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The Standard Model of Cosmology as a Tool for Interpretation and Discovery

Commentary on Matthias Bartelmann

Science does not live with facts alone. In addition to facts, it needs models. Scientific models fulfill two main functions with respect to empirical facts. First, they provide a net of theoretical relations by which we may *interpret* the data. By embedding data into the standard model of cosmology (sometimes by identifying the data as fulfilling a certain *prediction* of the theory), a fact about the universe that would otherwise be rather contingent and unrelated to other facts, will be located at a particular place in the causal net of the model, and hence will be supplied with *evidential* status with respect to other parts of the model. In reverse direction, the data thus integrated in the model may fulfill *evaluative* function: When further analyzed, they turn out to *confirm* or to *disconfirm* theoretical relations of the model. In the latter case, the model has to be modified or to be rejected altogether. Empirical data, which have been integrated into the model, cannot only confirm or disconfirm the model, but they can also be used to *specify* the values of theoretical parameters of the model.

This sort of interaction between the data and the model constitutes what may be called the *descriptive* (or puzzle solving) dimension of science. But there is also a *explorative* function of models that is responsible for the research dynamics of cosmology. Models do not only *describe* reality, they are also instruments for *exploring* reality. They are not only involved in the *integration* of known data, but also in the *discovery* of new data. This function is demonstrated by the standard model's prediction of the existence of dark matter and dark energy in the actual universe. The model requires, under the assumption of some previously accepted interpretations (flatness and critical density), that facts, not yet detected by observations, do exist. In order to be able to play that sort of role, the model must have gained high reputation (with respect to former successes in integrating data). Because of this reputation (contrary to the case of testing the model), not the model, but the observations are blamed for the disagreement of the observed data with predictions of the model. In contrast, for example, with the case of the deviation of the orbit of Uranus, compared to the predictions of Newtonian gravitation theory, assuming that some additional boundary condition is present that has not yet been detected by observation, would be no option. All possible boundary conditions have already been included in the model. The fact is also not conceived as an anomaly of the theory, but on the contrary, as indicating that, for the actual observations, there are *some hidden facts that have not been uncovered by these observations*. Actually, the model shows that our observations have been blind for important facts as yet; facts required by the authority of the model – this makes the case distinct to the usual case of prediction of novel facts by a model.

Matthias Bartelmann's presentation of the present state of research in cosmology nicely demonstrates how these four different sorts of interactions between models and facts are actually fulfilled: Interpretation (of observed facts by the model), evaluation (of the model by the facts), specification (of the model by the facts), and exploration (of not yet observed facts by the model).

Interpretation: The discovery of the cosmic microwave background (CMB) exemplifies a case of interpretation. After the unintentional finding of the isotropic radiation background by Wilson and Penzias in 1965, it appeared that this radiation might be interpreted as the microwave background predicted by Gamow and collaborators in the 1940s as the relict of the hot period of the universe near the big bang, in which the helium observed in the actual universe has been produced. The general background that made this interpretation possible was the Friedman class of models as a tool for the scientific understanding of the actual universe. Questions that had to be answered in order to launch that interpretation were: First, is the measured radiation actually *thermal* radiation, as the model requires? (This question has been answered to the positive by the later COBE findings). Second, are there fluctuations in the radiation as they have to be expected in order to account for the observed inhomogeneity of the matter distribution of the observed universe? To this question, the researchers, in the first instance, did not get the expected answer: the necessary fluctuations did simply not appear.

At that point the interpretation relation between the data (the COBE measurement results) and the model turns into an explorative relation: The disagreement between the measurements and the alleged inhomogeneity could possibly be removed, if the model would be enriched by additional mechanisms. Such an additional mechanism is the invention of the dark matter hypothesis: "If cosmic structures consisted not of ordinary matter as we know it, but of a form of matter that does not participate in the electromagnetic interaction, the present cosmic structures could be reconciled with considerably smaller temperature fluctuations in the CMB since then the imprint of the cosmic structures in formation on the CMB could be substantially lower" (Bartelmann 2011, 6). According to the dark matter hypothesis, dark matter had no interaction with light, and thus does not show up in the CMB data in the way ordinary matter does. If no such additional mechanism would have been available to remove the disagreements of the CMB data with the theoretical requirements, then this would have meant a potential negative evidence for the standard model of cosmology.

Evaluation: Actually, the measured temperature fluctuations in the CMB data have turned out to be the most decisive tool for testing the standard model. First, in 1992, the new fluctuation predictions, on the basis of the dark matter hypothesis, were confirmed by COBE measurements. Bartelmann comments this finding as the decisive breakthrough in recent cosmology: "This can be seen as a turning point for cosmology, and at the same time as a piece of evidence that cosmic structures are dominated not by the electromagnetically interacting forms of matter that we know, but by some dark matter of hitherto unknown composition" (Bartelmann 2011, 6). What appeared as a major challenge for the original standard model in the first instance, had turned out to provide some impressive confirmation of the enlarged version of the model. Even if the CMB data gained their theoretical relevance only by means of the background of an interpretation provided by the standard model, and thus were "theory-dependent" in that sense, this did not result in a problematic status of that empirical data concerning their capacity for testing the standard model. Instead, it appeared that the CMB data entail aspects conflicting with the original standard model and thus provoke a modification of it. Again, the prediction's compatibility resulting from that modification with the CMB data was not self-guaranteed, but actually appeared. In retrospect, CMB not only provided positive evidence for the standard model, but also turned out to work as a detector for the limits of the model – a circumstance that increases the empirical credibility of the model all the more. Since the model's confirming evidence not simply "fits" the model's predictions, but discloses some missing pieces of the puzzle, the evidence turns out to be highly *model-independent*. There obviously exists no self-contained agreement between the data and the model produced by the model's interpretation of the data.

Specification: Empirical data do not only have the capacity to confirm or to disconfirm a model. They can also be used to *specify* the values of the model's theoretical parameters. This connection between confirmation and specification of theoretical parameters has most clearly been pointed out by Clark Glymour in his bootstrap model of confirmation (Glymour 1980). He claimed that in interesting cases of theory confirmation the confirming evidence will not speak in favor of a theory, unless the evidence has been used, in connection with some part of the theory, as a resource to specify values of some parameters of the theory. To speak in favor of a theory therefore means to specify the values of those theoretical parameters that must be known to the scientist in order to enable him to determine whether the data satisfy some equations of the theory.

There are strong theoretical connections, according to the enlarged standard model, between the statistical properties of the temperature fluctuations in the CMB and important cosmological parameters, such as the densities of ordinary and dark matter, the total matter and energy density, and the expansion rate of the universe. Thus, the measurement results for these statistical properties also allow for specifications of those important parameters (cf. Bartelmann 2011, 7). Furthermore, the statistical analysis of the CMB, provides a measure of the global curvature of space. The results have been in favor of the global flatness of the universe; this, in turn, means that the universe must have a *critical density* which is about three times the observed matter density of the universe. The determination of the critical density leads to a prominent further prediction of the model: Even if dark matter is included, there is a gap of 70% between the critical density and the matter-energy of the universe. This means that there must be a high amount of *dark energy* in the universe.

Exploration: I have already mentioned that the use of the CMB data for the evaluation of the standard model also discloses some theoretically highly relevant disagreements between the data and the model. The data roughly fit the model, but to yield a precise fit, some modifications of the model would be required. Thus, the example of the recent development of the standard model of cosmology confirms the insight proposed by philosophers of science, such as Kuhn and Lakatos, according to which a disagreement between data and the model does not necessarily lead to a "falsification" of the model. There is an alternative scenario of postponed falsification, according to which the scientists continue using the model as long as all possible resources to remove the disagreement by modifications, either in initial and boundary conditions or in the equations of the theory, have been exhausted. But even if this is not plainly wrong, it seems at least to miss a decisive point as highlighted by our current example: Depending on the credibility of the corresponding model – and the credibility of the standard model of cosmology was extremely high when CMB was discovered – it can happen that the scientists take the disagreement as a positive indication of some not yet detected mechanisms. Then the data – in connection with the model – no longer figure as a tool for confirming or disconfirming an existing theory, but seem to transmute into a tool of *exploration* aiming at the discovery of possible missing pieces in the theoretical picture. Confirmation and disconfirmation are present also then, but related to the testing of particular mechanisms the introduction of which have been provoked by the data.

The new pieces within the theoretical picture, as demonstrated by the case of the cosmological standard model, may exhibit new theoretical riddles. Such a riddle is presented by Bartelmann in the last part of his paper, titled "Dark matter, dark energy, and the future of the Universe". The high isotropy of CMB in the recent period of the universe, Bartelmann argues, provokes the question of "how could the temperature information at one point of the CMB sky ever have propagated far enough to adjust the temperature to the same value everywhere" (Bartelmann 2011, 12). This again is the starting point for the invention of a new mechanism to be added to the standard model, namely the mechanism of the *inflationary expansion*.

The example of the standard model of cosmology clearly demonstrates how methodology of science misses scientific practice, if it is only devoted to the confirmation-or-falsification aspect of the dynamics of theories. New data drive the development of a theory not only by providing new information with respect to the evaluation of theories, but also – and sometimes more importantly – by provoking new ideas concerning the incorporation of new mechanisms into the theory. The observations not only pass their judgment on the predictions of a model – sometimes they drive the generation of new predictions. In those cases, the observations – on the basis of a well-established model – initiate the discovery of real mechanisms that the former picture had neglected.

References

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