Observing stars, representing atoms: images and objectivity in the physical sciences

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Abstract In cultural studies, scientific images are often considered social constructs, not essentially different from works of art. We will argue that imaging plays a key role in physics and that its epistemic realism shall not be systematically dismissed. However, in examining visual practices in science, we will not ignore their relations to artistic practices involved in the representation of nature. We will discuss in some detail two astrophysical theories closely intertwined with the ontological nature of microscopic phenomena: the large scale structure of the universe, in which the statistical analysis of instrumental observations sheds light on the concepts of cosmological inflation and primordial perturbations, and the Hertzsprung-Russell diagram, which relates stellar photometric and spectroscopic data to thermodynamic and atomic descriptions of astronomical bodies. Visual representations as part of good epistemic practice may permit to assess the fundamental constituents of the physical world and to objectively classify the natural phenomena.

Resumo Nos estudos culturais, as imagens científicas são frequentemente consideradas construções sociais, essencialmente não diferentes das obras de arte. Argumentamos que a imagiologia desempenha um papel fundamental na física e que o seu realismo epistémico não deve ser sistematicamente dispensado. Contudo, ao examinar as práticas visuais na ciência, não ignoramos as suas relações com as práticas artísticas envolvidas na representação da natureza. Discutimos com algum detalhe duas teorias astrofísicas fortemente relacionadas com a natureza ontológica dos fenómenos microscópicos: a estrutura de larga escala do universo, na qual a análise estatística de observações instrumentais esclarece os conceitos de inflação cosmológica e de perturbações primordiais, e o diagrama Hertzsprung-Russell, que relaciona os dados fotométricos e espectroscópicos das estrelas com as descrições atómicas e termodinâmicas dos corpos celestes. As representações visuais consideradas enquanto parte de uma boa prática epistémica permitem aceder aos constituintes fundamentais do mundo físico e classificar objetivamente os fenómenos naturais.

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Introduction – astronomical insights into fundamental physics

At the core of the question of scientific realism lies the problem of objective representation: how does a product of scientific research, in particular a visual rendition, relate to the ontic nature of a natural phenomenon? The perception of the reality of electrons and atoms offers a canonical approximation to the matter, and astronomy, with its own set of epistemic peculiarities, is historically related to the received image of the subatomic world. In this paper, we will see how a single image of the polarization of the cosmic microwave background in a patch of sky has been recently presented, allegedly, as evidence of the existence of gravitational waves, as confirmation of cosmological inflation, and as a window to quantum gravity, confirming the ever increasing relation between observational cosmology and fundamental physics. We will also discuss the development by visual means of the spectral classification of stars, and how one century ago it not only gave rise to stellar astrophysics, but also offered crucial support to atomic and nuclear theory. Our aim is to assess the nature of visual arguments in science using the tools of epistemology and art theory.

Epistemology – the objective value of visual representations

In recent studies on the relation of science and art, the stress is put on the historicist aspects of scientific imaging. Lorraine Daston reports about the displayed items in eighteenth century cabinets, and points out how the boundary between art and nature was redrawn during this period, even as both categories remained as distinct as ever; nature objects became artificial (considering the playfulness or "artificialness" of nature) and art objects became natural (as art imitates nature) in the eyes of their collectors.[1] Peter Galison reflects on the concept of objectivity as a historical notion, tracing back its genealogy to the practices of depiction in nineteenth century natural sciences: "truth to nature" idealised pictures made before 1800 were replaced after about 1830 by "objective" representations, i.e. mechanically produced homomorphic images; but a second displacement, brought by a repeated call for judgement in visual practices, saw the emergence of "interpreted" images in early twentieth century.[2] It seems as if visual practice would not only bring out subjectivity in any attempt to systematize the world, but it would also restrict the concept of objectivity to a vanished moment in the history of science, as has been restated by Daston and Galison in a more recent work.[3]

The rich and complex relations between image and nature are certainly present in scientific practice, but they appear also in many artistic representations. From 1821 to 1822, John Constable painted more than one hundred cloud studies and landscapes. In his *Hampstead Heath, Sun setting over Harrow* (figure 1a) he depicts the colours and shapes of clouds using a vivid palette and a dynamical brushstroke, and also notes on the back of the painting how the appearance of the landscape reflects the preceding heavy rains, as the north-west wind clears away the clouds at the end of the evening. In John Thornes' opinion, there is a good agreement between the painters' description and the atmospheric pressure records of 12 September 1821, which show a warm front in the morning and a vigorous cold front in the afternoon.[4] The accurate reporting of weather conditions is not the only meeting point for art and nature.

[1] Daston, 1998.
[2] Galison, 1998.
[3] Daston & Galison, 2007, 307.
[4] Thornes, 1999, 227.

Paul Klee started to collect plants in his childhood (figure 1b), and his interest in natural forms certainly inspired his paintings, but it is also noticeable in his theory of design, even before he taught the discipline at the Bauhaus school. In his journal, Klee states the need to reduce the means of artistic expression, in order to try to say more than nature does.[5] In the two artists, the development of a personal pictorial language allows the mimetic rendering of the light of the countryside, or the creation of abstract designs ultimately inspired in floral shapes.

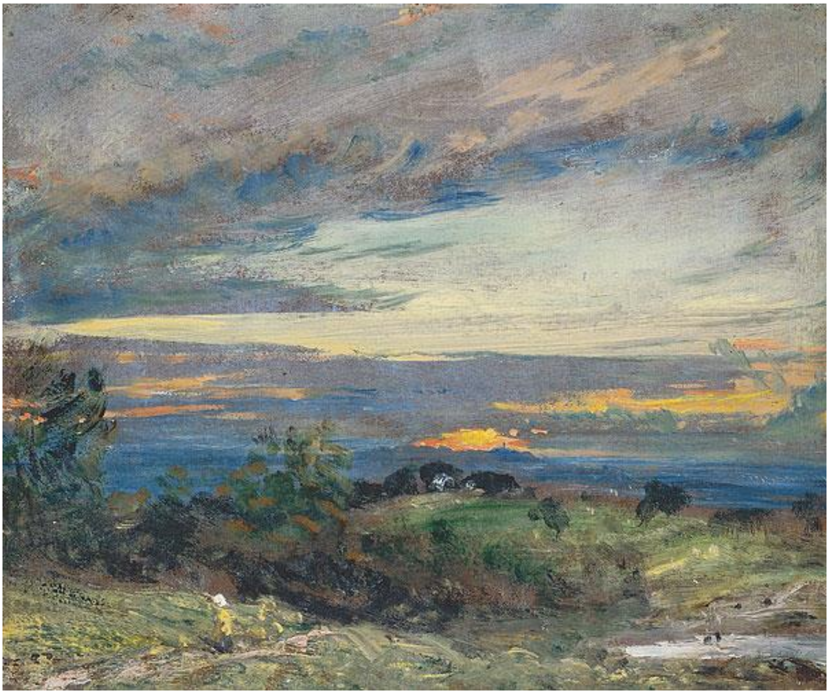

Figure 1a: Constable, J., 1821, *Hampstead Heath, Sun setting over Harrow*, oil on paper laid on board (private collection). From Thornes, 1999, 227.

[5] Klee, 1908, 274.

Figure 1b: Klee, P., ca. 1890, *Plants on primed paper* (Zentrum Paul Klee). From Baumgartner & Keller, 2008, 55.

In this work, we will examine how visual practices can be used to describe and classify fundamental phenomena. We will analyze the role of astronomical images in two fields of physics from the perspective of philosophy of science, and we will find useful also to understand the aesthetic values implicit in any pictorial representation. Our methodology to study scientific practice borrows from two main sources: Phillip Kitcher states that epistemologists should use the history of inquiry as a laboratory to test their methodological claims, and opposes the current trend of philosophy to search for *a priori* principles.[6] Galison, again, observes scientists as an anthropologist, and contradicts assumptions from positivist and historicist epistemologies about how physicists conduct research; he explains

[6] Kitcher, 2011.

that theorists and experimenters coordinate locally their actions, even when they disagree in their beliefs, without using protocol languages or retreating to their epistemes.[7]

Mimesis – natural phenomena representation in a pictorial language

During the second half of the twentieth century, it became increasingly apparent that there were large structures in the Universe far beyond the size of the clusters of galaxies. The Harvard-Smithsonian Center for Astrophysics Redshift Survey began in 1977, and in 1986 the collaboration presented a map plotting the distribution of 1061 galaxies in a "slice of the Universe". The surprising results showed the galaxies distributed on filamentary surfaces surrounding large voids with typical diameters of 30 megaparsecs, posing serious challenges to the then current models for the formation of large-scale structure.[8] Recent observations have shown however that the largest structures observed are smaller than 200 megaparsecs, which is compatible with the homogeneity required in the cosmological models.[9] With the advances in computational power, a team of astronomers led by the Max Planck Institute for Astrophysics was able to simulate by 2005 the distribution of matter in a volume of space 600 gigaparsecs wide; the formation and evolution of 20 million galaxies was modelled in the study, which showed that large empirical surveys are likely to reflect physics in the early Universe.[10] The leading theoretical framework for the formation and evolution of structure includes, besides cosmological inflation,

[7] Galison, 1997, 802-803.
[8] de Lapparent & al., 1986.
[9] Nadathur, 2013.
[10] Springel & al., 2005.

dark energy and cold dark matter, in fact two place holders for as yet unknown physical entities, accounting for several observations with well established empirical support in astrophysics and cosmology.

The inflationary Universe theory was first introduced by Alan Guth in 1981, as a possible solution to the horizon problem (homogeneous conditions are required in causally disconnected regions of space) and the flatness problem (the initial value of the Hubble constant must be fine-tuned); these problems would disappear if the early Universe experienced a period of exponential growth, as the result of a phase transition (symmetry breaking in unified interaction models).[11] The origin of primordial inhomogeneities, the seeds for the future formation of structure in the Universe, can be explained by the quantum effects due to strong gravitational fields expected in the pre-inflationary stage. The gravitational radiation produced in this early age would also preserve information about the physics of the period, as predicted by Alexei Starobinsky.[12]

The possible detection of such primordial gravitational waves has been recently claimed by a team of astronomers, led again by the Harvard–Smithsonian Center for Astrophysics: a polarimetry experiment, installed at the BICEP2 radio telescope build in Antarctica, detected in a region of sky a pattern in the polarization of the cosmic microwave background radiation compatible with the signal of inflationary gravitational waves.[13] The measure showed a strong significance compared against the simulations, however, the possibility of interstellar dust emission bright enough to explain the signal cannot be excluded at the moment. The long sought polarization modes could be observed directly in the map, and not as a numerical outcome calculated from the statistical analysis of the

[11] Guth, 1981.
[12] Starobinsky, 1979.
[13] Ade & al., 2014.

data, which was one of the key elements in the public communication of the result. An image from the article (Figure 2a) shows the curl only polarization (B-mode), and was presented by science journalists as confirmation of inflation theory, evidence of the existence of gravitational waves, and the first glimpse of the quantum nature of gravity.[14] The same image was widely relayed by the general media as a portrait of our newly born Universe.

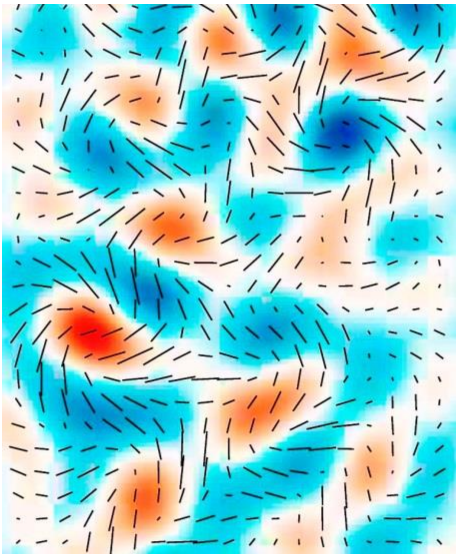

Figure 2a: BICEP2 Collaboration, 2014, B-mode map, figure 3, fragment (*Physical Review Letters*). From Ade & al., 2014.

This particular graph is quite intriguing, as two seemingly opposed factors concur in it. First, the graphic design of the map conveys quantitative information through symbolic language; and second, the image is perceived as the truthful representation of a physical phenomenon. Here we may find guidance in art theory, since artistic representation also confronts the increasing complexity of contemporary abstract languages. We can discuss for instance the

[14] Cowen, 2014.

work of Yves Klein, who refers to the poetics of Gaston Bachelard as an inspiration for his series about the natural elements.[15] In *Cosmogonies* (figure 2b), Klein reflects on what he calls the principles of an explanation of the Universe[16], and tries to capture the signs of the atmospheric phenomena, exposing for example the canvas to the weather. Klein's work in all its diversity can be seen as providing starting points for the *avant-garde* movements of the late twentieth century, and we may presume, for the aesthetic landscape of early twenty-first century. It is interesting in this sense to compare Klein's designs to BICEP2's maps, for their striking visual resemblance, but also for the tension between symbolic abstraction and mimetic immediacy in both of them.

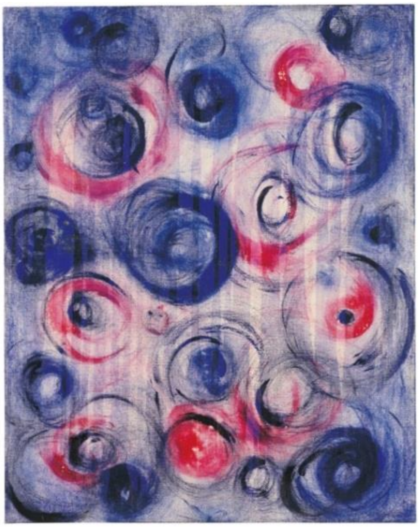

Figure 2b: Klein, Y., 1961, *Cosmogonie Bleue et Rose avec Traces de Vent, Sans Titre (COS 27)*, pure pigment and synthetic resin on paper mounted on canvas (private collection). From http://www.yveskleinarchives.org/. Accessed September 2014

[15] Puthomme, 1999.
[16] Klein, 1961.

The concepts of symbolic representation and mimetic representation may seem to be opposed, but they are not necessarily in contradiction. As Ernst Gombrich explained, Constable developed his personal language working through the exercises from a treatise on drawing by Alexander Cozens, practicing the conventions of the trade, but he still considered landscape painting as a science, part of natural philosophy, and the paintings as experiments.[17] Gombrich described the history of art as the forging of tools for opening our senses; thereby, pictures can be read in terms of natural objects to a degree that depends on our mental set.[18] Any language, with its arbitrary conventions, implies the introduction of some degree of artificiality in the representation of nature, but conventions do not entail its banishment from reality. Conceptual relativity, as Hilary Putnam calls it, is not incompatible with some kind of realism. Even if our concepts are culturally relative, the truth of everything we may say using those concepts does not depend only on the culture.[19] Following Putnam's definition, internal realism would be precisely the kind of realism compatible with conceptual relativity.[20] The precise identification and description of complex natural phenomena is crucial in contemporary science, and pictorial languages offer a useful set of tools that need not be rejected outright. We should keep in mind that the necessity to extract signal from noise, separate fact from artefact, is not exclusive to visual practices, as it encompasses the whole scientific process.

[17] Gombrich, 1960, 150-151.
[18] Gombrich, 1960, 304.
[19] Putnam, 1987, 20.
[20] Putnam, 1987, 17.

Atlas – visual practices and objectivity of natural classifications

The development of astronomical photography and spectroscopy at the end of the nineteenth century presented the occasion for the inclusion of spectral information in the stellar atlases. The Harvard College Observatory began to gather photographic plates in 1886 for the preparation of the Henry Draper Catalogue, published in its final version between 1918 and 1924, with the spectroscopic classification of 225 300 stars. Since the beginning of the project, graduate women were hired as "computers" to process the data, and in view of their expertise, some of them took a leading role in the definition of the spectral classification. In 1901, Annie Cannon published the Harvard classification scheme[21], still in use today. The spectra were divided in seven categories, with ten subcategories each; they were ordered in a continuous sequence, to make progressive changes in the aspect of atomic transition lines as gradual as possible (Figure 3a).

[21] Cannon & Pickering, 1901.

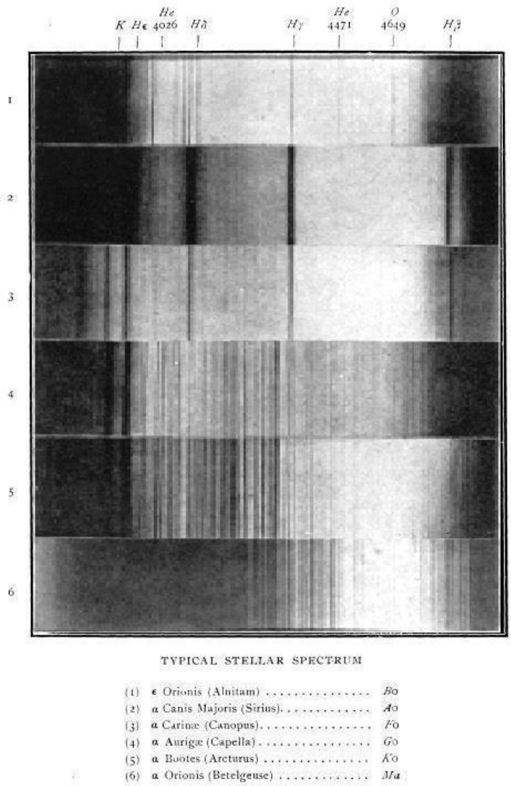

Figure 3a: Cannon, A., 1915, *Typical stellar spectra*, plate XVI (Journal of the Royal Astronomical Society of Canada). From Cannon, 1915.

The Harvard spectral classification was used by Ejnar Hertzsprung, along with his own estimates of absolute magnitude values, to identify two groups of stars, giants and dwarfs[22], which also displayed atomic lines with different widths inside the same spectral class. Working independently, and with much better absolute magnitude data, Henry Russell confirmed this effect. Hertzsprung's and Russell's diagrams of absolute magnitude versus spectral type showed the dwarf stars organized in a single linear sequence, and the giant stars grouped in a distinct branch. In 1914, Russell stated that the only physical

[22] Hertzsprung, 1909.

parameter responsible for the different spectral classes was the effective temperature of stellar atmospheres.[23] He also proposed tentatively a correlation between mass and luminosity along the main sequence. In 1926, Arthur Eddington published his treatise on stellar thermodynamics, including a derivation of the mass-luminosity relation which closely matched observational data.[24] In this influential book, based on general principles from quantum theory and relativity applied to radiation theory and atomic physics, he also postulated nuclear fusion as the probable source of stellar energy.[25] We can see that Eddington builds the foundations of stellar astrophysics using microphysics from early twentieth century as a tool, but we could also interpret that he uses astronomical data to validate fundamental physics.

We can claim that the atlas of stellar spectra published by the Harvard College Observatory lies at the heart of this foundational revolution. But we might question the objectivity of the atlas in the first place. Can we only declare as objective the mechanical production of spectral plates? Do the classification schemes reflect merely the subjective, albeit informed, interpretations of the "computers" and astronomers? Art history may provide again useful analogies. Aby Warburg composed the *Mnemosyne-Atlas* since around 1927, a picture series that combines historical and philosophical approaches, made with photographs arranged to illustrate the genealogy of the ideas behind Renaissance art. Warburg introduced visual language and analogical thinking into art history. For example, in the plates on astronomy (Figure 3b), Warburg traces the adoption of pagan images based in astronomy and astrology (the measurable and the mythological), from Classical Antiquity through the Middle Ages and

[23] Russell, 1914.
[24] Eddington, 1926, 151.
[25] Eddington, 1926, 314.

into the Renaissance.[26] Hence, the plates represent a mental map, the dynamics of the ideas of the author; his subjective, albeit engaging, vision of the material culture of art history. In what sense may Warburg's Atlas and the Harvard Atlas be different? Warburg's program constitutes an impossible archaeology, a project that would entail the completion of a set of particulars that ultimately embodies the universe of ideas in western art, whereas the endeavour of Cannon was to abstract a universal classification from the details of stellar spectra.

Georges Didi-Huberman has recently analysed Warburg's method through the general concept of atlas. As Didi-Huberman beautifully puts it, from the chaos of the world that comes to us in its disparity of prodigies, the sample gives us a chance to perceive a theoretical vision of the universal.[27] We could understand the atlas as a symbolic transition from the bestiary of the Middle Ages to the encyclopaedia of the Enlightenment, in which the discontinuity of free association opposes the continuity of natural classification. Accordingly, the pretence that a collection of mechanically produced pictures could escape subjectivity through lack of authorship does not seem consistent, since the mere fact of selecting the pictures would constitute already an interpretation; objectivity must be found elsewhere. But again, on what grounds can we trust abstractions built on instrumentally mediated observations? Ian Hacking relies on scientific practice, as practical ability breeds conviction to distinguish between instrumental artefacts and real observed structures.[28] Besides, the reliability of the representation is partially independent, as displays are often robust under changes of the instrument's theory: it is the engineering that counts.[29] Around 1900, spectroscopy, born in a

[26] Warburg, 1925.
[27] Didi-Huberman, 2010, 94.
[28] Hacking, 1983, 191.
[29] Hacking, 1983, 199.

lens-making workshop, became a key tool in thermodynamics and astrophysics, and was at the heart of the quantum hypothesis and atomic theory. This network, constructed from formal theories and experimental techniques, provided the framework to interpret the Harvard stellar atlas, and the empirical agreement between the morphological classification of spectra and the quantitative effective temperature of stars was proof of its objectivity.

Figure 3b: Warburg, A., ca. 1924, *Der Bilderatlas Mnemosyne, Planetenkinder*, panel 24 (Warburg Institute). From Warnke, M. (ed.), 2010, 41.

Conclusion – assessing complexity in observational physics

Research in contemporary physics depends on complex experiments, and demands the coordination of large groups of scientists and engineers. The astronomical surveys that are now undertaken require sorting through immense amounts of data, and must undergo exhaustive statistical analysis to pull out the signal from noise. The remoteness of the subject matters makes it difficult to empirically grasp their nature, and still the need to build a mental image of the physical processes remains. Visual practices are essential in this regard.

In conclusion, the artificiality introduced by experimental settings and representational techniques challenges the ability to identify natural phenomena, and the mimetic mapping of their observational features implies the use of pictorial languages, which also demand awareness of the conventions they impose. The systematic description of the observed phenomena, even as a set of images, relies on the judgment of an expert, and always implies interpretation as a first step in the process of abstraction from data; its empirical objectivity follows from the convergence of morphological and quantitative results in a network of theories and techniques, convergence which may eventually lead to a natural classification.

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