# CALIBRATING THE UNIVERSE: THE BEGINNING AND END OF THE HUBBLE WARS

**Genco Guralp**

## INTRODUCTION

Historians of science generally agree that the linear relationship that Edwin Hubble discovered, between the velocities of galaxies and their distances, constitutes a major breakthrough in the history of observational cosmology.[1] In addition to putting the *expanding universe* paradigm on a firm footing, Hubble's work provided the impetus for a research program that still continues to be of central importance in experimental cosmology today.[2] This is mainly due to a key component of the velocity-distance relationship, namely, the *rate of expansion of the universe*, known as the *Hubble constant*. The measurement of this constant is considerably difficult and depends crucially on correctly calibrating different methods of astronomical distance determination. As a matter of fact, Hubble's own value of the constant suffered heavily from calibration problems and was stricken by gross systematic errors. He was also aware that the result was obtained for a small distance scale and had to be confirmed for larger distances as well. Consequently, he "initiated an exploratory program to follow the relationship to the greatest distances attainable with the largest telescope."[3]
The exploratory program that Hubble initiated was brought to fruition by his student, Alan Sandage, one of the most influential astronomers of the 20th century. Through his observational program, Sandage set the stage for the post-war attempts to determine the value of the Hubble constant. His calibration scheme of "precision indicators" consisted of selecting the best standard candle[4] at each level of the cosmic distance scale and following this singular technique of calibration throughout the measurement process.[5] This approach was opposed by the French astronomer, Gérard de Vaucouleurs, who meticulously devised an alternative calibration scheme of "spreading the risks," which advocates the methodology of using as many techniques as possible and then averaging over them. For more than three decades, these towering figures produced incompatible values for the Hubble constant, based on their respective methodologies. Sandage obtained a value of 50 km/s/Mpc, whereas de Vaucouleurs insisted that the correct value was 100 km/s/Mpc.[6] This conundrum, which then came to be known among astronomers as the *Hubble Wars*, was only resolved in the early 2000's, mainly due to the efforts of a collaboration known as *The Hubble Space Telescope Key Project.* This collaboration was specifically formed with the aim of determining the

Hubble constant up to an accuracy of ±10%.

In this paper, I offer an account of the emergence, development and the resolution of this measurement conundrum. I analyse the history of the efforts to measure the correct value of the Hubble constant, on the basis of a theoretical framework that Hasok Chang introduced in his book *Inventing Temperature*.[7] I argue that even though each stage of this historical episode exemplifies Chang's notion of *iterative progress*, this notion by itself is not sufficient to understand how the conundrum was resolved. For a better understanding of how the Hubble Wars ended, I claim, we need to situate it within the general transformation that cosmology underwent in the early 90's, which is known as the *precision era*. More specifically, drawing on Galison's work,[8] I urge that within the precision era, a new *material culture of calibration* came into play in experimental cosmology, in which various working-groups using different methods sought error-reduction through precision measurements as their primary goal, as opposed to a "philosophical" commitment to a single methodology that we see in the cases of Sandage and de Vaucouleurs.[9]

The plan of the paper is as follows. First, I outline Alan Sandage's observational program and his methodology for measuring the Hubble constant. Next, I discuss de Vaucouleurs's approach to the problem and his attack on Sandage's methodology. I then describe the work of the *Hubble Key Project* and examine how the results of this project ended the controversy over the value of the Hubble constant. Finally, I offer a critical analysis of this episode and argue that a synthetic reading of Chang and Galison's works can help us to understand the mode of scientific progress that this case presents.

## 1. THE SANDAGE PROGRAM

In an article he published in 1970 in the journal *Physics Today*, Allan Sandage famously characterized cosmology as a "search for two numbers."[10] This was seven years before the *Hubble Wars* was officially launched by Gérard de Vaucouleurs, with his publication of the first paper of his eight-article series on the *extra-galactic distance scale*.[11]

The importance of Sandage's *two-numbers* article, as it then came to be known, stems from the fact that it provides a very clear statement of his program for observational cosmology, and in particular, for the determination of the Hubble constant. Sandage carried out the observational program outlined in the article during the decade following its publication. In the present section, I first provide the background to Sandage's research before embarking on his long-term program to determine the Hubble constant, by focusing on a cornerstone paper that he co-authored with Nicholas Mayall and Milton Humason. Occupying "nearly an entire issue of the *Astronomical Journal*," as one commentator notes, this paper was the result of a "multiyear effort to determine the nature of the expansion of the universe."[12] After analysing the main conclusions of this paper, I examine the *two-numbers* article to outline the elements of Sandage's program for experimental cosmology. I then study the series of articles he published between 1974-1981 under the general title "Steps Towards the Hubble Constant," in which he laid out and executed his strategy of "precision indicators," for the measurement of the Hubble constant.

Before I begin unpacking the details of Sandage's program, I would like to say a few words about the context of the search for the correct value of the Hubble constant. Firstly, one should note that the post-war period cosmology was dominated by the historic debate between the steady-state and the big-bang models. This question was only to be resolved in a definitive manner (in favour of the latter) with the advent of the measurements of the cosmic microwave background radiation, first detected by Penzias and Wilson in 1964.[13] Secondly, many cosmologists of the era shared the conviction that the expansion of the universe was decelerating. Finally, it was believed that the cosmological constant was zero.

All these factors contributed to the *measurement value* of the Hubble constant in experimental cosmology. As a key element for understanding the expansion history of the universe, a precise knowledge of the constant, as Sandage argued later on, could help select the correct model of the universe, and in particular, determine the "age of the universe," quite straightforwardly.

### 1.1. The HMS Catalogue and the Completion of the Hubble Program

In 1956, Alan Sandage, with his two colleagues, Mayall and Humason, published a 65-page long article entitled "Redshifts and Magnitudes of Extragalactic Nebulae," known as the *HMS catalogue* among practicing astronomers, after the initials of its authors. The importance of this article, which contained results of observations made "during the 20-year interval from 1935 to 1955,"[14] stems from the fact that it represents the culmination of the research program that Hubble started in 1929.[15] With data from over 800 nebulae, the paper represents the largest survey of its time. It is divided into three major sections, separately written by each author. The first two sections, composed by Humason and Mayall respectively, present the data and the third section by Sandage provides the analysis.[16] It was in this final section that Sandage pointed out an important mistake in Hubble's calibration of the distance ladder and announced the revised value of the Hubble constant.

In particular, Sandage targeted two questions in the analytical part: on the one hand, he inquired into whether the data was reliable, and on the other, to the extent that this was the case, he examined the empirical question of whether the velocity-distance relationship remained linear in large distances as well. He dealt with the question of the numerical value of the Hubble constant only in an appendix and in a very tentative manner. At the very beginning of his discussion of the constant, he indicated the difficulty of the task at hand as follows:

> The determination of the expansion parameter H is one of the most difficult problems in modern observational astronomy, since each step required for an accurate solution is just on the borderline of possibility.[17]

Sandage then noted that the main difficulty consists in finding a solution to the following dilemma: one has to observe objects distant enough so that the motions unique to individual galaxies are overcome by the general expansion. Yet, the reliability of distance indicators decreases the further out one goes, so objects have to be close enough for the measurements to be accurate. A common strategy to get out of this dilemma is to identify various astronomical objects within distant galaxies that can be used as "standard candles," whose intrinsic brightnesses can be determined by relatively better known objects such as Cepheid stars. If one can discover these objects at larger distances, one can then use their apparent brightnesses to infer their distance, using the inverse square law.

The key contribution of the paper concerning the Hubble constant was showing that Hubble's attempt to use this strategy was erroneous, which meant a reversal of the entire scheme of calibration that Hubble employed. As Sandage went on to explain, Hubble's calibration depended on the correct identification of the "brightest resolved objects in a sample of nearby resolved nebulae."[18] The particular calibration scheme Hubble used was as follows: The brightest objects in a given nebula were used as standard candles. Hubble believed them to be "supergiant stars." The absolute magnitudes of these objects were assumed to be known from the cepheid calibration of the blue supergiant stars M31 and M33. Lastly, the precise value of Cepheid brightnesses was determined from parallax observations, which constitute the lowest step of the ladder.

The results of the HMS catalogue showed that all these assumptions and determinations were questionable. First of all, starting from 1945, it was noticed that the zero-point of the period-luminosity relation that Hubble used in his calculations was erroneous. This revision in the Cepheid distance already affected all the higher steps of the ladder. In addition, Sandage realized that the key assumption that Hubble made in his calibration was mistaken: the brightest objects observed by Hubble were not stars but H II regions.[19] Sandage managed to

identify stars within these regions but they were much fainter than
Hubble assumed them to be. As he put it:

> ...although it will be possible to use the brightest resolved stars as distance indicators, they are faint and must first be isolated from the H II regions.[20]

This sentence gives the key to Sandage's attack of the problem of Hubble constant for the years to come. Once the stars are identified and separated from the H II regions, a re-calibration routine would be followed. Still, even within the limits of the HMS catalog, Sandage believed one can give a provisional value for the constant. For his readjustment of the expansion parameter, he offered two arguments as two "ways" of obtaining its value:
1. *Use of Andromeda Nebulae*: The rich data set the HMS contained gave Sandage enough confidence to assume that the nebulae had an upper luminosity limit. For calibration purposes, he further assumed that the Andromeda nebula is intrinsically the brightest object among the nebulae. Admitting the arbitrariness of the assumption, he justified it by the fact that the value of the constant thereby obtained coheres with the one that obtained from the second method.
2. *Use of Stars in NGC 4321*: As a second method of calibration, Sandage used the apparent magnitudes of the brightest resolved stars in the NGC 4321 galaxy. By comparing with the known values of the brightest stars in M31 and M33, one can obtain the absolute magnitude information. Combined with the redshift value of the Virgo cluster, to which the galaxy belongs, one can obtain a value for the Hubble constant.

Using these methods, Sandage obtained the value of 180, although he was careful in his statement of the result: "Although it is probably uncertain by 20 per cent, $H$ = 180 km/sec $10^6$ pc . . . appears to be the best obtainable from the present data."[21] It was clear to Sandage that a new observational program was needed.

### 1.2. The *Two Numbers* Article and the Beginning of the Sandage Program

Whereas the HMS catalogue was written in the full spirit of the observational program of Hubble, the two-numbers article represents a new context of observation which differs significantly from the previous one. Sandage now articulates the measurement of the Hubble constant together with the deceleration parameter $q_0$ "as a crucial test for cosmological models." Thus whereas in the HMS catalogue, the Hubble constant made only a tentative appearance in an appendix, it is now the main target of research, with a key role to play in adjudicating between different world models. Yet, Sandage again warned his readers concerning the difficulty of the enterprise:

> Although the observer's problem, to find $H_0$ and $q_0$, is easy to state, it has defied

solution for 40 years.[22]

After this pessimistic observation, Sandage immediately introduced the main problem which would make its mark on the next episode of experimental research: *distance calibration*. He put the problem as follows:

> Distance calibration is a stepwise procedure, with the errors proliferating with each step. First one measures the apparent brightness of certain well defined objects, the distance indicators, in the nearby resolved galaxies. If the absolute brightness of these indicators is known from a reliable previous calibration, the distance follows from the inverse-square intensity fall of. Because a unique relation exists between the period and absolute luminosities of Cepheid variable stars these stars are excellent distance indicators.[23]

It is important to note here that when Sandage uses the term "calibration," he does not refer to a particular measuring device. Rather, what is meant is the correct conversion of an astrophysical object's apparent brightness into an empirically valid distance information.[24]

The central theme of the story is contained in the first sentence in the above quote: *calibration is a stepwise procedure*. As the measurement of the Hubble constant fundamentally depends on measuring distances, it is the determination of the distances that involves this stepwise procedure. It is no coincidence that the central series of papers on the measurement of the Hubble constant that Sandage produced throughout his career carry the title: "Steps Towards the Hubble Constant." With his long-time collaborator, the Swiss astronomer Gustav Andreas Tammann, he wrote 10 papers, which span a time frame of 21 years. In these papers, they determined each step of the distance ladder, in which they executed (almost word by word) the plan that was introduced by Sandage at the end of the HMS paper and elaborated further in the 1970 *two-numbers* article. Below, after pointing out several key points that Sandage made in this article, I will focus on the *steps papers* in the next section.

The stepwise procedure, as we will see below, requires many methodological decisions to be made. But in order to understand how these decisions are made, their *material context* needs to be taken into account. As Sandage explains, the resolution capacities of telescopes play a role in the very definition of the range of measurement. In other words, as opposed to cases in which the measured quantity is within the range of the device capacity so that the measurement range is determined by theoretical considerations only, one sees in this case that the very definition of the measurement range depends on the device capacity and hence changes as the telescopic resolution gets better:

> The crucial distance range within which $H_0$ can be determined is quite narrow. It

> extends between $10^7$ light years, which is remote enough so that expansion velocities begin to dominate the spurious velocity effects and 6 x $10^7$ light years, which is the *upper limit for the indicators to be resolved in nearby galaxies with the 200-inch Hale telescope*. In this range, indicator objects include the brightest resolved red and blue supergiants, the angular size of H II regions, normal novae, and perhaps, after much new calibration, supernovae. *Each of these classes must first be calibrated in even nearer galaxies, less than $10^7$ light years away, where the more precise distance indicators of Cepheid variables can be measured* (emphasis added.)[25]

The distance range has to have a lower limit because in shorter distances the peculiar velocities of the galaxies dominate the expansion velocity and this “masks” the systematic effect of the expansion. The importance of the “nearby” field is for calibrating in a precise way the standard candles to be used for further out distances. This latter calibration forms the backbone of the research program that Sandage followed with the *Steps* articles.

The *two-numbers* article ends its discussion of the Hubble constant by reporting on the corrections made to the local distances and on the basis of these corrections it extrapolates the value of the constant to $15 \leq H \leq 40$. This almost eighty percent fluctuation in the value of the constant, which was tentatively given as 180 in the HMS catalogue, is one dramatic illustration of the difficulty of measuring it.

1.3. *The Steps Series*. The first paper of the *Steps* series, which was published in 1974, is titled: “Calibration of the Linear Sizes of Extragalactic H II Regions,” in line with the program outlined above. The opening of the paper neatly lays out the fundamental problematic as follows, in a way which is very similar to the earlier programmatic article:

> . . . the Hubble rate is extraordinarily difficult to measure directly because distances must be determined with high precision to galaxies that are so remote as to have significant expansion velocities. Cepheids have long since faded below plate limit for such galaxies. The redshifts must be large enough so that the effect of mean random virial motions, or of any local velocity perturbation, can be neglected. This requires new calibration of precision distance indicators that are brighter than Cepheids and that enable us to reach these distances. *Much of the work discussed in this series of papers concerns the isolation and calibration of such indicators*.[26]

This problematic of reaching higher distances sets the stage for the entire debate between Sandage and de Vaucouleurs, which could perhaps be more aptly called the *calibration wars*. For once the problem of reaching the higher steps of the distance ladder is identified, the question of method, that is, of *how to proceed* is to be addressed. Here is how the *calibration* *recipe* given in the first Steps article:

> 1. The linear sizes of H II regions in late-type spirals . . . are calibrated using galaxies whose distances are known from Cepheids. . .
> 2. This size calibration is extended to include supergiant spirals. The distance to the nearest of these (M101) is found in Paper III using six methods, including use of the brightest stars as calibrated in Paper II.
> 3. The H II region sizes are used to determine distances to 50 late-type field galaxies in the distance interval $m - M < 32$ (Paper IV). The *distribution of absolute magnitudes* of the galaxies in this 50-galaxy sample, as a function of luminosity class (Paper IV), follows from these data.
> 4. Redshifts of newly identified giant Sc I spirals with $m - M > 35$ have been measured as the last step. Combining the redshifts and the absolute magnitudes of step 3 gives $H_0$.[27]

In Step 1, one aims to reach a correct estimate of the diameter of the H II regions using cepheids. In order to do this, *galaxies as cosmological objects* are used as *calibrators* through a *physical property* roughly as follows: It is assumed that the size of the H II regions correlate with the brightness of galaxies that they belong to. Thus, if one can obtain the distance to the galaxy from an independent method, the H II region size will be calibrated and the ladder can be extended further. Step 2 is a variation of the first one, again aimed at using the H II regions to give distance information concerning supergiant spirals, which are further away on the distance ladder.

## 2. THE DE VAUCOULEURS OBJECTION

In a series of papers paralleling Sandage's *Steps* program, the French astronomer Gérard de Vaucouleurs offered a staunch criticism of Sandage's scheme of calibration and attempted to replace it with his own alternative. The main point of attack was that Sandage's method, for each step of the ladder, relied on a single procedure which carried enormous weight for the structure that is built on it. In the first paper of the series, we read the following "manifesto" by de Vaucouleurs:

> *Tradition notwithstanding, distances derived from Cepheids calibrated in open clusters deserve no greater weight than the others*. The unending discussions, revisions, and rediscussions of the *P-L*, *P-L-C*, *P-L-A*[28] relations make the point clear. Because of possible effects of age and chemical evolution on *any* indicator, it is risky to rely primarily or exclusively on any one indicator, while it is unlikely that *all* are

> affected in the same sense and amount by evolutionary differences between galaxies. Rather than rely entirely on a select few so-called “precision-indicators,” the basic philosophy of “spreading the risks” will be adopted here.[29]

In the 8th paper of the series of papers he wrote, executing his “philosophy” of “spreading the risks,” de Vaucouleurs obtained the value of 100 ±10. This contrasts with Sandage’s results sharply. Even though Sandage announced many results throughout his career, from the beginning of the research program of the *Steps* series, all his values centered around 50. For example, in the sixth paper of the *Steps*, published in 1975, Sandage and Tammann obtained: 56:9 ± 3.4.[30]30

In a 1982 monograph entitled *The Cosmic Distance Scale and the Hubble Constant*, de Vaucouleurs gave a more general and comprehensive characterization of how the two “approaches” - as he called them - differed, as follows:

> 1. In the treatment of the galactic extinction corrections: whereas the Sandage approach assumes a relatively low galactic extinction, de Vaucouleurs assumes a significant value for this.
> 2. In the choice of primary indicators: Sandage uses only one fundamental indicator (the cepheid period-luminosity-color relation) - *putting all their money on one horse, as it were* - while the author uses no less than five . . . following a philosophy of “spreading the risk.”
> 3. In the number of calibration methods: Sandage and Tammann use again only one technique - thus doubling their bet, so to speak, while the author used no less than *ten* methods (of which nine are independent . . .) to fix the zero points of his five independent primary indicators.
> 4. In the number of secondary indicators: Sandage and Tammann uses three of them, two of which depend for their calibrations on precarious extrapolations. The author used *six indicators* ... and carefully avoided any extrapolation of the calibrating relations.[31]

Although de Vaucouleurs lists a couple of other discrepancies, the above list contains the core ones and all of the items 1-5, in one way or another, relate to the question of calibration. For, in order to calculate the Hubble constant, two fundamental steps of calibration are required. Firstly, the distances to the nearest galaxies are evaluated by means of primary stellar distance indicators that are *calibrated by fundamental geometric or photometric methods in our Galaxy*. Secondly, a scale of relative distances to more distant galaxies is constructed by means of secondary and tertiary distance indicators calibrated in the nearby galaxies. As both these steps depend crucially on the galaxy extinction model that is used, it also forms a part of the calibration process.

For de Vaucouleurs, this situation presented a calibration conundrum that can be resolved on the basis of the following *methodological* principles:

> i. use the largest possible number of different distance indicators and *independent* methods of calibration in order to minimize accidental and systematic errors;
> ii. avoid extrapolations and use calibrating regressions only as *interpolation* formulae for reduction to central or mean values of the parameters;
> iii. beware of circular reasoning, unverified assumptions, and subjective choices based on intuition, predilection or plausibility arguments;
> iv. subject the distance scale so constructed to a multiplicity of *a posteriori* checks . . . by means of *independent* distance indicators not previously used in its construction.[32]

Armed with these methodological principles, de Vaucouleurs applied his philosophy of *spreading the risks* meticulously: he had 10 different calibration methods. He wrote with authority:

> To construct a distance scale on a secure basis a philosophy of "spreading the risks" *must be adopted. The belief that a single indicator (such as the cepheids) is superior to all others has no factual basis as a realistic assessment of errors indicates* (emphasis added).[33]

As a result of all this, de Vaucouleurs came up with the value of 100, which is double the value Sandage promoted.[34]

How did Sandage respond to these criticisms? His main line of counter-attack was accusing de Vaucouleurs of falling prey to the *Malmquist* or *selection-bias*. Basically, the *Malmquist bias* is the usual selection effect which stems from the fact that as one reaches higher and higher distances, the data points one selects will be intrinsically brighter objects, which will introduce a bias into one's data. As expected, de Vaucouleurs emphatically rejected this criticism, claiming that it was based on a misunderstanding. Referring to Sandage and his co-workers, he wrote that the Malmquist bias is

> elaborately discussed by Sandage, Tammann & Yahil . . . and freely invoked by them to discredit the work of others when it is in disagreement with their own conclusions concerning the extragalactic distance scale and the Hubble constant.[35]

The personal tone of these lines attests to the fact that the debate between the two scientists assumed the form of hostility towards the end. The issue of *Hubble Wars,* as the astronomical community chose to call it, was not to be resolved by either of them.

## 3. THE CONCORDANCE VALUE

Ironically, neither of the values promoted by Sandage and de Vaucouleurs are regarded as correct today. For example, the recently published paper by the WMAP mission, which did not directly measure the Hubble constant but derived it from extremely precise measurements of the cosmic microwave radiation, announced the value: $69{:}32 \pm 0{:}80$.[36] A more recent measurement of the Hubble constant, by the *Planck Mission* of the European Space Agency, produced the value of

$$67{:}80 \pm 0{:}77,$$

which represents the most precise value as of today.[37]

But the critical work that practically ended the controversy was the *Hubble Key Project* (HKP), which began in mid 1980's. Here, without going into the details, I want to quote from their penultimate paper to introduce several pivotal points that show the contrast with the Sandage-de Vaucouleurs debate.

Firstly, HKP works with an open "archival data-base." They write:

> As part of our original time allocation request for the Key Project, we proposed to provide all of our data in an archive that would be accessible to the general astronomical community. We envisaged that the Cepheid distances obtained as part of the Key Project would provide a data-base useful for the calibration of many secondary methods, including those that might be developed in the future.[38]

This is an instance of what I called the "material culture of calibration," following Galison: data-base is open to the community of researchers for purposes of calibrating secondary distance indicators. This communitarian aspect is also indicated in that HKP worked in a way that resembles collaborations in particle physics as opposed to the solitary or very limited collaborative work of Sandage and de Vaucouleurs. In contrast with the single or two-authored papers of the pre-precision era, the HKP paper has 15 authors, who all worked in different institutions.

Secondly, the pre-calibration data reduction was carried out by a "double-blind" technique, explained as follows:

> As a means of guarding against systematic errors specifically in the data-reduction phase, each galaxy within the Key Project was analysed by two independent groups within the team, each using different software packages: DoPHOT . . . and ALLFRAME . . . The latter software was developed specifically for the optimal

> analysis of data sets like those of the Key Project, consisting of large numbers of observations of a single target field. Only at the end of the data-reduction process (including the Cepheid selection and distance determinations) were the two groups' results intercompared. This "double-blind" procedure proved extremely valuable.[39]

This form of bias reduction was not a possibility for the solitary authors of the *Hubble Wars*. Thirdly, the discussion of calibration in the HKP paper differs significantly from the pre-precision era. In contrast to the "philosophical" debates over the methodology of data analysis, the problem of calibration is dealt with in the material context of the Wide Field and Planetary Camera 2 of the space telescope:

> Ultimately, the uncertainty in the Hubble constant from this effort rests directly on the accuracy of the Cepheid magnitudes themselves, and hence systematically on the CCD zero-point calibration. In view of the importance of this issue for the Key Project, we undertook our own program to provide an independent calibration of both the WF/PC and WFPC2 zero points, complementary to the efforts of the teams who built these instruments and the Space Telescope Science Institute.[40]

Lastly, HKP presents us with a methodological compromise between Sandage and de Vaucouleurs in their measurement program. For even though they write that "The Cepheid period-luminosity relation remains the most important of the primary distance indicators for nearby galaxies"[41] in line with Sandage, they seem to accept de Vaucouleurs' "wisdom" when they concede that "Cepheids alone cannot be observed at sufficient distances to determine $H_0$ directly, and an accurate determination of $H_0$ requires an extension to other methods."[42] Accordingly, the HKP employs four secondary methods, all based on the Cepheid calibration as the primary distance indicator.

The Hubble Key Project was completed in 1999. With the publication of their final paper in 2001, the "war" concerning the value of the *Hubble constant* came to an end.[43] As a co-leader of the group, Robert Kennicutt, put it: "The factor of two controversy is over."[44]

## 4. ANALYSIS

We can analyse this episode starting from the model of scientific progress Hasok Chang offered in *Inventing Temperature*. In particular, Chang's notion of *epistemic iteration* captures remarkably well the methodology of distance calibration in cosmology. However, as I argue below, *epistemic iteration* cannot explain the transition to the *concordance* value of the Hubble constant. A more comprehensive understanding of the resolution of the conundrum can be achieved if we supplement the notion of *epistemic iteration* with Galison's concept of *material culture* in science. Below, I will first introduce Chang's picture, and then explain how it can be combined with Galison's account to analyze the Hubble wars.

### 4.1. Progress through Iteration

On the basis of his case study of the development of thermometry, Chang argues that the circularity involved in empiricist methodology rules out a foundationalist approach to justification in science. He claims that this leaves us with no option but to follow a coherentist strategy. His particular version of this strategy, which he refers to as *progressive coherentism*, is built on the idea that "the real potential of coherentism can be seen only when we take it as a philosophy of progress, rather than justification."[45] In other words, Chang thinks that one give an account of scientific progress within the framework of coherentism. The distinguishing character of coherentism, according to Chang, is that a coherentist "inquiry must proceed on the basis of an affirmation of some existing system of knowledge."[46] The scientists may have reasons to be suspicious with this system of knowledge, but they still choose to work within its premises for "they recognize that it embodies considerable achievement that may be very difficult to match if one starts from another basis."[47] Chang gives the name of *epistemic iteration* to this methodology of critical affirmation:

> Epistemic iteration is a process in which successive stages of knowledge, each building on the preceding one, are created in order to enhance the achievement of certain epistemic goals. ... In each step, the later stage is based on the earlier stage, but cannot be deduced from it in any straightforward sense. Each link is based on the principle of respect and the imperative of progress, and the whole chain exhibits innovative progress within a continuous tradition.[48]

If successful, this self-corrective process leads to progress, though there is no guarantee that it will succeed. But what counts as progress? Chang thinks that an episode results in progress to the extent that it improves or enhances epistemic values such as simplicity, testability, or unifying power. In particular, he distinguishes between "two modes of progress enabled by iteration": namely, *enrichment* and *self-correction*.[49] As the name suggests, in enrichment, the knowledge system that one works with is not negated but enhanced in various ways, e.g., made more precise or unified. On the other hand, self-correction occurs when the inquiry based on the system leads into its alteration.

I claim that both Sandage and de Vaucouleurs are making use of *epistemic iteration* as part of their methodology. Moreover, the transition from the *two-factor debate* to the *precision era* value of the Hubble constant also involves modes of iterative progress. In general, any cosmological experiment based on distance measurements has to exemplify *epistemic iteration*, due to the very construction of the cosmological distance ladder. There are two main reasons why. Firstly, just as Chang describes, each step of the cosmological distance ladder has to be presupposed to calibrate the next step. Secondly, when the target distance is reached and the Hubble constant is determined, the resulting value has to be checked to see whether it coheres with other parts of our knowledge of cosmology. The case in point is the fact that the age of the universe that one obtains from the Hubble constant cannot be less than the age of the earth or of the oldest stars.

However, I think that the final resolution of the *Hubble Wars* cannot be understood solely within the purview of iteration. One needs to integrate the historical context into the picture. To this end, I propose to make use of the notion of *material culture* that Galison introduces in his *Image and Logic*. Galison borrows this term from the anthropology and archaeology literature to capture not only “the study of objects taken by themselves” but also “the analysis of objects along with their uses and symbolic significance.”[50] The study of material culture aims at an analysis of objects as “encultured” or “entangled.”[51] In this vein, Galison talks about the “the working physicist’s material culture and experimental practices” that “circulates around the detector. These might include the tools on the bench, the methods of calculation, and the roles of technicians, engineers, colleagues, and students.”[52] One should note that both aspects of the concept of *material culture* are equally important. On the one hand, the concept of *materiality* pertains to the role of detection devices and other technical equipment in knowledge production. On the other hand, the concept of *culture* implies the epistemological decisions[53] that are made by various practitioners on the basis of the technical equipment that are available to them.

Even though I have not fully delineated the forms of *epistemic iteration* at work in Sandage and de Vaucouleurs on the one hand and the *Hubble Key Project* on the other, certain significant distinctions can still be discerned concerning how the iterative processes are realized. In particular, with HKP, we see that methodological rules are not sacred and compromises can be made for accuracy. Also, the issue of *calibration*, perhaps the key ingredient of epistemic iteration in cosmological distance measurements, is handled differently in the two cases. For whereas for Sandage and de Vaucouleurs, calibration is to be achieved through a methodological principle that one adopts at the stage of data analysis and interpretation, for HKP it involves calibrating the CCD cameras i.e., the data collection devices themselves. My claim is that these differences can be explained by appealing to the concept of *material culture*, which played a major role in bringing the *Hubble Wars* to an end.

For without taking the material context of the HKP measurement into the picture, in which a precision measurement is not obtained by methodological or "philosophical" rigor, but by material interventions such as development of better software or introducing independent calibration methods on telescopes, their final result would not have been more than another discrepant number added to the list of Sandage's 50 and de Vaucouleurs' 100. It is the *material culture* that they operated with (and within), that made their 10% error claim - and the *epistemic iterations* that led to it - convincing enough for the scientific community to declare the Hubble Wars to be over.

## 5. CONCLUDING REMARKS

The measurement of the *Hubble constant* is still one of the active research areas in experimental cosmology and the debate over the value of the constant is far from being over.[54] Even though a discrepancy between the results of different teams still exists, scientists no longer talk about a "war." In this paper, I argued that this situation can be explained by observing that the *material culture* that Sandage and de Vaucouleurs worked with is no longer with us and, accordingly, its underlying epistemology no longer governs contemporary precision cosmology, even though the measurement and calibration issues are alive as ever. What ended the *Hubble Wars* was not only the existence of better measurements and data analysis techniques, but also the historico-epistemological context in which these activities took place.

---

[1] That this discovery constitutes a milestone is not generally disputed. However, it has recently been claimed that crediting Hubble with this discovery, understood as the discovery of the expanding universe, is not acceptable (H. Kragh and R. Smith, 'Who Discovered the Expanding Universe,' History of Science, xli., (2003)). The debate concerning who actually discovered the expanding universe does not have any direct bearing on the issues discussed in this paper. Suffice it to say that, within the period that constitutes the subject of this paper, it was generally accepted by the scientific community that Edwin Hubble was the discoverer of the expanding universe.

[2] In this the paper, I use the terms "experimental" and "observational" interchangeably. Even though the relationship between these terms is problematic from a general philosophy of science perspective, the context of this paper permits me to pass over this issue.

[3] M. L. Humason, N. U. Mayall, and A.R. Sandage. 'Redshifts and Magnitudes of Extra-Galactic Nebulae', The Astronomical Journal, 61(3):97-162, (1956).

[4] A standard candle is a type of astronomical object with an intrinsic brightness that is assumed to be reliably known.

[5] The idea of *precision indicators* constituted the heart of Sandage's methodology. As early as 1954, in his Helen Warner Prize Lecture, he argued that searching "precision indicators" that "can be isolated and measured" was a key step towards measuring the Hubble constant. See A. Sandage, 'Current Problems in the Extragalactic Distance Scale', The Astrophysical

Journal, 127(3):513-526, (1954), p. 514.
[6] The most commonly used units for the Hubble constant is kilometer per second per megaparsec, and I follow this convention in this paper. For ease of reading, I will suppress the units when reporting different measured values of the constant for the rest of this paper.
[7] H. Chang. *Inventing Temperature: Measurement and Scientific Progress*. (Oxford University Press, Oxford New York, 2004).
[8] P. Galison. *Image and Logic: A Material Culture of Microphysics*. (University of Chicago Press, Chicago, 1997).
[9] The *precision era* in cosmology is usually considered to have begun in the early 90s, when several high-precision measurements on the large scale structure of the universe were first made, thanks to crucial technological advances.
[10] A. Sandage, 'Cosmology: A Search for Two Numbers', Physics Today, 23(2), 34 (1970), pp. 34-41. The two numbers that Sandage is referring to are the *deceleration parameter* and the *Hubble constant.*
[11] G. de Vaucouleurs, 'The Extra-Galactic Distance Scale. I. A Review of Distance Indicators: Zero Points and Errors of Primary Indicators', The Astrophysical Journal, 223:351-363, (1978).
[12] P. Hodge, 'Humason, Mayall, & Sandage's Determination of the Hubble Expansion', Astrophysical Journal, 525:713-713, (1999), p.713.
[13] A. A. Penzias and R. W. Wilson, 'A Measurement of Excess Antenna Temperature at 4080Mc/s', The Astrophysical Journal, 142:419-421, (1965).
[14] Humason et. al, 'Redshifts', p. 97.
[15] As the authors explained in the introductory section, their "unified treatment of spectrographic and photometric data follows previous practice by Hubble, who, had he lived, would have participated as the senior author in the analysis and discussion" (Humason et. al, 'Redshifts', pp. 97-98).
[16] The first section included data from the Mount Wilson-Palomar observatories where Humason worked. The second section by Mayall presented the data he obtained at the Lick Observatory.
[17] Humason et. al, 'Redshifts', p. 159.
[18] Humason et. al, 'Redshifts', p. 159.
[19] H II regions are composed of low-density clouds of partially ionized gas.
[20] Humason et. al, 'Redshifts', p. 160.
[21] Humason et. al, 'Redshifts', p. 161.
[22] Sandage, 'Cosmology', p. 36.
[23] Sandage, 'Cosmology', p. 36.
[24] Due to the space limitations of this paper, I cannot go into the question of meaning of calibration in astrophysics research. For a general analytical inquiry on the notion of calibration in science, see L. Soler, 'What is Calibration? An Analysis of Calibration Focused on Normal Practices of the Investigation of Nature by Means of Already Standardized Instrumental Devices' in this volume.
[25] Sandage, 'Cosmology', p. 36.
[26] A. Sandage and G.A. Tammann, 'Steps Toward the Hubble Constant. I. Calibration of the Linear Sizes of Extragalactic H II Regions', The Astrophysical Journal, 190:525-538, (1974), p. 525.
[27] Sandage and Tammann, 'Steps I.', p. 526.
[28] Here, *P* stands for *period, L* for *luminosity* and *C* for *colour*.
[29] de Vaucouleurs, 'The Extragalactic Distance Scale. I.', p. 351.
[30] A. Sandage and G.A. Tammann, 'Steps Toward the Hubble Constant. VI. The Hubble Constant Determined from Redshifts and Magnitudes of Remote Sc I Galaxies: The Value of

$q_0$', The Astrophysical Journal, 197:265-280, (1975).
[31] G. de Vaucouleurs, The Cosmic Distance Scale and the Hubble Constant, (Mt. Stromlo & Siding Spring Observatories, Australian National University, Canberra, 1982), pp. 16-17.
[32] de Vaucouleurs, Cosmic Distance Scale, p. 39.
[33] de Vaucouleurs, Cosmic Distance Scale, p. 43.
[34] This is the reason why the Sandage-de Vaucouleurs debate was referred to as the factor of two controversy.
[35] G. de Vaucouleurs, 'Extragalactic Distance Scale, Malmquist Bias and Hubble Constant', Mon. Not. R. Astr. Soc. 202:367-378, (1983), p.368.
[36] C.L. Bennett et. al., 'Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results', The Astrophysical Journal Supplement Series 208:20 (54pp), (2013).
[37] Planck Collaboration: P.A.R. Ade et. al., 'Planck 2013 results. I. Overview of Products and Scientific Results', Astronomy & Astrophysics, 571:A1, (2014).
[38] W. Freedman et. al., 'Final Results from the Hubble Space Telescope Key Project to Measure the Hubble Constant', The Astrophysical Journal, 553:47-72, (2001), p. 50.
[39] W. Freedman et. al., 'Final Results', p. 50.
[40] W. Freedman et. al., 'Final Results', p. 50.
[41] W. Freedman et. al., 'Final Results', p. 51.
[42] W. Freedman et. al., 'Final Results', p. 51.
[43] The HKP obtained the value 72 ± 8 for the constant.
[44] http://hubblesite.org/newscenter/archive/releases/1999/19/text.
[45] Chang, *Inventing*, p. 224.
[46] Chang, *Inventing*, p. 224.
[47] Chang, *Inventing*, p. 225.
[48] Chang, *Inventing*, pp. 45-46.
[49] Chang, *Inventing*, p. 228.
[50] Galison, *Image*, p. 4.
[51] Galison, *Image*, p. 4.
[52] Galison, *Image*, p. 4.
[53] These may include decisions on questions such as which research programs are worth pursuing, which methods are to be followed and how to follow them, in addition to differing approaches to data collection and analysis.
[54] Above, I quoted the value from the recent Planck mission. Yet, a team of scientists employing the Hubble Space Telescope to look at the supernova explosions to determine the value of the constant obtained the result of 73.8 ± 2.4 (A. Riess et. al., 'A 3% Solution: Determination of the Hubble Constant with the Hubble Space Telescope and Wide Field Camera 3', Astrophysical Journal, 730:119 (2011).) Note that the error bars of the two results do not overlap.