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"What the Beauty of Images Exemplifies"

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What the Beauty of Images Exemplifies: Considerations about Scientific Images and Understanding

María del Rosario Martínez-Ordaz

RESUMEN

Las imágenes científicas no solamente tienen carga teórica, sino que también ejemplifican modelos científicos. En lo que sigue, argumento que los aspectos estéticos de las imágenes científicas desempeñan un papel epistémico en la ciencia en la medida en la que incrementan realzando la comprensión científica de lo que representan. Defiendo que en ciencia las imágenes ejemplifican modelos y que, cuando son estéticamente virtuosas, sirven de una gran ayuda para promover nuestra comprensión científica.

PALABRAS CLAVE: *imágenes, comprensión científica, ejemplificación, pilares de la creación, cúmulo bala*.

ABSTRACT

Scientific images are not only theory-laden, but they are exemplars of models of scientific data. Here, I argue that the aesthetic values of images play an epistemic role in science by enhancing our scientific understanding of what they represent. I claim that images in science are exemplars of models and that, when aesthetically virtuous, they constitute a great aid for the furthering of our scientific understanding.

KEYWORDS: *Images, Scientific Understanding, Exemplification, Pillars of Creation, Bullet Cluster.*

I. INTRODUCTION

Scientific images are powerful and impressive mainly because they allow us to put together phenomena in a unique remarkable way, a way that only science could lead to. What is represented in these images is more than brute phenomena, it is the scientific understanding of what is going on in a very specific parcel of the world. For this reason, scientific images have two main dimensions, on the one hand, an epistemic side, and on the other, an aesthetic component.

Concerning their epistemic side, images in science convey messages about scientific success. Yet, at the same time that their format varies, so does the type of success indicated by the images. Astronomical photographs, for instance, allow different audiences to witness distant galaxies which would have been out of reach without our current technology; considering this, their power lies in their capability of portraying in a detailed way those galaxies. In contrast, star atlas are visual simplifications of specific regions of space; therefore, their value lies in their simplicity and accuracy — as they exhibit the scientists' deep understanding of the highlighted objects in that region.

But images are not only epistemic, they are not only the result of combining information that scientists regard as true. An important feature of scientific images is their beauty, making aesthetic values crucial in their development and evaluation. The role of aesthetic considerations is best exhibited in the contemporary building of digital images. For instance, while the Hubble Space Telescope provided us with some of the most revealing photographs of the universe, all of these images were initially built into a black-and-white format. However, the ones that were shared with the public were in color, as they were considered to be more powerful and convincing than the original ones. The coloring of these photographs required astro-photographers to decide on the color palette for each one of the images taking into account both conventions in astronomy and social conventions of what would be considered familiar and visually harmonious in similar scenarios. Thus, the appreciation of these pictures has significantly depended on their previous embellishment.

In what follows, I argue that the aesthetic values of images play an epistemic role in science by enhancing our scientific understanding of what they represent. I claim that images in science are exemplars of models of phenomena and that, when aesthetically virtuous, they constitute a great aid when furthering our understanding.

To do so, I proceed in four steps. First, I briefly introduce the role that aesthetic values have played in the development and evaluation of empirical sciences, and their relationship with scientific understanding. Second, I extend this discussion to deal with visual representations, and I address the role that exemplification plays in furthering our scientific understanding when using visual resources. Third, I illustrate this with a case study from astronomy. Finally, I draw some conclusions.

II. The Epistemic Role of Aesthetic Values in the Sciences

Both scientists and philosophers of science have systematically reflected on the role that aesthetic values play in our theorizing of the world. The main question of this section is whether this role can be epistemic. The first part of the section deals with whether aesthetic values can play an epistemic role in the sciences, and the second part focuses on the specifics of such a role.

II.1. *Aesthetic Values in the Sciences*

The epistemic role of aesthetic values in science is initially challenged by the fact that aesthetic judgments are often (very) subjective, and therefore, unreliable for epistemic purposes. This concern, however, is ill-grounded as the large majority of aesthetic claims are inter-subjective; this is, we agree upon them collectively --in a similar way in which we agree about other components of scientific activity. This considered, if there is any legitimate challenge for the epistemic role of aesthetic values, it cannot consist of such a simplistic subjectivity placed underneath aesthetic judgments. Now, a more convincing problem emerges from aesthetic values' contextual nature: because they depend on particular communities and historical moments, their stability through time is significantly weak, which affects their reliability. For instance, the understanding of what 'beauty is' is broadly dynamic, varying from one historical moment to another [Cf. Duhem (1954), McAllister (1996)], and this dynamism complicates grasping and communication of the content of aesthetic judgments once seen from a different context from their original one.

In the corresponding literature, the stability and reliability of aesthetic values have been addressed by pointing to the similarities between epistemic and aesthetic values. For Poincaré (2001), beauty in science is rooted in features like harmony, unity, and simplicity, which, at the same time, are strongly linked to epistemic virtues such as coherence and comprehensiveness. In this sense, the satisfaction of aesthetic values is similar to that of the seemingly reliable epistemic values. As a result of this line of thought, two main perspectives on the issue have been formed: the first links beauty to the truth by focusing on the relation between aesthetic and epistemic features, while the second is grounded on the representational similarities between science and art. Yet, both reinforce the idea that aesthetic values have an epistemic role in scientific development.

According to the first view, when satisfied, epistemic virtues like parsimony, symmetry, coherence, and broad scope, increase the chances of theories and models being true. In addition, the previous satisfaction of these virtues is crucial for building any elegant and harmonious accommodation of diverse phenomena. When scientists recognize that their theory exhibits such virtues, in a useful and pleasing way, the corresponding aesthetic response is indicative of the epistemological superiority of the theoretical body. Nonetheless, as Poincaré pointed out, this aesthetic experience does not come from "the beauty which strikes the senses (…) What I mean is that more intimate beauty which comes from the harmonious order of its parts, and which pure intelligence can grasp" [Poincaré (2001), p. 368].

According to the second view, science has a primarily representational role: we build theories and models to represent the world. This understanding of scientific activity narrows the gap between science and art in a significant way and takes aesthetic values to be informative of the quality of the representations that are provided through different scientific products. This view has two main branches: (i) one that relates beauty to the reliability of the concrete representational vehicles; and (ii) another that pays attention to the qualities of the target systems and that expects that any adequate representation of them highlights these qualities.

> (i) The processes that underlie the development of scientific theories resemble those followed in the arts. For Rutherford, for instance, this was evident in the more abstract areas of the physical sciences; there, "the mathematical theorist builds up on certain assumptions and according to well understood logical rules, step by step, a stately edifice, whilst imaginative power brings out the hidden relations between its parts. A well-constructed theory is in some respects undoubtedly an artistic production." [quoted in Badash (1987), p. 352].
>
> While Rutherford's claim focuses on the similarities between the creative procedures carried out in both science and the arts, it can also be extended to the products of these procedures. The view of science as a representational activity highlights the similar ways in which both scientific and artistic products can satisfactorily represent specific target systems. With this in mind, the supporters of the so-called semantic approach to scientific theories have scrutinized how theories represent and the forms in which epistemic and aesthetic features interact and positively affect the quality of the resulting representations [Cf. Suppes (1960); French (2003), (2014); van Fraassen (2008)].[1]
>
> (ii) Regarding the second branch of the representational view, there are some scientists, like Einstein and Gödel, who assumed that the empirical domains are in themselves beautifully harmonious and therefore, any accurate depiction of them should also exhibit such virtues. As it might be obvious to the reader, one of the consequences of this view is the

> strengthening of the relation between beauty and truth; the reliability of beauty is not mediated by the previous satisfaction of other epistemic virtues but is the direct consequence of nature itself.

If aesthetic values play an epistemic role in the development of science, the question that remains is which role this is. One option is that they are reliable indicators of the truth of the theoretical bodies that possess them; either because they are indicative of adequate truth preservation or because they are indicative of high-quality representations of reality.

This option grounds the merit of aesthetic values in their connection to truth. Another option that has been recently put forward consists in considering that aesthetic values are often indicative of how epistemically ergonomics and useful theoretical bodies can be when used to approach the world.[2] My aim in the rest of this section is to address this alternative view.

II.2. *Aesthetic Values and Scientific Understanding*

It has been recently argued that the role of aesthetic values is that of enhancing our *scientific understanding* of both the theories and the phenomena that these theories represent [Cf. Kosso (2002); Breitenbach (2013); Ivanova (2017), (2020)]. In a nutshell: aesthetic values like harmony, unity, simplicity, and elegance, among others, concern how sets of information are arranged — and the quality of such arrangements. In addition, understanding consists of knowledge about relations of dependence, and the most salient feature of understanding is the adequate unification of relevant sets of information about phenomena. This is considered when a domain is arranged in a harmonious, simple, and elegant way, it is easier for us to understand it; and the task of understanding often coincides with that of preserving harmony, unity, simplicity, and elegance.

Scientific understanding – henceforth, 'understanding' – consists "of knowledge about relations of dependence. When one understands something, one can make all kinds of correct inferences about it" [Ylikoski (2013), p. 100]. In this sense, understanding is the relational phenomenon of satisfactorily combining doxastic bodies for the building of comprehensive 'pictures' of a particular domain using theoretical frameworks that could, initially, look disconnected. In this sense, understanding a theory requires that agents recognize the theory's underlying inference pattern(s) and "understanding the inferential structure of the theory involves understanding the structure of its domain" [Cf. Macías-Bustos and Martínez-Ordaz (Forthcoming), p. 22].

Because of our cognitive abilities and limitations, when a theory is consistent and parsimonious it is easier for us to use it, identify its logical constraints, follow the rules that hold within it, as well as spot challenges and problems that await to be resolved. But if the theory is inconsistent, vague, or messy, it would be so much harder for us to understand it and to employ it to understand the world. Beauty works in a very similar way. When we find a theory that is well unified, that holds harmonious relations within its parts and that is simple, the pleasing aesthetic experience is indicative of how accessible and efficient this theory is when used to represent the world.

According to Poincaré, in science, beauty emerges from virtues like unity, harmony, and simplicity, he "argues that these values persist as ideals of science rather than being subject to time and fashion and are conditions of thinking" [Ivanova (2017), p. 5]. In this sense, and regardless of its connection with truth, the beauty of theory can be telling of the theory's *epistemic ergonomics* when used (by human agents) to gain an understanding of the world. It is important to notice that for this view, aesthetic values point to how information is arranged, and not necessarily to the truth value of such information. In particular, those who endorse this perspective would agree on the aim of science not being

> truth but rather an understanding of how phenomena are related, and aesthetic values such as simplicity and unity are regulative ideals linked to this ultimate aim of science; they lead to an understanding of the relations that hold between phenomena. For Poincaré, beauty is experienced when one has grasped how different and apparently disconnected phenomena are unified [Ivanova (2017), p. 6].

This indicates that integration is what connects beauty (and aesthetic values in general) and understanding. Because beauty emerges from relational features and understanding aims at establishing neat and relevant connections between bodies of information, it seems that whenever these connections are of high quality, beauty, and understanding are both equally present.

Finally, it is important to make explicit that, while most of the discussions addressed in this section have circled around scientific theories, the morals resulting from such discussions should be extended onto other scientific products like models, visual representations, and narratives, among others.

Summing up: I take this section to have shown that aesthetic values play an epistemic role in science as being reliable indicators and enhancers of scientific understanding. This leads neatly to the issues concerning the reliability of aesthetic values in the building and later acceptance of specific visual representations in contemporary science.

III. THE AESTHETICS OF SCIENTIFIC IMAGES

This section focuses on the building and acceptance of images in cosmology. Sec. III.1, is devoted to the generalities of the aesthetics of scientific images, Sec. III.2. takes these considerations to the field of cosmology, and Sec. III.3. deals with the specifics of the building of contemporary cosmological images.

III.1 *Images in Science: Beauty and Impressiveness*

Broadly speaking, images are built to indicate resemblance and similitude between two items;[3] they can be graphical (pictures, statues, designs), optical (mirrors, projections), perceptual (sense data, appearances), mental (dreams, memories, ideas), and verbal (metaphors, descriptions) [Cf. Mitchell (1986), p. 11]. In what follows, I focus on graphical images.

Images are a crucial part of science; they are often used to communicate messages about scientific success, either by helping scientists to summarize their results, highlighting the significance of their contribution, and more importantly, unifying in a comprehensive way scientific knowledge about specific phenomena. Images in science go from drawings of observation, diagrams, and designs of experiments and instruments, to visual representations of data obtained and processed through heavy technological implementation. Depending on their format, they can take diverse forms and play different roles in the achievement and communication of knowledge and understanding. For example, diagrams and graphs provide us with simplifications of processes, dynamics, and even reasoning paths, and are expected to aid our grasping of how something changes from one stage to another. In contrast, photographs provide us with accurate depictions of specific domains; and in those cases in which the phenomenon that is portrayed is not accessible to us, photographs are the only sensory bond that can exist between agents and the phenomenon.

The images presented and employed by scientists are often considered beautiful and visually impressive – particularly in non-scientific contexts [Cf. Cazeaux (2015)]. On the one hand, the beauty of an image does not come from the artistic features of its composition, but it often results from how the information that grounds the visual representation has been previously structured. The beauty of images is in this sense not so different from the beauty of theories and models; it requires simplicity, elegance, and harmony, and it makes evident how much theoretical progress has been made. On the other hand, the visual impressiveness of scientific images comes from the fact that most visual representations, photographs in particular, are depictions of phenomena that are beyond human vision — because of their size or their location. Thus, is their beauty and impressiveness what make some images very attractive and accessible to the public, as well as revealing the underlying scientific success.

Because of the epistemic achievements that they are indicative of, the beauty and impressiveness of visual representations are thought to be non-intentional. The job of the scientist is not that of a curator, but of a theoretician that obtains, filters, and structures the information for the resulting images to only extend the virtues of the theoretical body into the visual realm. Therefore, aesthetic virtues of scientific images seem to result solely from the combination of theoretical labor and the nature of the phenomenon that is represented. However, there is much more to the aesthetics of scientific images.

The crafting of the images has two main facets: the first one concerns the message that is being communicated through the image. For this matter, scientists have to determine the relevant features of the phenomenon that they aim to portray as well as the epistemic achievement that is being communicated. In the case of images built through technological implementation,

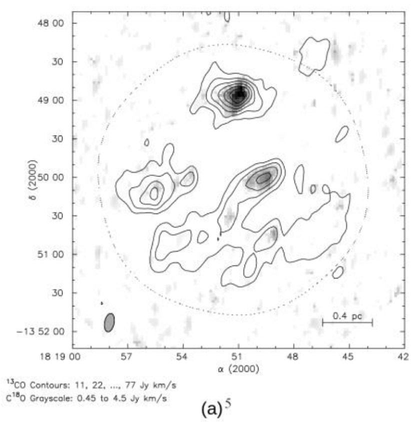
> [D]uring the production process, an image might be selected in the interest of salience, of allowing the point of the image to stand out more prominently (i.e., where there is minimal interference from artifacts, the distortions or intrusions introduced by the imaging technology), as well as in the interest of publishing an image that will maintain the research team's reputation for generating pictures that are strong technically [Cf. Cazeaux (2015), p. 189].

The second facet of the crafting of scientific images is guided by aesthetic considerations as it incorporates elements that will allow the viewer to relate to the image and ease an adequate sensory response. For instance, for images built through heavy technological implementation,

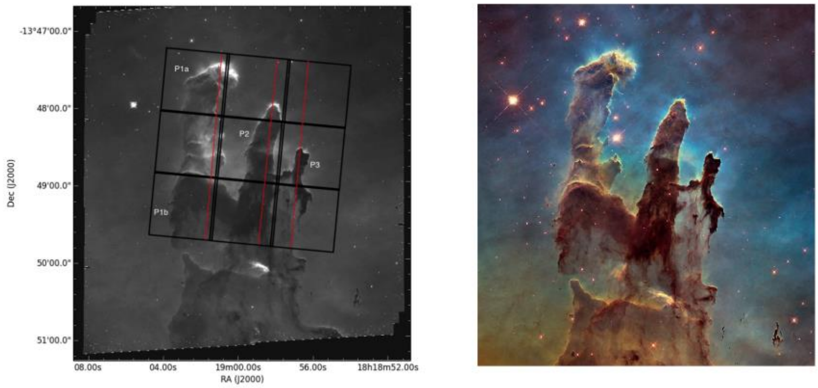
> [W]hen creating color astronomical images it is important to be mindful of how people interact with them. When first viewing a new astronomical image, a primary concern for many is its veracity. Commonly asked questions by the public include "Is this image real?," "Is this what it really looks like?," or even "If I were standing right next to this, is this what I would see?" [Rector *et al.* 2017, p. 3].

The combination of these two major moments in the making of scientific images takes their value and composition beyond the mere combinatory of true information. By highlighting the content of the message that is conveyed and creating visually pleasing representations, scientists reinforce the beauty and impressiveness of their images, making them more attractive and accessible to different audiences.

Take for instance the famous photograph of the so-called "Pillars of Creation" in the Eagle Nebula (M16), which was initially taken by the Hubble Space Telescope in 1995.[4] See the images below.



(a)[5]



(b) (c)

IMAGE 1. Comparison of visual representations of "Pillars of Creation". **(a)** Maps of CO isotopes, Eagle Nebula, from Pound (1998). **(b)** The nine MUSE pointing overlaid on the HST H α+[N II] image, from McLeod et. al, (2015). **(c)** Eagle Nebula "Pillars of Creation", from NASA, ESA and the Hubble Heritage Team (STScI/AURA), (2018).

While the most popular image is the one in color (c), the first visual representation obtained through the Hubble was the one that contained only measurements and distributions (a). Later on, and thanks to computer implementation, the shape of the three towers of gas and dust was reconstructed in a black-and-white format (b). And while all three images are built using the same raw data, is only the latter the one that seems suitable for the communication of the relevance and the scope of the observation to diverse audiences.

The moral is that scientific images, even those that are expected to be highly realistic representations of empirical domains, are the result of more than just combining true information. The remaining question is, however, whether the elements that are intentionally added to pictures to ease sensory responses have an epistemic role.

III.2. *Images, Exemplification, and Understanding*

I start by saying that the epistemic role of aesthetic virtues is equally important when talking about scientific theories and models than when referring to visual representations. My claim is that aesthetically virtuous images have a valuable epistemic role in our achievement of scientific understanding understanding — and that additional (artistic) embellishment done by scientists into these images is only epistemically relevant if and only if they highlight the aesthetic virtues of the model that underlies the image.

First, visual representations in science are theory-laden. In contrast with the images we obtain and use in our daily life, images in science are constrained and heavily informed by theoretical frameworks, they capture a particular phenomenon *in the eyes* of a specific theory or model. Especially, contemporary technologies build images that are not expected to be direct representations of the crude phenomena, they do not show us how the phenomena "look like"; instead, their "appearance is made possible and determined by the theories, apparatuses, and interpretations that create the images" [Cazeaux (2015), p. 193].

Second, scientific images are visual representations of the information given by (and arranged by) a theory or a model. In particular, they constitute visual exemplars of what the theoretical construct tells about a domain. This makes the crafting of scientific images a kind of *exemplification*. Exemplification is a selective activity, it requires the identification of particular features of the object/phenomenon that is being portrayed and the identification of similar features in another item (the *exemplar*).[6] Exemplification consists in showing that "a single item can, in the right context, exemplify any and many of its features, enabling the interpreter to forge a variety of epistemically valuable connections across a variety of domains" [Elgin (2017), p. 78]. The most salient challenge when building images as exemplars of models is to ensure a reliable translation between what the model says into a visual language.

Just like in the first facet of the crafting of images, when designing an exemplar, it is necessary to remove distractors (or idle features) to make the fit for conveying specific messages. However, "before we can remove the impurities or other irrelevant factors, we need to engage in some analysis: we need to conceptualize the item in question as made from components -- those we seek to exemplify, and those we do well to set aside" [Elgin (2017), p. 81]. This analysis is often straightforward, the prior success underneath the model is actually what guides the scientists' selection of the relevant components.

Third, the building of images as exemplars of models of data concerns equally the selection and highlighting of both empirical data as well as theoretical/conceptual virtues of the models. As images play a crucial role in the communication of scientific success, the virtues that result from that success (such as consistency, broad scope, accuracy and simplicity, comprehensiveness, and elegance, among others) should be shown through visual representation. Now, emphasizing certain features of the target system in the exemplar might require introducing correction factors to accommodate, illuminate and call attention to them. This can be done at the level of raw data when filtering and neglecting information that might be distracting from what is being portrayed; however, it can (and should) also be done at the level of visual design — which occurs in the second facet of crafting scientific images. In this sense, the embellishments added by the scientists constitute visual and cognitive aids that play a similar role to simplifications and distractors removal techniques play at an informational level.

Fourth, adequate exemplification leads and results from understanding. Understanding is an epistemic commitment to a systematically connected set of information, evidence of understanding is the ability of reasoning in an outstandingly successful manner within such a set when accommodating new evidence and providing an explanation regarding the understood phenomenon. Exemplification fulfills, at least, two important roles when talking about understanding.

- The first one is enabling the generation and the strengthening of a variety of epistemically valuable connections across different domains and thus, enhancing the interpreter's understanding of specific phenomena. This is why images are so powerful in science education because when adequate, they often lead to understanding.

- The second one consists in indicating that understanding has been achieved: the capability of providing an example "displays an understanding of the subject. It is not just an instance, it is a telling instance" [Elgin (2017), p. 77]. This is the task that is portrayed by scientists when creating images that aim at conveying the message that a particular phenomenon or domain has been understood (at least, up to a certain level).

If this is along the right lines, visual representations as exemplars of models of phenomena play an important epistemic role in both the achievement and the communication of scientific understanding. Furthermore, the highlighting of epistemic and aesthetic features of the target system is crucial for the epistemic ergonomics of the images, especially when used to promote and indicate understanding. Consequently, aesthetic values in visual representations play an epistemic science as indicators and enhancers of scientific understanding.

It is important to notice that I have focused mostly on digital images when addressing these issues; the reason for doing so is that for the case of images built from very rich datasets, it is easier to identify and evaluate the preservation of the aesthetic virtues — from the datasets and the models that they inspired into the resulting photographs. This, however, does not prevent all the conclusions presented here to be easily extended into other, more traditional, types of visual representation in science.

IV. From Beauty to Understanding: The Bullet Cluster

This section is devoted to discussing in more detail the epistemic role of aesthetically virtuous photographs in the empirical sciences. To make the claims more precise, the discussion focuses on the building and use of one of the most important astronomical photographs of the last fifty years.

IV.1. The Basics

The *Bullet Cluster* (1E 0657-558, also 1E 0657-56) is one of the most energetic known galaxy clusters in the universe [Cf. Schramm (2017), p. 13]. The cluster consists of "two merging galaxy clusters, in which the hot gas (ordinary visible matter) is slowed by the drag effect of one cluster passing through the other. The mass of the clusters, however, is not affected, indicating that most of the mass consists of dark matter" (Riess 2017). Up to today, the photographs of the Bullet Cluster are some of the most famous and revealing that we have ever obtained. See the image below.

Image 2. The Bullet Cluster 2006, from [NASA Chandra X-ray Observatory 2006].

IV.2. *Photographing the Universe*

In the 1980s, the emergence of Charge-Coupled Devices (*CCD*) changed dramatically the technology for astrophotography. A CCD

> is an imaging detector which consists of an array of pixels that produce potential wells from applied clock signals to store and transport charge packets.

> The large majority of these charge packets are made up of electrons which are generated by the photoelectric effect from incident photons or from internal dark signals. Gate structures on the silicon surface define these pixels in one direction, while electrical potentials from implants typically define the pixels in the orthogonal direction. A time-variable voltage sequence is applied to these gates in a specific pattern that physically shifts the charge to an output amplifier which acts as a charge-to-voltage converter. External electronics (and often a computer) convert the output sequence of voltages into a two-dimensional digital image [Lesser (2015), p. 1098].

CCD-cameras are the most common visible and near-ultraviolet imaging sensors in astronomy. Astrophotography employs CCD sensors that cab use relatively large pixels for large full-well capacity and dynamic range, require very low dark signal because they are used for long, photon-limited integrations, require total system noise of just a few electrons, and therefore are read out at very slow speeds, and that need near 100% efficiency over wide spectral range because they are used in photon-limited applications [Cf. Lesser (2015), pp. 1099-1100].

However, CCD sensors are not enough for the building of astronomical photographs. Once data is captured via CCDs, it has to be exhaustively filtered and processed to remove biases (offset of charge in each pixel). The emerging image has to go through flat-field correction, the identification of cosmic rays and satellites, and sky background subtraction. After this, each pixel has to be related to a position in the sky, and the numbers in the image should be connected to photons from the source (calibration). This allows a final round of recognition of objects in the domain.

The resulting image is very likely to not be in color but black-and-white; this is because the main purpose of CCDs is to measure the brightness of light reflected on objects in space --which is clearer in black-and-white [Cf. Lowndes (2019)]. To add color to the resulting images, scientists use filters that, first, indicate light in long, medium, and short lengths (*broadband filtering*), creating three mutually complementary images, each of which is assigned a color based on the precision of the visual spectrum. Later on, these images are combined generating a 'true-color' image, this is, a visual representation of how the object would look like to us if we were looking at it with our own eyes. In a further step, astronomical photographs also include color representations of how different gasses interact in the universe, this is called *narrowband filtering*. The most basic application of narrowband filtering isolates light from hydrogen, sulfur, and oxygen, adding a layer of gloss to specific regions of the visualization.[7] This is visible in both pictures: the Pillars of Creation [Sec. 3.1] and the Bullet Cluster.

Here it is important to say that, in contrast with what results from broadband filtering, which are true-color photographs, the coloring obtained through narrowband filtering is enhanced to a point in which the result is more a colorized map than an ordinary photograph. This transition can be illustrated in the following images of the Bullet Cluster.

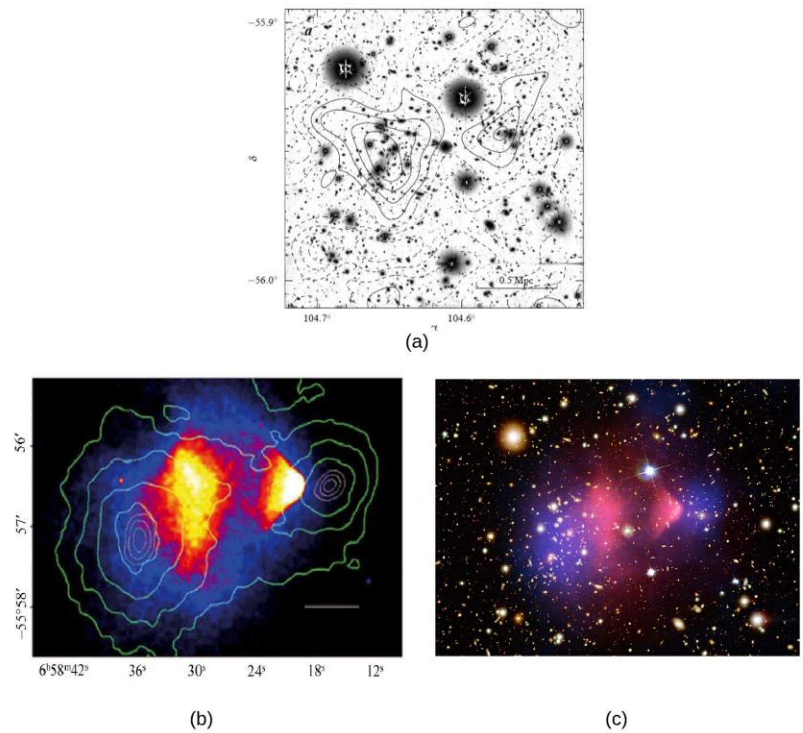


IMAGE 3. Comparison of visual representation of the Bullet Cluster. (a) Bullet Cluster 2004 from [Markevitch *et al.* (2004): 820]. (b) Bullet Cluster 2006, from [Clowe, D.*et al.* 2006]. (c) Bullet Cluster 2006, from [NASA Chandra X-ray Observatory 2006].

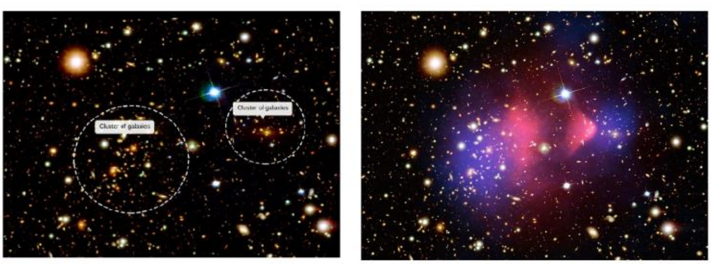
IV.3. *The Aesthetics of the Bullet Cluster*

Do aesthetic values play any role in the building of these astronomical photographs? If so, which role is it? The photographs of the Bullet Cluster have become so popular because we never expected to witness, with such detail, a phenomenon like this one. Furthermore, the scientific significance of these images is that thanks to the precise measurements that underlie the images, the scientific community took them to provide strong evidence in favor of the existence of dark matter. This is very telling of the quality and relevance of the information that was used to create these photographs; in particular, the fact that the images were built in such a comprehensive manner reveals that the dataset that gave rise to them (and the later resulting model) was not only rich but very well structured.

Thus, from the outset, there were different epistemic and aesthetic virtues present in the model that gave rise to the Bullet Cluster photographs; these virtues include novelty, empirical adequacy, accuracy, consistency, as well as simplicity, and harmony, among others. But, were these virtues 'translated' into a visual language?

While there are aesthetic features that might have not been expressly emphasized in the visual representation, it seems that, at least, *simplicity*, *comprehensiveness*, and *harmony* were intentionally preserved.

Regarding simplicity. The initial concern should be whether the photographs of the Bullet Cluster recreate the straightforwardness of the model's structure and whether they highlight only the necessary elements for conveying the intended message. To respond to this, it is necessary to pay attention to the two different types of photographs that can be created from the same dataset: an infrared image which would be closer to our visual perception [Image 4. (a))], and the image that has been popularized through NASA, research papers and various outreach channels [Image 4. (b)]. While the infrared picture would be much closer to how we would be able to perceive the phenomenon if observing it with our own eyes, it has been less popular. The reason for this? The infrared image is more likely to take our attention away from the most salient features of the scientific discovery that these photographs are indicative of. Let me press forward this point.



(a) (b)

IMAGE 4. Comparison of visual representation of the Bullet Cluster. (a) Bullet Cluster 2006, Visible light image from [Viewspace]. (b) Bullet Cluster 2006 (with dark matter), from [NASA Chandra X-ray Observatory 2006].

The fact that the most iconic Bullet Cluster image is with the region in between the two galaxies colored in pink, purple, and blue is telling of the message that is transmitted through the image: the significance of this discovery goes beyond seeing two galaxies interacting, the real contribution is the visualization of the mass distribution within the clusters (determined via weak gravitational lensing) and the later effect that this might have in our understanding of dark matter [Cf. Gramling (2017), p. 24]. The fact that the colors used for pointing to this region so straightforwardly allow us to direct our attention toward the most revealing features of the image. In this sense, the composite image [Image 4. (a)] is much simpler and more elegant than the infrared one.

With regard to the comprehensiveness and harmony of the images. These photographs are some of the most comprehensive images in the whole field, as they are the result of a harmonic integration of very different types of data. The first visual representation of the Bullet Cluster [[Image 3 (a)], from 2004, was a grayscale I-band VLT image. It was largely based on the detection of infrared waves and optical radiation. The 2006 pictures were the result of comprehensive integration of optical data, X-ray data, and a reconstructed mass map, giving birth to one of the most famous and informative images in all of astronomy. The reason for which these images had to be integrated into each other is that the more galaxies we can detect behind the Bullet cluster, the more accurate the measurements will be -especially the ones regarding Strong and Weak lensing. That said, the fact that the model that was used to create these images can integrate all this information tells a lot about its comprehensiveness. Similarly, [Image 4. (b)] harmoniously portraying such complexity is telling of the comprehensiveness of the representation.

Finally, the combination of these criteria, simplicity, comprehensiveness, and harmony, is what makes the visual representation extremely ergonomic for the beholder. The mix of these aesthetic features allows audiences to grasp the relevant elements portrayed in the picture and how they interact, it directs the attention of the viewer toward the central aspects of the discovery, but it also leaves room for her to interact with the enormousness of space.

IV.4. *The Epistemology of a Beautiful Bullet Cluster*

Scientific images aim at exemplifying thesis, models, or even (segments of) scientific theories, and when doing so, they help us to further our understanding of either the world or of the theoretical construct that they exemplify. The question is whether aesthetic virtues, when possessed by these images, can play any epistemic role in the strengthening of our understanding; and, in particular, if they had done so in the case of the photographs of the Bullet Cluster.

As the primary role of images in science is that of convening messages about specific instances of scientific success, the use and reception of those images should depend on how they transmit these messages. That said, in the case of the Bullet Cluster photographs, the level of success that was aimed at communication was extremely high mainly. This is mainly because the observation of the two galaxies provided sufficient precision to determine the mass distribution of the underlying galaxies through weak gravitational lensing and, even more importantly, it allowed scientists to gather evidence around the hypothesis of the existence of dark matter [Cf. Schramm (2017), pp. 13-14].

Now, when establishing a relation between the models of phenomena (built upon data obtained by the space-based telescopes) and the visual representations, one should wonder whether it is legitimately exemplification. For the case of digital images this relation is quite straightforward: as both the model and the picture are created using the same raw data, the link between them is, at least information-wise, robust. Yet, this is not enough for exemplification. On the one hand, as the model is built, additional information is incorporated into the mix obtained through mechanical detection, this information often concerns the type of contribution that this observation constitutes as well as its relevance for the discipline. If images were to exemplify these models, they should also emphasize these extra criteria and leave aside distortions, distractors, and idle features.

There are two levels of the construction of an exemplar. The first one consists in determining which information coincidences between the model and the visual representation are going to be maintained. For the cases of digital images, this is mostly done automatically. The second stage of exemplification is the selection and disregarding of features that are not considered useful for the exemplification. Most of the work of emphasizing and calling the beholder's attention to certain elements of the visual representation is done in one of the latest (and more intentional) stages of photograph building. In this regard, it is important to acknowledge that "how color and composition are used in the image is just as important, if not more so, than the quality of the data itself. (...) A color in an image is similarly intensified or weakened by contrast with other colors present [Albers (1963); Itten (1970a)]. Thus, contrasts between colors in an image can be used to highlight or de-emphasize other elements of the image" [Rector *et al.* (2017), p. 9]. For the case of the

Bullet Cluster photographs, the selection of colors and the emphasis on the most salient contributions is key for them to be considered exemplars of the model that they are linked to.

But does this exemplification concern the epistemic and aesthetic virtues of the original model? First of all, as Poincare pointed out, beauty in science is what comes from the harmonious ordering of things and affects how intelligence apprehends these things. In this sense, beauty has a cognitive pay-off, the more aesthetically virtuous artifacts (theories, models, visualizations, etc.) are, the more epistemically ergonomic they would be. The answer to this question comes directly from the analysis presented in Sec. 4.3. While the virtues of the original model might have exceeded those of simplicity, harmony, and comprehensiveness, the fact that at least the three of them are inherited by the photographs make them significantly ergonomic for different audiences.

Finally, can the aesthetic virtues of the photographs of the Bullet Cluster affect positively the achievement of scientific understanding? Yes. When talking about theories, virtues like simplicity, harmony, and comprehensiveness are indicators of relations between the elements of the theory (as well as of the quality of such relations). When a theory is virtuous in this sense, it is easier for the user to identify and navigate the logical bridges (inference patterns) that assure the trustworthiness of the theory, and therefore, to gain some understanding of the theory and its domains of application.

Similarly, the same virtues of a photograph, because they are partially inherited from the virtue of the theory/model, help the viewer to construct and navigate a very concrete logical space around the conditions according to which the portrayed phenomena would make sense. This makes the photograph much more ergonomic for the understanding of the portrayed phenomena as well as for the grasping of similar scenarios.[8] It is important to notice that, regardless of not having been initially present in the model or the raw data that fed the photograph, other aesthetic considerations like color palettes and visual enhancements play a crucial role in creating a sort of visual familiarity (this is, if the visual representation is a continuum with our ordinary visual experience) that will, in the long run, ease the pursuit of understanding, especially for not-trained audiences.

VI. Concluding Remarks

Scientific images are not only theory-laden, but they are exemplars of models of scientific data (often about particular empirical domains). Here, I have argued that the model's aesthetic virtues, like simplicity, harmony, comprehensiveness, and elegance, tend to be indicative of the scientific success that underlies the building of the model. In addition, images are used in science for furthering the communication and understanding of such a success. So, if the message that is conveyed is supplemented by an aesthetically virtuous model, the image should inherit and portray these virtues. I illustrated this with a case study from astronomy.

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NOTES

[1] In recent years, Elgin has extended these ideas into exploring how exemplification works in both science and art for the promotion and achievement of understanding [Cf. Elgin (1993), (2007)], emphasizing, even more, the similarities between these two fields.

[2] The *epistemic ergonomics* of scientific products consists of a set of features that respond to human abilities and limitations and that are crucial for the improvement of the agent's interactions with the world when using these products.

[3] Here, I adopt a pluralist perspective on what it means for an image to capture and represent an item; for which the idea of representation does not require any strong realist commitment [Cf. Elgin (2017)].

[4] The photograph portrays three towers of gas and dust, standing light-years tall, giving birth to new stars.

[5] It is important to notice that, regarding (a) and after that original paper was published, it was later discovered that excess noise was added to that image by a software bug. The corrected image is the one presented in Image 1. (a). Thanks to Marc W. Pound for the pointers.

[6] It is important to highlight that exemplars often can simultaneously exemplify multiple features. Nevertheless, they should never exemplify *all* the features of a particular studied object [Cf. Elgin (2017)].

[7] The assignment of colors to specific elements is, broadly speaking, the result of conventions in astrophotography. While colors, assigned through narrowband filtering, represent real data and indicate features of the chemical makeup of objects in space, they do not correspond to how we would perceive these objects if we were looking at them directly.

[8] For a broader discussion on the achievement of understanding of the Bullet Cluster see [Martinez-Ordaz (2022), Sec. 5.2].

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CÓMO HABLARLE A UN NEGACIONISTA DE LA CIENCIA

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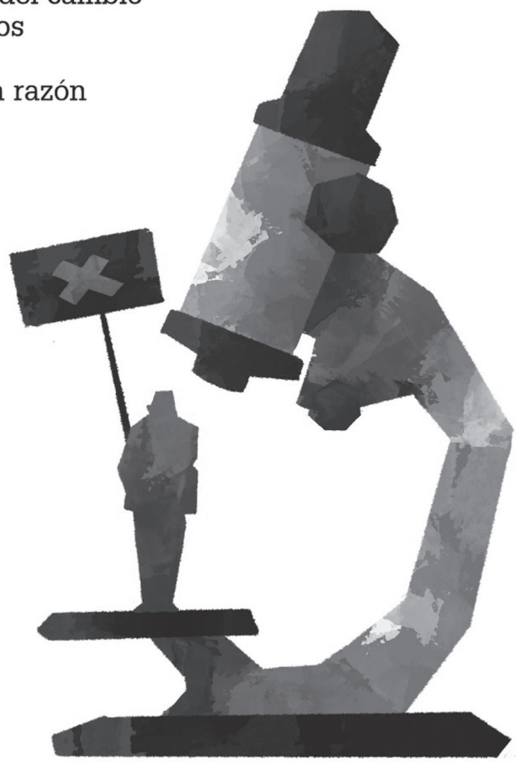

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