Pg. 382.

Limits on parameter space by other investigations are an important part of producing measurements from the observed power spectrum though the measurement itself can still be said to be significantly independent of these other investigations. For example, a purely Friedmann-Robertson-Walker model, one with no cosmological constant, is only possible with a value of the Hubble parameter of $H_0 < 40$ km s^{-1} Mpc^{-1}, well below contemporary determinations of the value. In this case, while the parameter space is constrained by other investigations, there is no direct influence on the process of measuring parameter values and, again, the cut-off of the parameter space is well below the majority, if not all, of the determinations of the value for the Hubble parameter.

A trickier case for independence is the case of the limitation of the parameters considered in the WMAP fit to a flat, $\Omega_{Total} = 1$ ($\Omega_k = 0$), cosmology. This point is noted by Peebles, Page, and Partridge in a footnote comment on the reference cosmological model of the WMAP project. They write that other investigations are "not really independent [of the WMAP project] because they influenced thinking on flat space sections."[187] In order to justify this restriction, the WMAP team appeals to the constraints placed on the parameter in conjunction with a number of other investigations. The WMAP investigation alone does not constrain Ω_{Total} to a small region, but rather limits the parameter space to a diagonal region in the plane of Ω_{Total} versus Ω_Λ.[188]

The restriction of the WMAP results in a constraint on the combination of Ω_{Total} and Ω_Λ rather than to the parameters alone, is due to *geometrical degeneracy.*[189] These parameters are not read from the power spectrum of fluctuations, but rather from the way

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187 Peebles, P.J.E., Page, L.A., Partridge, R.B. 2009. Pg. 467, footnote.
188 Komatsu, E. et al. 2009.
189 Stompor, R. and Efstathiou, G. 1999.

that the overall geometry of the universe shifts the angular power spectrum from how they would look in a purely Euclidean geometry. This extrapolation is, in effect, much like the determination of the luminosity distance, discussed Chapter Three, as it is a measurement of the effect that the geometry has on the path of light from one location to another. In this case, we are looking at how the light from the surface of a sphere reaches a single point rather than how the light from a single point spreads out to form a sphere. This geometry is governed by the overall density and the mass-energy density associated with the cosmological constant. These parameters play little role in the dynamics of the early universe as the relative density of matter and radiation was so much larger in the early universe. Thus within the WMAP project, the determination of the Ω_{Total} and Ω_{Λ} are fairly independent of the measurement of the other parameters.

The use of independent cosmological investigations can dramatically tighten the WMAP measurement of Ω_{Total}, and thus the measurement of Ω_{Λ}. Spergel et al. (2007) show the result of combining the WMAP data with the data from a number of different investigations separately; even using the results of only any one of the other investigations constrains the value of Ω_{Total}, at worst, to within four percent of $\Omega_{\text{Total}} = 1$.[190] These investigations are not simply independent in the sense that they are performed by separate scientific institutions. While all of these investigations yield results based on many of the assumptions of the standard cosmological model, each one uses different equipment, observing techniques, and systematic dependencies between data, phenomena, and theoretical parameters of the standard cosmological model in order to produce their results. A dramatic figure (reproduced as Figure 4.1) shows how limiting simply the value

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190 Spergel, D.N. et al. 2007. Pg. 398.

of the Hubble constant rather tightly constrains the WMAP results to close to a flat universe. According to the 5th year reports of the WMAP team, the most significant constraint on Ω_{Total} comes from the combination of the WMAP data with the Sloan Digital Sky Survey (SDSS). Fortunately for our later analysis of the combination of the WMAP with the type Ia supernova investigation, the SDSS is another large-scale structure investigation that is at least as independent from the the supernova investigation as is the WMAP project, thus we need not rely on any overlap between the WMAP project and the supernova investigation in measuring Ω_Λ.

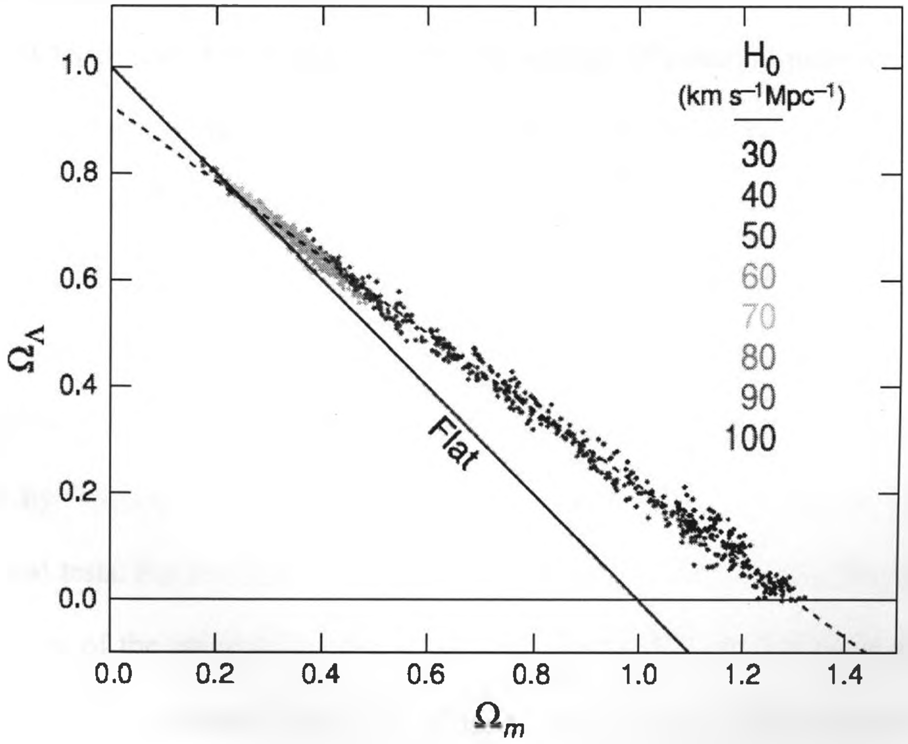

Figure 4.1: Cosmological parameters and H_0.This figure shows the range of cosmological models without the assumption of a flat universe, that are consistent with the WMAP data only. The models in the figure do not have the constraint that $\Omega_{Total} = 1$. The colours of the dots indicate the probable value of the Hubble constant. The dashed line shows an approximation to the degeneracy of Ω_{Total} and Ω_Λ. From D.N. Spergel *et al.* (2007), pg. 398.

The third method of comparison used to evaluate alternative models is to look at the effect that different specific models have effects on the peaks within a hypothetical power spectrum. This difference was noted by Peebles and Yu, who demonstrate a dramatic difference between the shape of peaks in the open model and in the flat model that they consider.[191] By comparing the fit of a model to particular peaks, the WMAP team can demonstrate the failure of the model to account for the observed spectrum due to the operation of the physical principles involved. For example, the WMAP team point out that Modified Newtonian Dynamics, an alternative theory of gravity, can be used fit the overall power spectrum to an extent, but they cannot produce a third peak as high as that which the WMAP team has found.[192] Given the amount of potential parameters that can be used to fit the power spectrum, other parameters could perhaps be used to make up for the deficiency of a particular element of a larger model to match a particular feature. Thus such a comparison ultimately is resolved through an appeal to some constraint on the parameter space, through the constraints placed by other investigations as mentioned above. In practice, this appeal is carried out by testing whether or not the measurements produced by varying a parameter produce measurements that agree with other cosmological tests. For example, as demonstrated in Figure 4.1, allowing the total mass-energy density of the universe to vary from that required for a flat universe produces a measurement of the current value of the Hubble parameter that lies well outside contemporary measurements from other sources.

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[191] Peebles, P.J.E. and Yu, J.Y. 1970. Figures 4 and 5

[192] Spergel, D.N. et al. 2007. Pg. 382. McGaugh, Stacy S. 2004. Skordis, Constantinos. 2006.

Systematic Errors in the WMAP Measurements

The WMAP team divides the systematic error of their observations into six categories.[193] These categories are calibration errors, map-making errors, beam errors, sidelobe response, baseline errors, and striping. As expected, these systematic errors are a mixture of peculiarities of the equipment used and the nature of the analysis performed on the data collected.

Calibration errors arise from corrections to the data from known and observed features of the sky.[194] The data being recorded is calibrated to previous observations and ongoing observations made by the instrument itself. A significant source of calibration is the dipole anisotropy in the CMB caused by the movement of the instrument in the solar system and through the galaxy relative to the rest-frame of the background radiation. Also significant is calibration based upon observations of Jupiter made by the instrument. The data recorded by the instrument is also adjusted based upon previous observations of the sky by the instrument itself. The known features of the solar system and our galaxy, chiefly the Sun, the planets, and the movement of our planet in the solar system and through the galaxy relative to the rest-frame of the background radiation, are all taken into account in the corrections. Ideally, this process removes signals that are spurious to the background radiation. However, the process of adding and subtracting to the recorded signal could add noise to the signal that is correlated, either to a feature of the instrument, a feature of the environment, or to the mathematics of the algorithm. Some of the correction to the data is based upon a determination of the position of the WMAP satellite

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193 Hinshaw, G. et al. 2003.
194 Hinshaw, G. et al. 2003.

in relation to the barycenter of the solar system. This serves as the baseline for applying corrections to the data based on measurements of the movement against CMB rest-frame performed by COBE. This correction, and others, relies upon a determination of the mean temperature of the CMB. In any case, this error is likely to be peculiar to the process of this particular investigation and is likely to be correlated to position in the visible sky, not to redshift or distance as in other cosmological investigations

Calibration errors are checked by looking at model data run through the same correction procedures and by looking at difference maps.[195] The model data is used to check for systematic artefacts produced by the correction process. Difference maps, maps produced where no sky signal should be present, are used to check for structure introduced by the correction techniques.

Map-making errors arise from improper techniques used to generate the sky maps from raw data and from errors in the determination of the pointing of the instrument. The use of Jupiter twice a year to calibrate the instrument can be used to test the pointing of the instrument. Two additional sources of error here may be the spatial drift of the satellite or the errors in identifying the observations with the correct time. This is another error that is associated with surveys that study the span of the visible sky rather than attempt to determine cosmological distances.

Beam errors, sidelobe response, and baseline errors are all errors associated with the particular instrumentation used in this investigation.[196] Errors associated with beam shape and window function, in addition to those associated with calibration noted above,

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195 Hinshaw, G. et al. 2003.

196 Hinshaw, G. et al. 2003.

arise from instrument noise, the asymmetry of the beams, and the mathematical analysis technique used for the window function. Sidelobe response error arises from the contamination of the signal from sources outside of the beam of the instrument. Particularly bright sources can add to the signal recorded by the instrument. This error can be estimated by previous observations of the sky and the instrument's behaviour. Baseline errors arise from changes in the operation of the instrument that arise from the environment of the instrument or its internal operation. The primary environmental influence on the instrument is temperature. Changes in temperature associated with the spin of the instrument are a possible source of systematic error and must be taken into account through correction of the data or through error budget. The temperature of the instrument could possibly be correlated with its position in the solar system, thus influencing the observed anisotropy. Temperature changes to the instrument are monitored to track the potential influence of thermal changes. The operation of the instrument leads to changes in the electrical signals of the instrument that could potentially change the recorded signal. Pre-flight testing of the instrument was used to set limits on the extent of this error.

Striping error arises from signals in the time-ordered data that are not associated with a source fixed in the sky.[197] Such signals can arise from $1/f$ noise or from calibration errors. $1/f$ noise is noise with a power spectral density that reduces with frequency; noise of this sort is often present in electronic equipment. Attempts to limit striping error are included in the attempts to limit calibration error. Additionally, a test of consistency in the data from each year is used to reduce this error. This error is associated with the method

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[197] Hinshaw, G. et al. 2003.

of transferring observational data in the form of a time ordered stream and is not likely to be found in other observations relying on different instrumentation and means of recording and transmitting data.

Of course, there are some sources of error that do not fit well into the above categories that are nonetheless possibly systematic error; one such error is error caused by the influence of one radiometer on another, where the first radiometer is observing a particularly bright area of sky.[198] This source of error is particular to this instrument, and accordingly this error is limited based on pre-flight testing.

Microwave sources in the sky that show extreme variability can also cause error not associated with the above categories as they may be incorrectly left in the area of the sky processed for background radiation fluctuations.[199] The WMAP team assumes that such sources are rare enough to be of little significance if they remain undetected. In part, this systematic error is reduced by the ongoing collection of data. There are two reasons for this. The first reason is that it is unlikely that the behaviour of such an object could remain unnoticed in the data over the continuing run of the instrumentation and would be identified as a point source and eliminated. The second reason is that the continued success of the project in generating a more accurate assessment of the power spectrum that does not widely diverge from previous estimates lowers that chance that there is significant pollution from such light sources. The ability of the project to discover the same phenomena in the data in repeated passes strengthens our confidence that the phenomena discovered in the data are not simply phantoms of our analysis. This is

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198 Hinshaw, G. et al. 2003.
199 Hinshaw, G. et al. 2003.

especially the case when considering a possible source of error that changes over time; such a source of error must be coordinated with the timing of repeated passes in order to influence both observations. Thus even the slight independence between to consecutive observations by the same team of investigators can be enough for the agreeing measurements of each observation to influence the confidence that we have in the observation.

Methodological Notes

Though, due to the complexity involved, an analysis of the methodology of the background radiation not quite so straightforward as it is in the supernova investigation, we can also cast the methodology of the background radiation investigation in a similar way. The goal of the background radiation investigation is not simply accurate prediction of the data by the theory, but the accurate measurement of relevant theoretical parameters that accurately approximate the dynamics of the physical systems involved. As the standard cosmological model, together with theories of particle physics and fluid dynamics for the early eras of the universe, places constraints on how inhomogeneities develop, this makes identifying the power spectrum of inhomogeneities relevant. The anisotropies are directly relevant to the inhomogeneities at the era of decoupling because the standard cosmological model does not simply predict that these inhomogeneities will be imprinted as anisotropies, but because the standard cosmological model provides a systematic relationship between the inhomogeneities and the anisotropies that can be used to produce information on the way the parameters of the standard cosmological model mediate the relationship between inhomogeneities and anisotropies.

While the methodology of the background radiation investigation may sometimes begin with something of the "desperate course" of early cosmology, it produces results not simply be relying on simplicity but by producing detailed measurements that are amenable to comparison with other results. This progress was exemplified above in the inclusion by cosmologists of cold dark matter as the main dark matter parameter in the analysis. While it may be that many cosmologists initially adopted cold dark matter on the grounds of simplicity, the continued success of cold dark matter relies on the measurement results given the assumption that it plays a role that allow the researchers to produce measurements of cosmological parameters that agree with other sources, something no alternative approach can accomplish. Due to the systematic dependencies of the theoretical parameters on the power spectrum of anisotropy, the support that we have for the correctness of the methods of the investigation can gain support from the independent support for matching parameter values. For example, Figure 4.1 above, taken from Spergel *et al.* (2007), demonstrates how the measurements of different values of the Hubble constant can significantly shift the measurements of the density parameters from the WMAP data if the assumption of a flat universe is dropped. While Spergel *et al* (2007). are able to produce a better fit to the data without the assumption of a flat universe, such a model cannot produce measurements that agree as well with those measurements from other sources. Thus again and again, the WMAP team decides on the correctness of the procedure of assuming a flat universe, at least for the purposes of reporting parameter measurements, because that assumption produces measurements that best accord with the measurements of projects that we would otherwise consider to be independent. This sort of combination of results is to be discussed in more detail in the next chapter.

Chapter 5: The Combination of Independent Results

As discussed in Chapter One, accurate agreeing measurements of cosmological parameters from independent sources seems to be the driving force for the widespread acceptance of the cosmological constant in the cosmological community. The force of this agreeing measurement is illustrated in Figure 5.1, which shows a figure almost ubiquitous to recent cosmological publications and presentations on measurements of the mass-energy density parameters. The figure shows the measurement results from the supernova investigation, from the WMAP investigation, and from other large-scale structure investigations (listed as "BAO" in the figure). Any two investigations are sufficient to constrain the measurements to a small area of the parameter space examined (the mass-energy density of all matter versus the mass-energy density associated with the cosmological constant). Further constraints are possible with the inclusion of the remaining investigation, but the region of overlap is already restricted significantly by the use of only two investigations, especially by the two investigations discussed in Chapter Three and Chapter Four.[200] The region to which these investigations restrict the parameters coincides with an overall flat universe, that is, they coincide with a total mass-energy density of the universe of $\Omega_{\text{Total}} = 1$. This restriction is used in the reporting of the values of cosmological parameters, as given in Table 5.1. As seen in the table, the results of these two investigations continue to produce agreeing results; with Kowalski *et al.* and Komatsu *et al.* as the most recent parameter determinations, we have a measurement of the energy density of the cosmological constant of approximately 0.713 and 0.726 (with

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[200] Adding in other cosmological investigations, such as the measurement of the current value of the Hubble parameter illustrated in Figure 4.1, serves to pick out the same region in parameter space, at least in combination with the WMAP results. See D.N. Spergel et al. (2007).

overlapping error bounds) respectively.

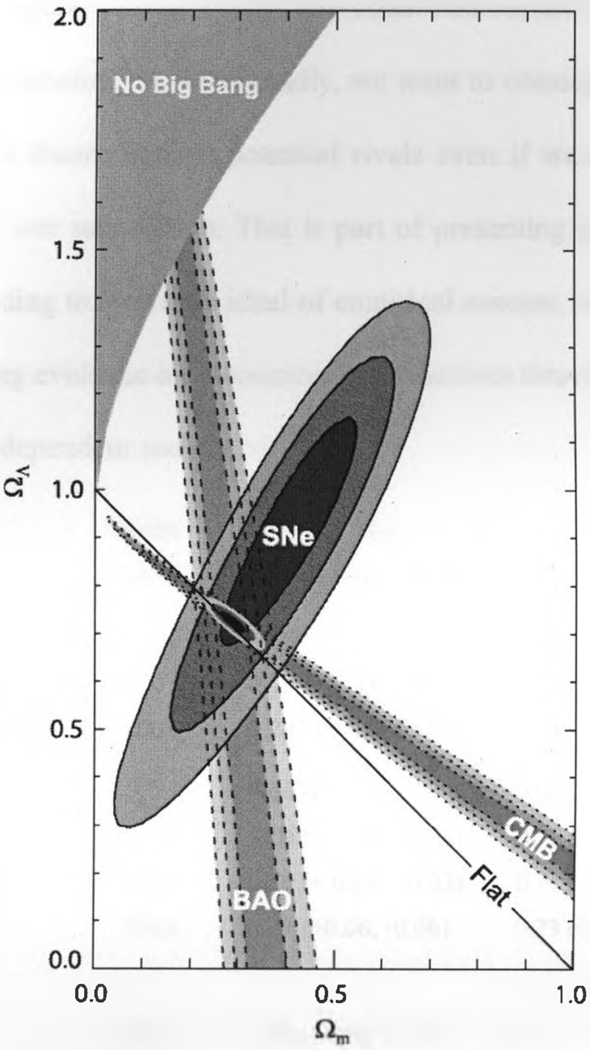

Figure 5.1: Overlapping constraints. An example of the sort of graph presented in the many contemporary cosmological papers reporting measurements of cosmological parameters. The graph shows the constraints on the parameters (at the 68.3%, 95.4%, and 99.7% confidence intervals) resulting from each investigation individually, with the small region on the graph indicating the region in the parameter space favoured by the combination of the data from all sources. From M. Kowalski *et al.* 2008.

In this chapter, we want to investigate the extent to which the supernova investigation is independent of the background radiation investigation and to discuss the benefit of this independence to the standard cosmological model and the security of the cosmological constant within cosmology. In so doing, we hope to give some content to the desire for "a more tightly woven web of interconnected results" expressed by Peebles and echoed by other cosmologists. Additionally, we want to consider how such a web of evidence strengthens a theory against potential rivals even if we do not consider it to establish the theory to our satisfaction. This is part of presenting these investigations as moving forward according to Newton's ideal of empirical success, which seeks to address the reliance of gathering evidence on theoretical constructions through the use of agreeing measurements from independent sources.

Authors	**Year**	$\boldsymbol{\Omega_M}$	$\boldsymbol{\Omega_\Lambda}$
Perlmutter et al. (SCP)	1999	0.28 (+ 0.09, - 0.08)	0.72 (+ 0.08, - 0.09)
Knop et al. (SCP)	2003	0.25 (+ 0.11, - 0.10)	0.75 (+ 0.10, - 0.11)
Kowalski et al. (SCP)	2008	0.287 (+ 0.068, - 0.063)	0.713 (+ 0.063, - 0.068)
Riess et al. (HSST)	1998	0.24 (+ 0.56, - 0.24)	0.72 (+ 0.72, - 0.48)
Riess et al. (HSST)	2004	0.29 (+ 0.05, - 0.03)	0.71 (+ 0.03, - 0.05)
Spergel et al. (WMAP)	2003	0.27 (+0.06, -0.06)	0.73 (+0.06, -0.06)
Spergel et al. (WMAP)	2007	0.23 (+0.05, -0.05)	0.77 (+0.05, -0.05)
Komatsu et al. (WMAP)	2008	0.273 (+0.015, -0.015)	0.726 (+0.015, -0.015)

Table 5.1: Parameter measurements.

In Newtonian terms, the argument for a non-zero cosmological constant proceeds from the measurement of a number of independent phenomena to an identification of this measurement with a specific property of the cosmological constant, at which point the identification allows us to produce a more robust measurement of the specific value of the cosmological constant that will, with time, be expected to continue to produce agreeing measurements from other independent measurements of the parameter through measurements of other phenomena.

This can be summarized as follows before addressing the results in more detail. From the supernova investigation discussed in Chapter Three, our Newtonian argument uses as phenomena the kinematic parameters associated with the redshift-distance relationship. From the background radiation investigation discussed in Chapter Four, our Newtonian argument uses as phenomena the determination of the geometry of the universe that is produced from the apparent change in the size of the angular scale of primordial fluctuations between their source and our observation of the background radiation. The General Theory of Relativity allows us to use the measurements of these parameters to provide information about the different mass-energy densities of the contents of the universe, including the mass-energy density associated with the cosmological constant. Working together, these provide independent constraints on the possible values of this mass-energy density that restrict its value (and the value of the cosmological constant itself) to a narrow region of parameter space. That these independent measurements of cosmological parameters can produce overlapping agreement is itself something that is not guaranteed and so counts as an important success of the theory from the available evidence.

Additional empirical success comes from the ability of the restricted parameter measurements produced from the combination to continue to agree with the results of continued research. Such success is seen in the ability of the measurements to coincide with those produced by other sources such as investigations of galaxy clustering and even the determination of the present value of the Hubble parameter from relatively nearby galaxies. The inclusion of the cosmological constant in the General Theory of Relativity and in our cosmological bestiary allows us to not simply fit the data but to use the phenomena extrapolated from the data to provide measurements of the theoretical elements of the cosmological theory.

The phenomena from the supernova investigation are the kinematic parameters of the Robertson-Walker metric and these phenomena are themselves backed up by empirical evidence mediated by theoretical considerations. They are regularities in the data that are specifically constructed and explained by the overall theory and that are measured by their best fit to the available data. The kinematic parameters are the scale factor and, more importantly to the actual measurement of the cosmological parameters, those parameters associated with different orders of the derivatives of the scale factor: the Hubble parameter representing the first derivative, analogous to constant motion; the deceleration parameter representing the second derivative, analogous to acceleration; and higher derivatives, analogous to jerk and snap. It should be noted that while cosmologists can and sometimes do determine the kinematic parameters from the observations and report the results, the kinematic parameters are not themselves often reported or represented in the equations printed in the literature reporting results. Nonetheless, it is the systematic relationship between the observations and the kinematic parameters and the systematic relationship between the kinematic parameters and the cosmological parameters that is the justification to derive measurements of the cosmological parameters from the observations. This is so the observations allow us to make determinations of the geometry of the universe and it is through this that measurements of the cosmological mass-energy density parameters can be systematically related to the observations. Because of this chain of systematic relationships, mathematical substitution allows for the direct confrontation of data with cosmological parameters, but this does not undermine the reality of this chain of systematic relationships as both the kinematic parameters and the dynamical parameters of the standard cosmological model have other applications in other investigations. The result of these systematic dependencies is that, while the measurement of the kinematic parameters and their values is more or less direct, the measurement of the mass-energy density of matter and the mass energy density associated with the cosmological constant is a constraint on the parameter space of their combination, as seen in Figure 5.1. Under the assumption of a flat universe, the parameter space collapses to one dimension, and we will discuss this constraint later.

The supernova investigation's determination of kinematic parameters (and cosmological parameters) arise from the relationship between redshift, used to determine the Hubble parameter, and brightness, used to determine distance. The determination of redshift relies on the assumption that the physics of the spectra of distant supernovae is that of the other physical systems for which we determine spectra. This can be seen as a straightforward application of Newton's Rule 3. That is, we expect the mathematical values of the qualities of the spectra everywhere follow the principles discovered for spectra as established in all of our experiments and observations. The determination of brightness relies on the strength of the systematic relationship between the peak brightness of type Ia supernovae and the curve of the brightness of these events over time. In both of these cases, we are relying on reasoning in accord with Newton's Rule 1 and Rule 2, *viz.*, that natural effects of the same kind must be explained by physical causes that are similarly of the same kind.

Here again, we are relying on the application of Rule 3: we are relying on the definition of what a type Ia supernova is, using criteria of photometry and sampling of light curves similar to those of Phillips discussed in Chapter Three. Using that definition we are able to discover in the data those events that match the criteria and apply the principles governing such events as determined by our investigations into those events where such investigation is possible. Additionally, this extension is warranted by the application of Rule 4, which exhorts us to use the determinations that we have established until such time as we can replace them with a more exact determination or our usage of them shows them to fail. In this way, the use of these two assumptions, and the theory associated with it, turns the success or failure of the supernova investigation into a test of the theory behind these assumptions. If the supernova investigation was to fail to produce accurate results, or if the investigation produced results that disagreed with independent measurements of cosmological parameters, then we could take these results as an indication that the application of the phenomena associated with type Ia supernovae were liable to exception and thus should not follow extension via Rule 3.

The phenomenon from the background radiation investigation used in the argument for a non-zero cosmological constant is the overall geometry of the universe and this is also backed up by empirical evidence that produces measurements mediated by theoretical considerations. The main observational work of the background radiation investigation is to determine the power spectrum of fluctuations in the background radiation. These are phenomena in the sense that they are regularities expected to hold in the data as more and more data is produced, something so far born out by the WMAP project and its repeated observations of the background radiation. These phenomena can be used to measure a number of cosmological parameters and this measurement fixes the scale of the fluctuations in the primordial material at the surface of last scattering. In this, like in the supernova investigation, we are also applying the theories that we learn from our investigations of physics to the distant regions of the universe where we are able to assign similar causes. The results from this prior investigation allows us to determine the difference between the apparent size of such fluctuations in universes of different geometries. Thus the overall geometry of the universe becomes a phenomenon that is discovered by the theory mediated measurements of the primordial fluctuations.

The galaxy clustering investigation relies on primordial fluctuations in a manner similar to the background radiation investigation. This investigation of large-scale structure uses both theories of primordial structure formation and theories of structure formation since the emission of the background radiation in order to turn observations of present galaxy structures to measurements of cosmological parameters. One important different between these large-scale structure investigations and the background radiation investigation is that the galaxy clustering investigations are currently able to examine fluctuations in density on a much finer scale than that available to the background radiation investigation. This is so because galaxies and galaxy clustering are representative of the fine scale density distribution and these objects are much closer to us and easier to identify against their background than are the anisotropies of the background radiation. Additionally, one can observe galaxies and galaxy clusters that are relatively close to our position, thus one need not take into account the overall geometry of the universe when carrying out the galaxy clustering investigation, unlike the background radiation investigation. Thus the galaxy clustering investigation provides information about the mass-energy density parameters in a manner different from the background radiation investigation. This difference is illustrated in Figure 5.1, where one can see that the galaxy clustering investigation (listed as "BAO" in the figure) places measurements on the mass-energy density of matter that is fairly insensitive to the mass-energy density associated with the cosmological constant. As the combination of the three investigations limit measurements to the same small region of the parameter space, a space within the limits of the combination of any two investigations, this should strongly improve our confidence in these investigations.

In the above we see the use of theoretical constructions to turn data into something which directly shapes the theory itself and our understanding of the physical systems, not merely as assumptions that work together to produce a prediction to be tested against data. This begins with the use of theoretical constructions that allow us to identify the expected ongoing regularities of the physical systems and these regularities are the basis for the understanding of the theory. In the case of the supernova investigation in particular, we use the relationship between peak brightness and light curve to identify a regularity in such physical systems and to identify the regularity in the relative position of galaxies in space and cosmological time with the behaviour of the scale factor. This regularity provides information about the way that the mass-energy densities interact with the scale factor and allows us to produce a measurement of the cosmological parameters. The results are only as strong as our confidence in the underlying regularities. Conversely, that the assumption of these underlying regularities produces these measurements of cosmological parameters, measurements that agree with the results of other investigations, bolsters the strength of our confidence in these underlying regularities. Continuing to test the a theory on its ability to continue to produce accurate results into the future is maintained in this methodology, but the test of the theory is focussed on how much the theory continues to produce accurate agreeing measurements from these later observations. A theory that provides a coherent explanation and predictive success without demonstrating the ability to systematically gain information from the elements that it purports to explain is not being held to the same standard.

One of the canonical examples of the power of unification in Newton is his use of the Moon test to extend terrestrial gravity beyond the limits of the surface of the Earth. In the Moon test, Newton relies on the agreement in measurement between two otherwise independent forces: that force maintaining the orbit of the Moon (against the inertia that would cause the Moon to fly off in a straight line) and the force of gravity. Newton uses the approximate orbit of the Moon to measure the amount that the Moon would fall if it were stopped in its motion. Assuming that the distance from the Earth to the Moon is exactly 60 times the radius of the Earth, he is able to calculate that the distance the Moon would fall in one second, if it were at the surface of the Earth, is approximately 15 1/12 Paris feet (a measurement of length distinct from the contemporary foot). Newton notes that this measurement is in close agreement with the measurement of the speed at which terrestrial gravity causes objects to fall as measured by Christiaan Huygens. Even if Newton had based his calculation on any of the range of distances to the Moon accepted by other scientists of his day, the results would have produced close agreement bewteen the force holding the Moon in orbit with the force of terrestrial gravity.[201] This unification

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[201] Harper, William. 2002. Pg. 183.

not only changes the understanding of terrestrial gravity, but it also serves to provide a larger pool of evidence to draw upon in the measurement of the strength of gravity. The agreement of the measurement provided by the Moon provides support for the measurements derived from terrestrial experiments, even though the terrestrial experiments have greater accuracy. Alternative explanations to the interpretation of the terrestrial experiments that would alter the value of the strength of gravity as determined by these experiments now must also address the measurement as determined by the observations of the Moon.

In the case of the cosmological investigations discussed here, the combination of investigations produces a restriction of measurements not merely to one parameter but to two, the mass-energy densities associated with matter and with the cosmological constant, due to the systematic relationships between the phenomena and the cosmological theory. The combination works to build precision and robustness in two parameter values, precision and robustness that grows with the inclusion of the results from additional independent investigations that provide agreeing measurements, such as those of the galaxy clustering investigation.

This continued investigation of the parameter measurements in the face of additional independent investigations is addressed in a recent review and history of astronomical and cosmological investigations of the background radiation by Peebles, Page, and Partridge (PPP). In the introduction to their review of the independent tests, they write of the various cosmological investigations,

> All of these different measurements are difficult and their interpretations hazardous: we are attempting to draw large conclusions from exceedingly limited data. But the consistency of the considerable network of theory and

> observation.... argues that we are not likely to be misled by an inadequacy of theory or by systematic errors in the difficult measurements: we have reason to be confident that the cosmology that fits the evidence, the ΛCDM model, is a useful approximation to reality. That is not to say that the model is reality – we make progress by successive approximations – but that when it is replaced by some deeper theory the successor will predict a universe that behaves much like the early 2008 ΛCDM model.[202]

PPP identify a number of elements in contemporary cosmology that accord with our case study, primarily the power of accurate agreeing measurements from independent sources and the methodological goal of providing theoretical parameters that seek to explain physical systems through successive approximations. In a later section of the book, which spans from the initial theory and discovery of background radiation to contemporary large-scale structure investigations, is an assessment of the comparison of the parameter values as determined by the background radiation investigation with the results of other investigations.

PPP seek to demonstrate the power of the combination of independent tests by comparing what they call a "reference model" of the results of the WMAP project with the results produced by other investigations. Their reference model is the collection of the measurements produced by the WMAP team more-or-less independently, with the one significant influence on the reference model being the restriction to $\Omega_{\text{Total}} = 1$. This restriction, common in reporting cosmological results, is something derived from the restrictions on the available parameter space established by the relationship between the WMAP results and the results of other investigations. As we can see from Figure 5.1, both the only region of overlap between the WMAP results and the supernova investigation and the only region of overlap between the WMAP results and the galaxy

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[202] Peebles, P.J.E., Page, L.A., Partridge, R.B. 2009. Pg. 466. The chapter on the contemporary investigations was written with J. Richard Bond.

clustering investigation lie very close to the line that designates a flat overall geometry of the universe. As discussed in the last chapter and documented in Spergel et al. 2007, and other WMAP papers, the combination of WMAP results with a number of independent cosmological results effectively constrains the results to that region where the universe is close to flat. Thus this restriction to a flat universe is very reasonable based on how this assumption is backed up by the agreement of measurement from these independent sources. This is especially reasonable in cases where one is attempting to assess the investigation in the face of other results. Here we should follow Newton's Rule 4 and take the propositions gathered from phenomena to be true or very nearly true until they can be shown to be liable to exception or be replaced by a more accurate claim. By taking the universe to be exactly flat we can test how liable to exception such a model is.

PPP use a basic statistical measure to compare the results of the reference model to independent measurements. Whether or not a measurement of a parameter from another investigation agrees with the reference model, within its range of calculated error, indicates whether or not there is some systematic error in the investigation or whether or not there is something wrong with the reference model. The authors plot the difference between the reference model and the other investigations as the difference $(M-R)/\sigma$ for each investigation. The quantity $(M-R)/\sigma$ is the difference between the measurement of a cosmological parameter and the value determined by the reference model, divided by the standard deviation of the measurement. The majority of the tests they examine line up nicely with the reference model, while other tests fall significantly higher or lower than the values of the reference model. As they give equal weight to each measurement, the overall evaluation of this look at the combination of results is "not as close to ideal," as the fit of the reference model to the background radiation results.[203]

However, that there is not agreement on these parameter values is not taken by the authors as a difficulty for the reference model or for the results of the background radiation investigation. PPP explain:

> That is not surprising because it is difficult to understand the errors in many of these tests, in part because some are works in progress, and in part because some depend on complex processes we never will be able to analyze to a high degree of accuracy. Whether the model fit to these tests is acceptable under these conditions is a more subjective judgment call. But that is part of science.[204]

After making this claim, they do briefly address the various investigations they include and give some caveats for providing different weights to some results. Later, they write,

> The decision on when the weight of experimental evidence forces the transition of a useful working hypothesis into a convincingly established standard model is in part a personal one and in part a herd effect. The consistency – within reasonable uncertainties of difficult measurements – of these probes of many different aspects of the large-scale nature of the universe convinces us that the spatially flat ΛCDM hot big bang cosmological model is a good approximation to reality.[205]

While we may certainly agree with their sentiment about the sociology of scientific communities, it is important to note that even with the lack of proper assessment of how much weight to give to particular investigations that provide outlying measurements of cosmological parameters, PPP rely on the strength of the agreeing measurements of cosmological parameters from a core of investigations in order to claim security for the standard cosmological model with the inclusion of dark matter and the cosmological constant.

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[203] Peebles, P.J.E., Page, L.A., Partridge, R.B. 2009. Pg. 469. Peebles, Page, and Partridge report a statistical test of $\chi^2 = \Sigma\ (M - F)^2/\sigma = 26$ for the 16 investigations they consider, a result they consider to be 1.6 times what they would expect given the reported error bars for the investigations.

[204] Peebles, P.J.E., Page, L.A., Partridge, R.B. 2009. Pp. 469-470.

[205] Peebles, P.J.E., Page, L.A., Partridge, R.B. 2009. Pg. 475.

Seen as a case study for Newtonian methodology, the combination of these cosmological investigations should allow confidence in the parameters of the theory derived from agreeing measurements of these parameters to bolster confidence in the phenomena used to produce the measurements. As part of Newton's rich ideal of empirical success, the constraints on the parameters of the theory should produce constraints on phenomena that purport to describe physical systems such that these phenomena accurately match the data gathered from these systems. If this is the case, the confidence that we have in the measurements of the parameters of the theory can be used to support the identification of the phenomena used to provide measurements. Any challenge to these phenomena must address not only how we identify these phenomena, but how these phenomena are able to produce agreeing measurements.

One result of this is that the extent to which two investigations are independent, in the sense that they rely on different systematic relationships between gathering information and measuring theoretical parameters, plays an important role in determining the impact of their combination. While an individual investigation may fall prey to systematic error that mimics the behaviour of a parameter such that the systematic dependency is between phenomena and error rather than between phenomena and the theoretical parameter, if it is unlikely that this same error is at work in the same way in another measurement of the same parameter, then agreeing measurements make the likelihood of such systematic error much lower. In multiple measurements that purport to be of the same parameter, systematic error is only likely to play this role if the same systematic error is present in all measurements. Determining whether such systematic error is present in different investigations is thus a measure of their independence and their effectiveness in combination.

Additionally, even if we are not able to determine the exact measurements of the parameters, if the independent investigations provide an overlapping range of accurate measurements, we can use this agreement to place boundaries on what other systematic effects may be at work either in all investigations or in specific investigations. Due to the systematic relationship between the theory and the phenomena used to measure the parameters of the theory, we may be able to make do with approximations of the phenomena that still provide fairly accurate measurements of the parameters. Such was the case with the phenomena associated with primordial nucleosynthesis and element abundance in the 1990s. While the exact measurements of many parameters of the standard cosmological model could not be captured at the time, at least because the overall mass-energy density of matter in the universe could not be well established, even the rough boundaries on primordial nucleosynthesis that could be established were enough to place boundaries on the mass-energy density of baryons. These measurements were generated from the analysis of the relative abundance of different light elements, each of which provides a more-or-less independent constraint on baryon density if we assume the standard cosmological model. Thus within a fairly wide family of models, where the values of the mass-energy densities of matter and the cosmological constant could have a wide range, the mass-energy density of matter in the form of baryons could be fairly well measured with little chance of unaccounted for systematic effects producing later significant changes in the measurement. Thus even while some parameters were not well established, the ability of the standard cosmological model to produce agreeing measurements of some of its parameters from independent sources was a convincing success.

This methodological approach lays out the means by which a successor theory may supplant the standard cosmological model. The potential successor theory must undermine not only the core assumptions of the standard cosmological model, but this theory must also overcome or adopt the ability of the standard cosmological model to produce the agreeing measurements of its parameters. One way for the successor theory to accomplish this is to provide both significant evidence for its own fundamental assumptions while at the same time demonstrating significant conspiring errors in the investigations supporting the standard cosmological model. As such, it must be accompanied either by a demonstration of how various investigations have lead the standard cosmological model down a garden path or a demonstration that the standard cosmological model is a limiting case of the more accurate successor theory. The possibility that the standard cosmological model has been lead astray is diminished by the extent to which the independent sources of determining the measurements of the parameters agree on these measurements. This increases the chance that the observations that we make in our investigations are accurate depictions of the physical systems. As such, these phenomena become more entrenched in the sense that they are more likely to be of use to an eventual successor theory in a similar attempt to produce empirical support.

The Independence of Systematic Error in the Investigations

In identifying these two investigations as a case study for the methodology of using theoretical constructions as an aid to a richer idea of empirical success, we would like support in the sense that the theoretical constructions do not simply allow us to reproduce the activity observed in the physical system, but that the theoretical constructions that we use accurately represent the regularities of the physical system itself. One of the challenges that this methodology must address is the threat of systematic error influencing observation in such a way that our theoretical constructions are dependent on the error, on some unknown physical regularity in the physical system or in the observation procedure, not on the regularities of the physical system that the theoretical constructions purport to address. One benefit from getting agreeing measurements from independent sources is that, as it is likely that systematic errors from one source would either not influence another source or would not influence the other source in the same way, we can reduce the chance that the systematic dependencies with which the methodology relies are responding to systematic error. There is still the possibility that there are two or more independent sources of systematic errors that, by chance, happen to be working in concert, but the chance of this is less than the chance that systematic error influences a single investigation.

As we will investigate below the sources of systematic error in these investigations are almost completely independent of one another. The first reason we will discuss below is that many of these errors arise from the the potential for error unique to the instrumentation. As these two investigations share very few instruments, this error is specific to each investigation. The second reason that these errors are independent is that the fundamental observations of these investigations are so different that, even if there is some significant error in our understanding of the physical systems underlying these observations, it is unlikely that our mistake in understanding in one investigation is related to our mistake in understanding the other investigation. The exceptions to this case may lie in our understanding of cosmological evolution and in our understanding of extragalactic dust in extragalactic space, so we will address that later in this chapter. Below we will discuss the various sources of systematic errors in the two investigations and examine why we should not expect correlations between the two investigations on the basis of these potential sources of error.

One source of error that may be troubling for the supernovae investigations is the influence of selection bias within the observations; however, selection bias in this case is too particular to the nature of type Ia supernovae to be expected to play a role in the investigations of the background radiation. The primary worry with selection effect is that due to some cut-off in the lowest brightness events that make it into a sample, the light curve to luminosity relationship upon which the supernovae investigation is based is incorrect. This could be because due to selection effects, we only record the brightest of a range of anomalous supernovae or even because there are two or more populations of supernovae out there that have similar light curve to luminosity relationships, but we fail to note the dimmer of the two populations farther out. This selection bias introduces a systematic regularity into the luminosity that depends on distance, and thus skews the determinations of distance that are systematically tied to the determination of the kinematic parameters of the spacetime, the Hubble constant and the deceleration parameter, and thus to the mass-energy densities of the standard cosmological model.

Selection bias cannot be seriously considered as a systematic error in both the supernova investigation and the background radiation investigation because the cut-off in recording an event into the sample is particular to a method of observation in the supernovae investigation and not in the background radiation investigation. In the case of the background radiation investigation, there light being observed is known to have a very small dispersion in brightness and great effort is made to be sensitive to the range of difference, so selection effects of the sort expected in the supernovae investigations play absolutely no role in the background radiation investigations. Additionally, the systematic effect that selection bias would have is particular to the specifics of the behaviour of type Ia supernovae: it depends on how this selection bias would introduce a regularity into the relationship of distance to redshift. While the relationship of distance to redshift does play a role in the background radiation investigation, a regularity based on the peculiarities of observing supernovae that is due to choosing what supernova to let into the sample should play no direct systematic role in the background radiation investigation. Thus the agreement in measurement produced by the two sources limits the degree to which this systematic error could be playing a role.

A similarly one-sided possible source of selection bias is the presence of variable microwave point sources in the sky, as this may be considered a source of error due to selection effects in the background radiation observations. Part of the background radiation investigation is the use of maps of the sky to exclude known foreground sources of microwave radiation that may contaminate the observation of the background radiation. Variable sources of microwave radiation are less likely to be recorded and omitted from the data used in the background radiation investigation. If these sources are distributed with some regularity, they could alter the determination of the scale of inhomogeneity in the background radiation. This would change which models would best fit the recorded power spectrum of inhomogeneity and thus the measurements of cosmological parameters. However, these sources should play no role in supernovae investigations, as even if such a source of microwave radiation somehow coincided with a supernova observation, the microwave radiation would not be in the range of the record made of that supernova. Additionally, even if such microwave sources lead to systematic error in the background radiation investigation, these sources would have to coincide with a number of supernovae observations and influence these observations in much the same way in order to become a source of systematic error in the supernova investigation in such a way as to change the supernova investigation's measurements of cosmological parameters in the same way that it changes the background radiation investigation's measurements. While not in the realm of impossibility, this seems to rely on a host of coincidences in addition to relying on some unknown mechanism through which a variable microwave source could systematically influence an observation of or near the visible spectrum.

Gravitational lensing is something that does influence both investigations, but it is likely to influence the investigations in different ways. In the supernovae investigation, it is possible that, due to the concentration of matter into the relatively small regions of galaxies, the passage of light from supernovae will be dimmed in its passage through the void relative to what we expect in a homogeneous spacetime. Though the effects of this inhomogeneity are likely to average out over a large sample, there may still be an overall increase in the dimming of distant supernovae and thus an increase the value of the cosmological constant as determined by the systematic dependencies at work in the investigation. In the background radiation investigation, the influence of gravitational lensing can be used to break geometrical degeneracy, the insensitivity of the background radiation investigation in setting independent boundaries on both the overall mass-energy density and the cosmological constant.[206] Due to geometrical degeneracy, the background radiation results more tightly constrain the sum of total energy density and the mass-energy density associated with the cosmological constant than these results constrain these parameters individually. In practice, geometrical degeneracy is addressed by the combination of the WMAP results with the results of other cosmological investigations. However, the influence of gravitational lensing on some scales of inhomogeneity can be used to overcome this geometrical degeneracy, at least to some extent, from within the WMAP results themselves. Thus while it is possible for gravitational lensing to influence the results in both investigations, in the case of the background radiation investigation this influence would not be error but would be a correct part of the process of measuring cosmological parameters. Thus the agreeing measurements of cosmological parameters from the two sources would be a useful more-or-less direct check on the possible influence of gravitational lensing on the supernova investigation.

The error arising from K-correction in the supernovae investigation is unique to this investigation and should play no role in the background radiation investigation. K-correction attempts to reconstruct the original colours of an observation from the observed colours. This process is specific to both the type of instrument used to make an observation and to the type of object or event observed; the K-corrections for supernovae are not the same as those for stars. This makes this process very specific to the investigation. No K-correction is applied to the background radiation investigation. This source of error is particular to the supernovae investigation because it is wholly confined to the specifics of the process of observation.

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[206] Stompor. R. and Efstathiou, G. 1999.

The background radiation investigation has a host of very specific sources of systematic error that depend entirely on instrumentation and should not be influencing the supernovae investigation. Such specific error includes errors from the calibration of the instrument itself and potential errors from the shape of the beam, from sidelobe response, or from the baseline determinations. These errors reside in the nature of the satellite used to make the WMAP observations and play no role in the supernovae investigations. Another very similar source of error is the error associated with map-making, which is intended to preclude known foreground sources from entering into the data. These sources are sources of microwave radiation and should be irrelevant to the supernovae investigation which observes events in the visible or near visible spectrum wherever these events are discovered. Yet another similar error is the striping errors that arise in converting the time-ordered data recorded by the satellite into a two-dimensional map of anisotropies. While supernovae observations do depend on time, there is no need to translate the recorded date from a time order into a two-dimensional representation of the observed sky. Thus this should not be an influence on the measurements produced by the supernovae investigation.

Challenges In Independent Systematic Error: Evolution and Dust

One of the most difficult challenge for cosmological theories to overcome is the hypothetical evolution of physical systems, or even the evolution of physical laws. The evolution of physical systems, or the laws they depend on, may influence the results of cosmological observations in ways that mimic the influence of the causes that we assume are at work in the observations. This challenge may be particularly pernicious for cosmological investigations that depend on differences in the geometry of spacetime over cosmological time. Such investigations attempt to correlate the properties of phenomena with distance and time. Thus cosmological evolution, which may introduce properties of phenomena that depend on cosmological time and are independent of distance, could be mistaken for properties that depend on both time and distance. Dwelling on such purely hypothetical challenges to a physical theory are not often useful, but even if the cosmological evolution is not wholly responsible for mimicking an influence, it may somehow distort the results of investigations.

In the context of looking at these investigations as a case study for this methodology of theoretical constructions, addressing such a challenge is particularly important. If the theoretical constructions are to accurately represent the actual dynamics of the physical systems themselves and accurately measure the theoretical parameters at work in these systems, then we should have some confidence that it is these theoretical constructions, and not some more complicated theoretical construction, that is the proper basis for our investigation. As the measurement of theoretical parameters depends on systematic dependencies on the theoretical constructions in our investigations, parameter measurements will be mistaken if we are using the wrong theoretical constructions. Conversely, if our parameter measurements are correct, then we can have greater confidence in the theoretical constructions used in our investigations. This is why establishing that sources of error are not shared between different investigations can be used to support not only the parameter measurements themselves, but also the theoretical constructions used in the particular investigations and the phenomena that these constructions identify.

The primary challenge that supernova researchers address regarding the possibility of systematic error due to evolution is the possibility that the fundamental nature of type Ia supernovae changes over cosmological time.[207] If these events were simply dimmer in the past, this could mimic the influence of the cosmological constant in creating a dimming relative to distance. Thus the supernova investigation would be incorrectly applying a relationship of brightness to distance, a relationship that the investigation then ties to the systematic dependency established between distance, redshift, and the parameters of the standard cosmological model.

One check against such evolution is through the use of the supernova investigation to produce accurate measurement of the kinematic parameters of the standard cosmological model from a range of supernovae extending to a great distance.[208] While the cosmological constant produces acceleration of the scale factor at the current era, in the past one expects that the acceleration had to begin at some point, the point where the influence of the cosmological constant on the deceleration parameter overcame that of the mass-energy density of matter. While the measurement of acceleration is sustained by the observation of supernovae that are dimmer relative to what we expect them to be given a coasting universe, a measurement of deceleration is sustained by an observation of supernovae that are brighter than expected. Thus if there was deceleration in the past, there should be a distance beyond which we observe supernovae begin to be brighter than expected from acceleration. The supernovae data supports this observation and thus supports a measurement of the kinematic parameters that demonstrates this change in the deceleration parameter, a change supported by the measurements of the cosmological

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[207] Perlmutter, S. and Schmidt. B.P. 2003.

[208] Riess, Adam G. et al. 2007.

parameters.

This difference in the luminosity that we observe thus indicates a more complicated relationship between the observed luminosity of supernovae and distance than could be sustained by a model of supernova evolution that merely assumes that these objects become brighter over cosmological time. The HSST use this argument to rule out the simplest of evolution models for type Ia supernovas.[209] The argument establishes that only a sophisticated evolution of type Ia supernovae could mimic the results of observation. Thus any account of systematic error based on evolution must provide a more complicated theory that must account for more data in a more sophisticated way in order to be expected to significantly alter our confidence in these measurements. However, even if the evolution of type Ia supernovae is rejected as a wholesale alternate hypothesis, it may be that there is some evolution that acts as a source of systematic error in the investigation, one limited by the above results.

Supernova evolution can be further discounted as a serious threat to these observations as the potential error that may arise from the evolution of supernovae over cosmological time is one we should not expect in the background radiation observation. Such error would arise from some difference tied to cosmological time that changes the nature of the light curve to luminosity relationship of the type Ia supernovae. Such a change is, seemingly, something to be considered only in those investigations in which the type Ia supernovae are a part. These events play no role in the background radiation investigation so we should not expect that any evolution of these events over time should impact this investigation. The confidence that we gain in our parameter measurements

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209Riess et al. 2007

from the background radiation measurements constrains the possible evolution of SNe Ia because the systematic relationships between the parameters and the measurements of the supernovae provide only so much room for this sort of error.

Undetected cosmological evolution of a more general sort that influences the results of both investigations, while not impossible to rule out, is difficult to support. This evolution could perhaps alter the properties of light over time such that it influences both the observations of supernovae and such that it influences the observations of the background radiation. However, in the case of the supernovae, the observations are observations of the relative redshift and luminosity of point sources, whereas in the case of the background radiation, the observations are observations of the scale of anisotropy over regions of the sky. There is some room for the operation of such a parameter as part of the background radiation investigation relies on a determination of the overall distance to the source of the radiation and this sets the scale of the peaks and troughs of the power spectrum of fluctuations. However, the measurements of cosmological parameters from the background radiation is not so wholly dependent on this one parameter that it is likely to have such an overwhelming effect, even if it is one that does act in the same direction and extent in each investigation. Therefore we should conclude that some sort of evolution that introduced similar systematic error in both cases would have to be a very versatile influence.

Seeing these cosmological investigations as a case study for this method of using theoretical constructions to produce evidence provides a context for evaluating potential challenges to the standard cosmological model through such versatile influences. We may consider the density parameters of the standard cosmological model to be versatile influences: these parameters determine much of the extent of cosmological evolution in these two sets of observations. Density parameters are the main influence on the dynamics of the scale factor and in the dynamics of structure formation. This means that a source of cosmological evolution that would act as systematic error in both of these investigations would have to mimic the influence of density parameters in both of these observations while presumably not actually being a density parameter. If the source of error was a density parameter, then presumably like the inclusion of the cosmological constant, we could view this density parameter as an increased specification of the standard cosmological model rather than a source of error. Any density parameter has a place in the standard cosmological model and in the methodology of using the parameters to generate systematic dependencies between the parameters of the theory and observations that measure these parameters. If the source of error was not a density parameter, then it seems it would be something very special to seemingly act like one. This is in the realm of possibility, but this would not be simply adding a source of potential systematic error but be adding an additional parameter to cosmological theory. We should expect of this additional parameter that it also has the same support as that which we can generate from the systematic dependencies of the mass-energy density parameters.

Proponents of Quasi-Steady State Cosmology offer a special kind of extragalactic dust as an explanation for both the supernovae investigation and the background radiation investigation.[210] Below we will examine the role of dust as a source of systematic error as discussed by the two investigations and then turn to the special extragalactic dust

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[210] Hoyle, F, Burbidge, G., Narlikar, J. 2005

proposal.

Extinction due to dust within the host galaxy of supernovae is a source of error for the supernova investigation but not likely a source of error for the background radiation investigation and is likely to be independent in each case even if extinction influences both investigations. This dust leads to a certain amount of dimness in the light that reaches us from a supernovae and it also introduces a characteristic redness to the spectrum we observe for these events. Mistakes in the estimates of the relationship of extinction to the redness may systematically effect the supernovae investigation. However, dust in the galaxies is unlikely to have an effect on the microwave background as this dust is unlikely to have the properties necessary to extinguish that radiation. This would be the case even if the extinction and redness due to galactic dust changes over cosmological time, though neither is there a clear mechanism for such evolution nor evidence of such evolution. Additionally, even if the dust did influence the background radiation investigation, its influence, which would be relative to the redshift of an observation, there is no reason to suspect that the influence of this dust would result in the same sort of systematic error in the final measurement of cosmological parameters as the systematic error that it introduces to the results obtained from the background radiation investigation that works with anisotropies across the sky rather than with distance.

This difference also speaks to the independence of error from dust in our own Galaxy that may influence both investigations. In the supernova investigation, a mistaken understanding of the dust in our own Galaxy could alter our distance determinations. In the case of the background radiation investigation, the dust in our own Galaxy could introduce polarization into the background radiation. We may want to consider this a significant source of error even though the effect of such polarization would likely be minimal, as anisotropy in the polarization of the background radiation is of secondary importance to the results of temperature anisotropy. In any case, the influence of dust in our galaxy is through a very different mechanism for each investigation, extinction versus polarization, so again there is no reason to suppose that that the error introduced by the dust would be correlated between the investigations.

It is in the dust of extragalactic space that the potential for a serious challenge to both investigations may lie. If the nature of this dust is such that is both introduces dimness, extinction for which the supernova investigation does not account, and significantly influences the background radiation then this dust may stymie both investigations. This sort of dust would thus act like a density parameter in that it would have an effect on both observations due to its nature. Accordingly, we should expect that the observations associated with both investigations should be able to put constraints on the parameters associated with this dust.

Within the supernova investigation, the presence of evolving dust is ruled out on the basis of the effect that the dust would have on distant supernovae and on other investigations. Dust of only relatively large grains could cause extinction with minimal reddening; it is certainly in the realm of possibility that the processes though which dust is ejected into extragalactic space preferentially seed the space with larger grains of dust. This profile of this dust would differ from the effect of the cosmological constant at very large distances and it is on this basis that this sort of dust is ruled out.[211] While the dust would continue to extinguish the light from more distant supernovae, the difference

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[211] Riess, Adam G. et al. 2004, 2007.

between the action of the mass-energy densities of matter and the cosmological constant leads to a relative increase in the brightness of more distant supernovae. We can see this effect in distant supernovae.[212] Additionally, such dust would change the appearance of the infrared radiation reaching us from beyond our Galaxy.[213] Early results of the supernova investigation together with measurements of the infrared background were able to effectively eliminate a model where dust, within the standard cosmological model, could account for the observations assuming that the universe was flat. Later results of the supernova investigation, with more distant supernovae in the recorded sample, were able to effectively eliminate simple large grain dust models entirely.[214]

More complicated models that contain an evolving purely gray dust component may not be able to be eliminated completely using the supernova investigation alone. If the ejection of the dust from galaxies into extragalactic space is tuned exactly right, then it could mimic the relative action of the mass-energy densities influencing the scale factor. Such dust would have to begin with a certain density in the early universe and become more dense at a specific rate relative to the increase of the scale factor.[215] Goobar et al., dismiss such hypothetical dust as unnatural, writing, "The point to make is that realistic dust firstly has to be related to astrophysical sources, such as star formation, and secondly that it always implies some wavelength-dependence in the absorption and scattering properties."[216] The requirement that Goobar et al. are laying out is that in order to be considered as a viable theory, such dust must have a mechanism for its creation and

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[212] Riess, Adam G. et al. 2007. Kowalski, M. et al. 2008.
[213] Goobar, A., Bergström, L., Mörtsell, E. 2002.
[214] Goobar, A., Bergström, L., Mörtsell, E. 2002. Riess, Adam G. et al. 2007.
[215] Goobar, A., Bergström, L., Mörtsell, E. 2002.
[216] Goobar, A., Bergström, L., Mörtsell, E. 2002.

this dust must match certain properties that we identify for all dust. The latter requirement, at best, could be viewed as an application of Rule 3, whereby the properties that we are able to measure in all dust must be attributed to all dust where we cannot directly measure these properties. However, it may be possible for a source of dust to be gray enough in the range of observations made so far. The former requirement would carry the most weight if it were a demand that the method by which the dust be replenished be amenable to determination through astrophysical investigation independent of measurement of the rate required provided by the supernova investigation. That is, this requirement could be a demand that the replenishing dust hypothesis be able to produce agreeing measurements of its theoretical parameters from independent sources. Otherwise a demand for a specific mechanism does not seem warranted, as the supernova investigation is itself based on a description of type Ia supernova that is not dependent on a particular astrophysical mechanism.

A similarly ineffective argument against the replenishing dust hypothesis is based on the charge of *fine-tuning.* Such charges attempt to claim that specific values of a parameter or set of parameters are *a priori* improbable. However, it is not always clear how this *a priori* improbability bears on our belief in a hypothesis given the available evidence. Riess et al. dismiss the dust hypothesis on such grounds, writing,

> However, a more pernicious kind of dust was also suggested by Goobar et al. (2002), a "replenishing dust" in which a constant density of gray dust is continually replenished at just the rate it is diluted by the expanding universe. This latter dust is virtually indistinguishable from an Ω_Λ model... via the magnitude-redshift relation because the dimming is directly proportional to distance traveled and thus mathematically similar to the effects of a cosmological constant. Dust of this sort with the required opacity, replenishing rate, and ejection velocity from galaxies (>1000 km s-1 for it to fill space uniformly without adding detectable dispersion) may

> always be virtually undetectable in the Hubble diagram of SNe Ia, but its degree of fine-tuning makes it unattractive as a simple alternative to a cosmological constant.[217]

The charge of fine-tuning of cosmological parameters is an all-too common one, though it is often levelled against the standard cosmological model rather than on its behalf. In the interests of finding some common ground between the two positions, a better response to the possibility of such dust is to reject such dust on the basis of the agreement in the measurements of the supernova investigation with those measurements of other investigations. In this respect, the cosmological constant provides a better explanation of the observations than does replenishing dust. On the one hand, we may charitably accept that the hypothesis of replenishing dust does provide a structural explanation for the results of the supernova investigation and through this some retroductive support. We may even charitably accept that the results of the supernova investigation provide a measurement of the parameters of this dust, at least in the amount of such dust and the rate at which this dust is replenished. However, we cannot produce agreeing measurements of these parameters from multiple independent sources, nor can this dust hypothesis provide an explanation as to why the background radiation investigation should produce measurements of the parameters of the standard cosmological model that agree with those of the supernova investigation. Though, as we will discuss below, this is the hope of the proponents of Quasi-Steady State Cosmology.

Dust in the form of metals, primarily iron and carbon, in the shape of thin rods or whiskers could provide the required degree of grayness and could conceivably be produced in some supernovae and enter into intergalactic space through the force of such

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217 Riess, Adam G. et al. 2007. Pg. 111.

explosions. Such dust would be a remarkably gray dust and would not be subject to the standard tests used to detect extinction due to dust through reddening, even those tests that might discover the influence of large-grain spherical dust.[218] Additionally, while the magnitude of this dust in extragalactic space may be "speculative", that such dust could exist in extragalactic space is not.[219] The dust can be created in laboratory conditions and astrophysical theory provides a means for the creation of such dust in supernovae and these supernovae provide a means to eject the dust into extragalactic space.[220] However, this dust should still not account for the reversal of the trend to dimness seen in distant supernovae discussed above unless its production is governed by some parameter that is sensitive to cosmological evolution. Thus the replenishing dust hypothesis must meet a substantial evidential burden to be seriously considered as a viable alternative to the hypothesis of a positive cosmological constant.

Proponents of a rival theory that wish to make use of dust as a significant phenomenon at the cosmological level should have to produce an account of the dust that provides the same sort of agreeing accurate measurements of the parameters of their theory. The standard cosmological model takes dust into account as a fairly negligible source of systematic error and part of the justification for this is that doing so is justified by the agreeing accurate measurements of the theoretical parameters of the model that we get without including significant influence due to dust. Proponents of Quasi-Steady State Cosmology argue that dust in the form of metallic whiskers plays an important role in their account of the results of both the supernovae investigation and the background

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[218] Aguirre, Anthony. 1999a.
[219] Aguirre, Anthony. 1999a. Pg. L22.
[220] Aguirre, Anthony. 1999a.

radiation investigation and indeed they claim that they can produce measurement of the amount of this dust from a number of independent sources.[221] Not only does the dust introduce extinction in the supernovae investigation, but as it is the source of the background radiation, it is the source of any observation of the background radiation. With such a role, the dust plays a systematic role in their theory and we can then take their theory, and the problem of such dust, a seriously as warranted by the agreeing accurate measurements of the parameters of the theory.

Quasi-Steady State Cosmology (QSSC) is an adaptation of physical principles developed through consideration of the Steady State model, but it is its own theory and rejects many of the core principles of the Steady State model.[222] Two of the core principles of QSSC are shared by both the Standard Cosmological model and the Steady State model. These three theories all hold to homogeneity and isotropy at the largest scale and to the expansion of the universe as governed by the Hubble relationship. While the Steady State model takes the commitment of homogeneity and isotropy to the extreme of the Perfect Cosmological Principle, QSSC abandons this commitment. In its shared adoption of the expansion of the universe, QSSC, like the Steady State model before it, adopts the Robertson-Walker metric,

$$ds^2 = c^2 dt^2 - a^2(t)\left(\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta \, d\phi^2)\right) \qquad (5.1)^{223}$$

However, the governing spacetime theory of QSSC is not the General Theory of Relativity but Hoyle-Narlikar theory of gravitation, a theory which, among other

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221 Hoyle, F, Burbidge, G., Narlikar, J. 2005.

222 Hoyle, F, Burbidge, G., Narlikar, J. 2005. It should be noted that QSSC is significantly on the fringes of contemporary cosmology.

223 Hoyle, F, Burbidge, G., Narlikar, J. 2005.

variations from Einstein's theory, includes a field governing the creation of matter and energy.[224] The use of the Hoyle-Narlikar theory of gravitation leads to an equation governing the scale factor, $a(t)$, as follows:

$$a(t)=e^{t/P}\left[1+\eta\cos\left(\frac{2\pi\tau}{Q}\right)\right] \qquad (5.2)$$[225]

It is of note here that the $e^{t/P}$ element on the right-hand side of the equation is equivalent the continual expansion term of the traditional Steady State theory, making the remaining factor in the equation a cycle of expansion and contraction overlaid upon this continual expansion. While mass-energy densities do play a role in the dynamics of a system, they are not included in the overall equation for the cosmological model because of the creation of matter and energy at key points in the cycle that essentially determines what the dynamics due to the mass-energy densities will be.

It is the position of the QSSC proponents that, given their assumptions of where we are in the cycle of expansion and contraction (given by the relative values of P and Q and the current value of the Hubble parameter), the observed anisotropy of the background radiation is the product of local grains of dust that have been given the form of a homogeneous black body because of their close association in the past, at the peak of contraction.[226] This close association in the past allows radiation from the past cycle to effectively mix with the grains at that time to create the appearance of homogeneity, an appearance that is maintained throughout the cycle with some variation due to the local influence of galaxies. Under this scheme, anisotropies in the background radiation are due

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[224] Hoyle, F, Burbidge, G., Narlikar, J. 2005.

[225] Hoyle, F, Burbidge, G., Narlikar, J. 2005.

[226] Hoyle, F, Burbidge, G., Narlikar, J. 2005. Narlikar, J. et al. 2003.

primarily to the local distribution of galaxies and thus should be on the same scale as galaxies.

In addition to the role that the dust plays in generating the background radiation, according to QSSC proponents, the dust also provides the extinction required to produce the supernova results. It should be noted that in at least one paper that attempts to address this issue, the proponents also appeal to the addition of a cosmological constant in the field equation of the Hoyle-Narlikar theory of gravity in addition to dust in order to account for the theory.[227] The supernovae themselves are the origin of the dust in extragalactic space. Accordingly, a model of dust production would provide a parameter which could be systematically linked to the parameters of their model in a manner similar to the link between the SNe Ia light curves to the parameters of the standard cosmological model.

Few cosmologists have taken the time to respond to the claims of QSSC proponents. This may be because of the attitude expressed by Riess et al. above that the amount of fine-tuning required to introduce both increased extinction in recent times and decreased extinction in the past is simply not a viable physical scenario. The only direct response in recent years known to this author is the response of E.L. Wright on his cosmology website and in the physics pre-print archive.[228] Wright points out deficiencies in the ability of the QSSC models to adequately match the available data. While the QSSC proponents are able to provide a match to the 3rd-year WMAP data up to a point in Narlikar *et al.* (2007), Wright points out that while the predicted power spectrum fails to

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227 Narlikar, J., Vishwakarma, R.G., Burbidge, G. 2002.
228 Wright, E.L. 2003, 2008.

match the observed spectrum as well as the ΛCDM model up to an angular frequency of *ell* = 1000, the predicted power spectrum significantly diverges at higher angular frequencies that are provided from a number of sources in addition to the WMAP results.

Even if QSSC could provide as good a fit to the available data as that provided by the standard cosmological model, the theory should not be considered to be a serious rival to the standard cosmological model without a demonstration that QSSC can follow the methodology outlined for the standard cosmological model above. With the ability to produce agreeing measurements of the parameters of the theory from independent sources comes the ability to discover the parameters to be at work and support this discovery with the agreement in measurement from the other sources. This methodology sets a higher standard for a theory than simply providing accurate predictions for a number of tests. As we have seen, this weaker standard does seem to be all that is required for McMullin's hypothetico-structural account. If a theory can meet this higher standard of agreeing measurements from diverse sources, this raises the bar for any alternative to be considered a serious rival.

In the case of the background radiation, the standard cosmological model does not simply predict relative element abundance, or the scale of primordial fluctuations, or the temperature of the background radiation, or the relationship between the observed brightness of supernova over distances, or any of the other tests, it uses these in an interconnected way to constrain the underlying theory. On the one hand, it is possible to think of this in a purely predictive way. That is, we may think of each particular confrontation with the evidence as a test of a particular set of parameter values. Accordingly, only one range of parameter values survives all tests. On the other hand, in doing so, we should not forget the systematic dependencies that enable us to produce a given test of the standard cosmological model. These systematic dependencies are what enable us to not only test the theory with the data and they do this only through our ability to find phenomena in the data that provide measurements of theoretical parameters. Confidence in these phenomena are bolstered not merely because they allow successful prediction, but because through the production of accurate agreeing measurements from diverse sources they are successful in pointing us to the same restricted set within the family of models that is the standard cosmological model. This gives us more confidence in the standard cosmological model than we would have in a rival theory that matches the evidence but does not also provide similar support for the phenomena through which that theory turns data into evidence.

It should be noted that turning to measurements of phenomena in order to produce evidence for a theory is something that Hoyle, Burbidge, and Narlikar (2005) seem to explicitly reject. For example, they describe the determination of the mass-energy density of baryons from *Y*, the relative abundance of helium compared to hydrogen, as "*ad hoc.*" They write of the baryon density,

> It is a free choice that is hopefully adopted to make things come out right. In particular, it has been used to make the calculated value of *Y* agree with the observational scenario.[229]

As discussed in Chapter Two, the determination of the baryon density from relative element abundance is not simply one derivation from the density of helium relative to hydrogen, but it is the product of agreeing measurements of the parameter from the relative abundance of a number of different elements.[230] Under the methodology we have

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[229] Hoyle, F, Burbidge, G., Narlikar, J. 2005. Pg. 97.

[230] Olive, K.A. et al. 1981. Yang, M.S. et al. 1984. Peebles, P..J.E. et al 1991.

been discussing, the agreeing measurement of baryon density is what delivers on the warrant of the explanation that the standard cosmological model gives for the relative element abundance and for the background radiation.

However, according to Hoyle, Burbidge, and Narlikar, such an account does not provide an explanation. They write,

> It is common to find students emerge from a cosmology course in modern times believing that the big-bang theory *explains* the observed microwave background and that it also *explains* a cosmic helium value with Y close to 0.25. This is to distort the meaning of words. Explanations in science are normally considered to be like theorems in mathematics, to flow deductively from axioms and not to be mere restatements of the axioms themselves... Thus the radiation dominated early universe is an axiom of modern big-bang cosmology, and the supposed explanation of the microwave background is a restatement of that axiom.[231]

This limitation of explanation in science to a very strict and straightforward, almost naïve, hypothetico-deductive account of explanation is not unsurprising given the history of Steady State theorists, who have tended to prefer Karl Popper's account of scientific reasoning.[232] More important than their statements about their methodology, which may be echoed by cosmologists promoting the standard cosmological model, is how the proponents of QSSC seek to advance their work.[233] As far as this author can tell, proponents of QSSC do not seem to make any appeal to the ability of their model to provide agreeing measurements of the parameters of their theory. As there is no account of agreeing measurements for the parameters of QSSC, we should not take it seriously as a rival to the standard cosmological model.

The characterization of explanation above again highlights that the focus on the

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[231] Hoyle, F, Burbidge, G., Narlikar, J. 2005. Pg. 97.

[232] Kragh, Helge. 1996. Pp. 244-246

[233] It is the opinion of this author that such cosmologists promoting the standard cosmological model would be mistaken in their methodological statements.

use of phenomena to measure theoretical parameters provides an important addition to something like the McMullin's hypothetico-structuralism. With hypothetico-structuralism, or a similar methodology, one does not necessarily have any resources to compare two theoretical structures that provide similar fits to the available data. However, with the focus on the agreeing measurements that observations of phenomena can provide, we have the means of qualitative and quantitative comparison between rival theoretical structures. We can ask of these structures how well each produces evidence through agreeing measurements from independent phenomena. Additionally, we answer such questions quantitatively by examining the degree to which agreeing measurements of theoretical parameters limit the possible influence of systematic error on the phenomena used to provide evidence for the theory. Part of this advantage is gained through an extension of explanation beyond deductions to specific claims. In the Newtonian methodology, the explanation of a system is accomplished through the use of the phenomena that can be discovered in these systems and this discovery bears on the construction of the theory itself, in the sense that the observations of phenomena provide the measurement of theoretical parameters.[234]

The Inclusion of the Cosmological Constant

The cosmological investigations used to support the inclusion of a positive cosmological constant are above presented as a case study in the power of combining evidence from independent sources. In so doing, a specific methodology is offered to account for some of the important reasoning in the supernova investigation and the background radiation

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[234] In her interpretation of explanation in Newton, Barbara Tuchanska identifies the key difference between explanation in Newton and in McMullin's hypothetico-structuralism is that in the latter theory construction is separated from empirical verification. Tuchanska, 1992, page 107, footnote.

investigation. This methodology is as follows:

1. Use the standard cosmological model to not simply to make predictions about what we will find in the universe but to create theoretical constructions that we can use to measure phenomena, in the form of expected on-going regularities, in the data.
2. Use the measurements of these phenomena to produce systematic measurements of the parameters of the cosmological theory. Accordingly, measurements of the phenomena constrain measurements of the theoretical parameters and existing constraints on the theoretical parameters constrain their application to phenomena, limiting their flexibility in explaining the recorded data of a physical system.
3. We may evaluate any investigation on its own merits, but if our investigations produce accurate agreeing measurements of our theoretical parameters, we may take this as support for the theoretical constructions used to identify phenomena and thus more support for the standard cosmological model as a whole.

This methodology seeks to capture a rich ideal of empirical success for the standard cosmological model. In this case, it seeks to provide support for the standard cosmological model not only in that it is able to predict the dynamics of the universe at the largest scale, but that it also accurately represents the dynamics of the physical systems involved in the universe at the largest scale. It seeks to establish that the parameters of the standard cosmological model are truly causally (or otherwise) relevant to and representative of the physical systems of concern.

In the two investigations we examine, we find the methodology at work in the following ways:

1. The Robertson-Walker metric is used to determine a relationship between distance and redshift that produces, from the data recorded from the supernovae, a regularity represented by the Hubble constant, the deceleration parameter and other kinematic parameters that relate to the scale factor of the Robertson-Walker metric. This same relationship is used in the background radiation investigation, to the extent that the relationship is part of determining how large the fluctuations that we observe are relative to their size at the time that they were emitted. These fluctuations from homogeneity in the background radiation gain meaning in the investigation from the theory of structure formation which provides the basis for identifying why the power spectrum of these fluctuations is informative of the physical processes going on at the time.
2. The standard cosmological model then licenses the use of the Friedman-Lemaître equation that provides the systematic dependence between the kinematic parameters produced by the supernova investigation and the density parameters of the standard cosmological model. It also works with the theories of particle physics involved in nucleosynthesis to derive measurements from the power spectrum of fluctuations in the background radiation. One element of importance in the background radiation investigation is using the limitations on the parameter space provided by independent investigations (both from the supernova investigation and from other investigations) to limit the possible models that can be said to fit the data. Because of the systematic dependencies at work, one cannot simply adjust the available parameters to match the phenomena identified in the background radiation.

3. As discussed in Kirshner, the cosmological community is convinced by the agreement from the different sources. Efforts to secure the inferences within each investigation continue, but in each investigation, the authors make reference to the ongoing consensus of their results and even note the possibility for systematic error in their results when these results move away from the consensus established by other independent investigations.

This use of the available evidence is not significantly different from that used to build support for the model before the introduction of the cosmological constant. In both cases, it seems to be a good case study of Newtonian methodology.

An important aspect of this methodological approach is that it provides an answer to the charge that the use of the cosmological constant, or the use of dark matter, is *ad hoc*. To a certain extent within this methodology, theory construction is bound up with theory justification. Thus within this methodology, the question of whether or not an element of the theory is added before or after confrontation with the data is not an important question. In place of this question of priority is the question of whether or not ongoing investigation supports belief in the phenomena discovered in the data and whether or not ongoing investigation supports belief in the measurements of theoretical parameters produced by the observations of relevant phenomena. Through the systematic dependencies between theoretical parameters and phenomena, the discovery of agreeing measurements from independent sources provides support for belief in both the parameters and the phenomena. In this case, this agreeing measurement supports the use of the cosmological constant.

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