Making the Invisible Visible

A Study of Exoplanet Visualisation

A Master's Thesis for the Degree of Master of Arts (120 Credits) in Visual Culture

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Abstract

Making the Invisible Visible:

A study of exoplanet visualisations

Ankita Sharma

Exoplanets are planets found around other stars in the Universe. Although astronomical studies have found and confirmed the existence of exoplanets, they are too far away to be photographed directly, so there are dedicated visualisation scientists who use the data collected on them to create hypothetical visualisation. This thesis project aims to conduct the duality of science and art that exists in the production of exoplanet visualisation, to answer the questions of how the scientific gaze evolved with respect to artistic representations and how illustrations affect the dissemination of science in the public. This shall be achieved by analysing images from *NASA Eyes on Exoplanets* and *OpenSpace* through the lens of a Theoretical Framework postulated by Luc Pauwels that allows for understanding the issues and variations in production, mediums, and contexts of distribution and the purposes achieved by exoplanet visualisations. The reflection is also guided by the influence of the three epistemic values (Truth-to-Nature, Mechanical Objectivity, and Trained Judgement) posited by Daston and Gallison.

Keywords: exoplanet, visualisations, scientific representations, TRAPPIST-1, objectivity.

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Glossary

Exoplanet: A planet outside the Solar System. Most exoplanets are found orbiting another star, but there can also be some rogue exoplanets that are not bound to any star.

Geocentrism: The theory that assumed that the centre of the universe was Earth, and all other heavenly bodies revolved around it.

Habitable Zones: Also known as the 'Goldilocks' Zone', it is the distance from a star at which liquid water could be found to exit; an exoplanet in this zone could have the right conditions to support life.

Heliocentrism: The theory that postulates a structure of the solar system where the sun is in the centre, orbited by other planets, who in turn have moons orbiting them.

Light Year: it is a unit of measuring astronomical distance. One light year is the distance that light travels in one year. (9.4707 x 10^{12} km, or nearly 6 million million miles).

Orbit: An elliptical path of a celestial body or spacecraft around a star, planet, or moon, usually in a fixed period of revolution (for example: the Earth's orbit around the Sun takes a little over 356 days).

Planet: It is a celestial body that orbits the Sun in a regular, elliptical orbit. Planets do not emit light of their own, but reflect the light of the Sun.

Star: A star is a massive, gaseous, celestial body that produces light and radiation of its own as a result of internal chemical reactions.

Introduction

Background and Relevance

Exoplanets are planets that orbit other stars outside our own Solar System. The field of exoplanet research is relatively new in the context of decades-old space exploration. While we have always known that planets like Earth possibly exist in the universe, it is only since 1995 that actual results have been found. As of April 2022, there are around 5000 discovered exoplanets.[1] It is known today, thanks to NASA's Kepler Space Telescope, that there are more planets than stars in our galaxy. Our knowledge of existing exoplanets is currently limited to a relatively small part of the Milky Way.[2] Exoplanets are commonly found orbiting a star, but rogue planets- free-floating and untethered to any star- have also been noted. Present technology can ascertain a planet's mass and size (diameter), which helps to show that planets are akin to those in our Solar System in size and composition, ranging from being small and very rocky (like Venus and Earth), or bigger and rich in gas (like Jupiter and Neptune). They are composed of elements similar to one found on Earth, but in varying combinations; some might be dominated by water and/or ice, others have high amounts of iron or carbon, and current technology can determine the amounts of these elements in their atmosphere. NASA's current database includes worlds with seas of molten lava and 'puffy planets with the density of Styrofoam'.[3] The nature of the exoplanets also depends upon their distance from the star, and whether or not they lie within the 'habitable zone' of the star.[4]

Extrapolating from everything we know about our Solar System, finding exoplanets is a major step forward in looking for habitable conditions and possible life on these planets. Their visualisations are a great source of interest because they are data informed illustrations created by visualisation scientists working with astronomers in discovery teams who know how to interpret the data, they receive into images that make sense. These planets are too far away to be seen, or rather, *directly imaged* by Earth- or space-based, high-powered

[1] *Exoplanet Exploration*, [website], https://exoplanets.nasa.gov/. (Accessed on 13 May 2022).
[2] 'What is an exoplanet?', *Exoplanet Exploration: Planets beyond our Solar System* [website], 2021, <https://exoplanets.nasa.gov/what-is-an-exoplanet/overview/ >, (accessed 16 April 2022).
[3] Ibid.
[4] Habitable Zone or "Goldilocks'zone" of a star is 'the distance from a star at which liquid water could exist on an exoplanets' surfaces (..) where the conditions might be just right-neither too hot nor too cold-for life.', 'The Search for Life', *Exoplanet Exploration: Planets beyond our Solar System* [website], 2021, <https://exoplanets.nasa.gov/search-for-life/habitable-zone/ > (Accessed 21 April 2022).

telescopes. Creating visualisations of such distant objects is not only a credit to mankind's intellectual prowess but also a way to chart its progress.

Aim and Research Questions

Through this project, I want to explore how the process of exoplanet visualisation can be understood by the layperson with varying levels of general knowledge of the astronomical sciences. The idea was inspired by my interest in space images, and how their seemingly fantastical nature is taken to be the truth devoid of any intervention. The fact that exoplanetary visualisations are man-made illustrations based on data collected by telescopes and other instruments that are currently used by space research programs across the world is easy to miss unless it is explicitly stated within the images, and even then, it is hard to believe. Keeping in mind the research ongoing in the field of exoplanet discovery and visualisation, this thesis aims to discuss the visual culture of data informed imaging and the role of artistic creativity in present-day astronomical sciences. The questions that fuel this research project are:

1. How has the evolution of scientific thought affected the ways of looking at scientific images?
2. In what ways do artistic visualisations of exoplanets broaden the scope of understanding and interacting with scientific images?

The first question will give us a chance to explore the development of astronomical sciences from the perspective of the history of ideas of Plural Worlds, the speculation of finding other planets like ours, and life like ours. It is also important for the reader to understand the evolution of ideas that helped shape and change our views of the world and the universe in a time when technology was limited, and imaginative ideas abound. Human curiosity is a very crucial factor behind philosophers, physicists, and astronomers continuously attempting to formulate theories that explain the motions of bodies not only on Earth but also in space. Through this question, I also attempt to explore the link between these evolving ideas and the ways of recording them as observations; from representing objects and phenomena in their truest sense possible (using artistic skill to record knowledge by creating realistic illustrations) to applying an objective approach (removing the subjectivity of the artist entirely), and finally reaching a stage where both skill and objectivity are more or less equally acknowledged. This question enables me to delve deeper into how the relationship between illustrations and science has progressed in the course of history.

The second question acts as the leading question of this thesis; exploring the creative aspects of exoplanet visualisations, and the role of human intervention in their creation and dissemination. Because the visualisations have piqued the space enthusiast in me, I want to further explore how these images should be communicated so that the general reader realises that they are highly data informed speculative images; and if the visualisations depicting the process of discovery of exoplanets manage to do so accurately.

Empirical Material

For the purpose of discussion in this project, I shall be using existing visuals of the TRAPPIST-1 exoplanet system on *NASA's Eyes on Exoplanets* database and those developed in *OpenSpace*. The main reason for choosing these two platforms as my subject of study is because NASA's platform is perhaps the most accessible visual tool for exoplanets for anyone with an Internet connection, while *OpenSpace* is an open-access software for visualisation that provides a high degree of interactivity and scientific detail. Collating all the information available to me as a layperson and as a researcher will help me proceed with clarity towards my thesis questions and findings.

NASA's Eyes on Exoplanets is a 3D visualisation software that lets its user fly to and explore any exoplanet of their choice, from around 1000 exoplanets. It gives several scientifically accurate details about what exoplanets are and how we know what we know about them. In comparison to NASA's discovery feature, *OpenSpace* has more features like planetary surface rendering, space weather visualisation and functionality to be used in domes, which makes it a more complete astro-visualisation software.[5]

[5] K. Reidarman, 'Exoplanets: Interactive Visualization of Data and Discovery Method', Master Thesis, Linköping University, 2018, p.3.

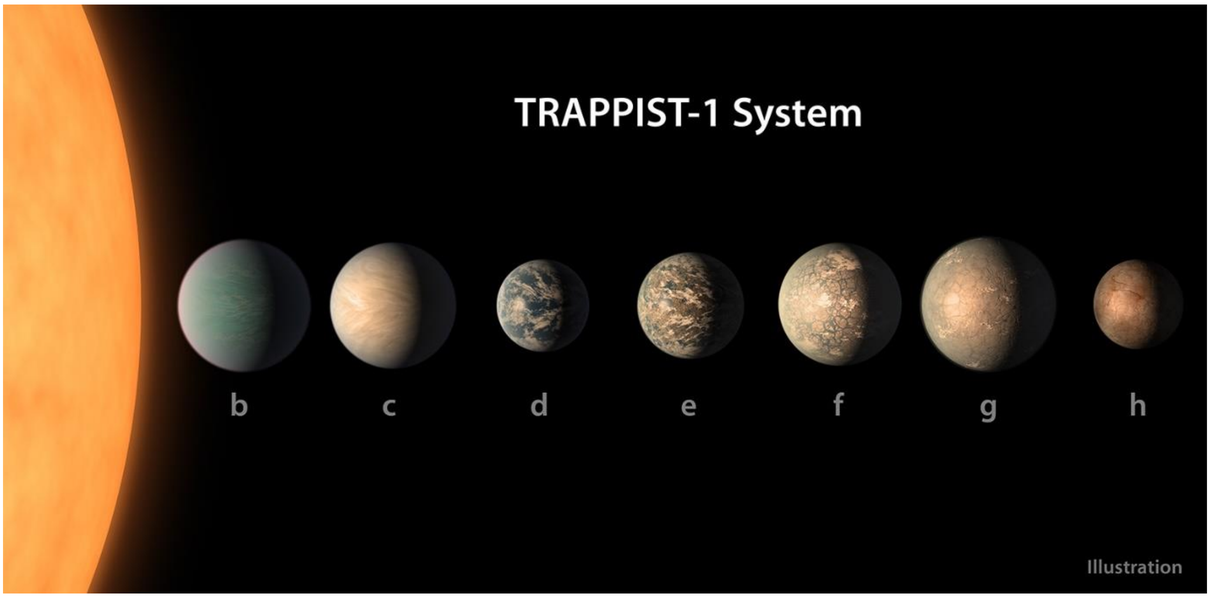

Figure 1: An Artist's visualisation of the TRAPPIST-1 exoplanet system, as it might possibly look like. There are seven exoplanets in very tight orbits around a red-dwarf star. Image Credits: NASA/JPL-Caltech, R. Hurt, T.Pyle (IPAC).

Theory and Method

Exoplanet visualisations taken from *NASA Eyes on Exoplanets* and *OpenSpace* will further be analysed with help of a 'Theoretical Framework for Assessing Visual Representational Practices in Knowledge Building and Science Communications' as postulated by visual sociologist and communication scientist Luc Pauwels[6]. This analysis will be complemented with a discussion of the nature of these images through the lens of 'Objectivity' as written by Lorraine Daston and Peter Gallison.[7] Both of these theories are specifically aimed at studying scientific images and illustrations and provide frameworks for studying images in a way that can do justice to their functions towards their viewers.

[6] L. Pauwels (ed.), 'A Theoretical Framework for Assessing Visual Representational Practices in Knowledge Building and Science Communications', in *Visual Cultures of Science: Rethinking Representational Practices in Knowledge Building and Science Communication,* Hanover (N.H.): Dartmouth College Press, 2006. pp. 1-25
[7] L. Daston & P. Gallison, *Objectivity*, New York: Zone Books, 2007.

Matters of ***truthful*** *Representation*

The analysis that this thesis undertakes starts out with an assertion that exoplanetary visualisations are visual representations of bodies that are too far away to be directly imaged or photographed. For this, I take the support of Luc Pauwels' thoughts on science and visual representation, where he begins by saying that 'Visual representations are not to be considered mere *add-ons* or ways to popularize a complex reasoning; they are an essential part of scientific discourse.'[8] He also uses semiotician Jay Lemke's statements of scientific discourse being fundamentally reckoned as a 'multimedia genre', because verbal descriptions cannot achieve the same impact on the reader as a pictorial rendition can; somewhat in line with the popular saying *A picture is worth a thousand words*.[9]

What then, is the expectation from these representations to be true to the nature of the object they represent? Pauwels writes,

> The often-heard claim that (visual) representations should be 'truthful' or 'according to nature' is flawed for several reasons. Not only is the notion of reality itself highly contested, but also a degree zero is lacking in visual perception, that is, there is no state where things are perceived in an uncolored and unbiased form. Furthermore, any technique or medium, however sophisticated and advanced, at best can provide some highly mediated *renderings* of that presumed reality.[10]

In this thesis, I use the term *visualisation* to imply the mediated rendering mentioned in the above quote. *Render* in design-speak refers to the added layer on computer-aided design graphics to make them realistic. In the case of the images of exoplanet visualisation, the rendered effects like colours, cloud patterns, and weather effects are important because they reflect the scientific information necessary for a realistic view of an exoplanet.

That being said, the role of visualisations in science is not just to faithfully describe or attempt to replicate scientific reality, but also to make it understandable and accessible in a variety of ways to an audience of myriad backgrounds. Therefore, the exercise of looking at such visualisations, in order to better understand their role in reproducing scientific reality as presented to a scientist, should primarily be an attempt to understand not how the nature and

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[8] Pauwels, *Visual Cultures of Science*, p. vii
[9] J.L. Lemke, 'Multiplying meaning: Visual and verbal semiotics in scientific text', in J.R. Martin & R. Veel eds., *Reading science*, London, Routledge, 1998 in Ibid.
[10] Pauwels, p viii

culture of science is copied, but how revealing it is. What problems do they resolve? What gaps in common knowledge do they bridge, and how do they facilitate additional knowledge building and transfer among its viewers? The purposes of these visualisations lie not in the reproduction of nature, but in the value of their functionality.

Understanding the Theoretical Framework of Referents

> Visual representations in science differ significantly in terms of how they relate to what they purport to represent (i.e., their representational and ontological status), the means, processes, and methods by which they are produced, the normative context involved, the primary purposes served and the many ways in which they subsequently are used and combined, to name but some of the more crucial aspects.[11]

The issue of visualisations in science is multi-faceted. Scientists develop and produce graphical representations, schemes, and imagery to communicate their findings through several complex processes and numerous means that range from the use of a simple paper and pencil to advanced computer renderings or optical devices. Therefore, it is not only the resulting visualisations that are of importance to scientific studies but also the process of how they were accomplished. Their subsequent use and impact are also dependent on these factors. Due to the diversity in the appearances and the broad contexts of the dissemination of scientific visuals, it is difficult to make generalisations of their functions and uses in discourse.

Referent theory is a framework that allows for an analysis of scientific representations and visualisations while being mindful of the factors mentioned above. The main intention of this model is to emphasize that despite their differences, the sciences have a lot of common obstacles and solutions. Bridging across the differences through similarities can help upcoming practices. I believe that exoplanet visualisations, like any other kind of scientific representations, can have much to offer if we attempt to understand not only their usage but the process and contexts of their production as well.

[11] Ibid. p. 1.

The codes of epistemic virtue

Daston and Gallison describe objectivity as being composed of mainly three epistemic virtues, 'truth-to-nature, mechanical objectivity, and trained judgement.'[12] These virtues developed alongside historical scientific advancements, each of them paving the way for the next. As such, today's scientific gaze incorporates all these virtues in differing degrees. Truth-to-nature was born in the eighteenth century as a way of reproducing the essence of botanical and anatomical observations. Mechanical objectivity developed in the late nineteenth century as a response to the earlier forms of true-to-nature representations. Trained judgement was a later reaction to objectivity in the early twentieth century as technology evolved beyond cameras and computerised data started getting involved in scientific proceedings. This sequential evolution was by no means an elimination process, but one of analogous synthesis. Each reaction was built on the failings of the previous movements, which means that trained judgement could only be achieved with the preconditions of mechanical objectivity and truth-to-nature. The meaning of these virtues also changed with the existence of each other; for instance, judgement was an act of practical reasoning before objectivity, but was afterwards construed as 'an intervention of subjectivity, whether defensively or defiantly exercised.'[13] The relationship between the three virtues can sometimes be viewed as one of quiet compatibility, and other times conflicting. The main methodical application from Daston and Gallison's theories being used here will be the discussions of Representation and Presentation of scientific images with the help of a categorisation postulated by the authors, which will be illustrated at the end of Chapter 3.[14]

[12] Daston & Gallison, p. 18.
[13] Ibid. p. 19.
[14] Daston & Gallison, 'Representation to Presentation', *Objectivity*, pp 363-415.

Methodology

The images and visuals mentioned above have been acquired by any of the six methods through which the characteristics of exoplanets can be studied. These are- Transit Photometry, Radial Velocity, Imaging, Microlensing, Timing, and Astrometry. [15] (They will be explained further in detail with images in chapter 2).

The aim was to explore exoplanet visualisations through a compositional and cultural analysis of the images, their sites of production, and circulation in their technological modality as described by Gillian Rose.[16] This will be achieved by using Pauwels' Theoretical Framework which uses referents (physical/mental attributes, concepts, or phenomena) as the building blocks of visualisations.[17] I chose this framework because it was the best way to talk about the nuance of data in the style and contextual aspects of the visualisations. The framework also connects the referents to the socio-cultural contexts of production and circulation, the variations in depictions through different mediums, and the purposes served by the different kinds of images and mediums. To round out this discussion and place it in the overall context of artistic productions in science, I also included the aspects of mechanical objectivity and trained judgement by Daston and Gallison.[18] Through the duality of this analysis, this thesis will be able to provide a detailed insight into the production and dissemination of exoplanet visualisations and how they can play a part in altering the ways we look at and believe in scientific images.

This thesis is also inspired, in its general discussion, to work along the lines of the methodology for scientific images as described by art historian and critic James Elkins in his book *6 Stories from the End of Representation*. Elkins notes that there are many writers who have tried to write about sciences from a humanities perspective and vice versa and that this rift is intensified because writers from respective factions tend to speak to audiences of one primary side instead of a blend of both.[19] He explains this further in the form of three main problems occurring in writing that is a mix of science and humanities. There is an inherent difference in the style of writing in sciences and humanities- the formers' accounts rely heavily on equations and numbers, while the latters' are more set in prose. The humanities

[15] K. Reidarman, 'Exoplanets: Interactive Visualization of Data and Discovery Method', p. 5.
[16] G. Rose, *Visual Methodologies: An Introduction to the Interpretation of Visual Materials,* 4th ed., London, Sage, (2001) 2016. p. 50.
[17] Pauwels, pp 1-24.
[18] Daston & Gallison, pp 363-415.
[19] Ibid.

also rely more heavily on the use of metaphors and models to explain theories and their applications. This can make a text inexplicably dense for any reader without a background in the humanities, especially when the models or metaphors were not part of the original discourse of a scientific subject. These problems are more evident when the relation between scientific and humanistic theories is not explicit in a work of a mixed or collaborative nature.

After he highlights the problems faced by scholars of humanities writing about science and vice-versa; Elkins goes on to provide a solution in the form of three pointers for issues of narrative, explanation, and interpretations, and I have tried to abide by these pointers throughout the writing of this thesis.

1. Regarding Narrative, Elkins suggests that one must keep geometric discourse as is; and throughout my thesis, I have tried to stick with the knowledge and style of writing of the subject matter. It might not have been fully attainable, as incorporating some data and equations requires me to have a higher level of expertise that I (currently) lack, but in terms of basic concepts and theories, I have tried to stick with a style of writing that might be easy to read.
2. Regarding Explanation, Elkins advises to not make disciplines depend on each other by denying their relations of cause-and-effect. He explains the four distinct configurations he encounters in collaborative writing: either the science explains the art or vice versa, or a third discipline like philosophy attempts to explain both the science and the art, or lastly, science and art explain each other inconsistently and with ambiguous insinuations.
3. Regarding Interpretation, Elkins cautions against the use of unnecessary metaphors, especially those that might not be present in the original discourse of the subject matter. As far as possible, Elkins hopes that writing can remain a neutral aspect that can function for all applicable fields, but at the very least, it should resemble the disciplines or fields of study that are being written about.

These pointers will act as guidelines for me, as the writer of a thesis in the realm of visual culture. as a first-time attempt at writing about a subject on the cusp of astronomy and visual culture, I hope to achieve clarity through these principles and do it justice.

Previous Research

The visualisations of exoplanets have been created with the help of artists who have a background in the astronomical sciences. Of the tools of visualisation that I mention, those from *OpenSpace* and *NASA Eyes* are discussed in much more detail. Some other platforms that work along the same lines are *SER*, and *ExoPlanetSystems* by Tommy Kruger. SER (Scientific Exoplanets Renderer) is a software tool used to produce photorealistic exoplanet visualisations. By using adjustable parameters of the physical characteristics of parent stars and their exoplanets, it can show their possible visual appearance with atmospheric and surface effects like cloud and weather motions realistically. SER aims to be a scientific tool for reconstructing and interpreting 'physical and chemical interactions of light with matter at planetary scales', which is a very time-intensive process for computers.[20] Unlike *Eyes on Exoplanets*, it is not swiftly interactive but is very technically detailed. *ExoPlanetSystems* is a visualisation platform similar to *OpenSpace*, and was developed by a master student in HTW, Germany. [21] While these are tools that help in a very realistic way, exoplanet research data is also visualised in several other traditional ways like tables, bar charts, scatterplots, parallel coordinates, etc. The purpose of these visualisations is directed mainly towards the scientific researchers and not communication.

Two cultures poles apart

Scientific visualisations have been a subject of much debate, not only in a discussion of their role in scientific study but also in the wider range of their accessibility to the general viewer. These visualisations developed on the fundamental premise of communicating developments in research visually. They fuelled the understanding of complex information through illustrations, infographics, and later, photographs. The shifts in these mediums were caused by the tools used to create them. Before the camera became a common personal possession, having artistic skill in oneself, or in a close associate, was a long-standing requirement for a scientific career. A complicated scientific discovery, something either exotic or unfamiliar, was most easily explained with the help of a detailed illustration. Why

[20] 'SER: the Exoplanet Sketcher', *PHL@UPR Arecibo*, [website],< https://phl.upr.edu/projects/ser-the-exoplanets-sketcher >, (accessed 26 April 2022)
[21] T. Kruger, *ExoPlanetSystems*, [website], < http://exoplanets.tommykrueger.com/ >, (accessed 07 May 2022)

then, is there a historic wedge between art and science, if they seemed to have evolved as partners? This disparity is still debated in academia today, and in a discussion like this thesis, one must periodically step back and reconsider the relation of art to science.

Humanities has often been diminished in stature from the *hard* sciences, by being labelled a *soft* science. Fine art is placed even further away, not even being classified as a science. Snow described the ‘literary’ and ‘intellectual’ factions as ‘two cultures’.[22] Elkins dubs these factions ‘humanities’ and ‘sciences’, carrying forward Snow’s assertions that there is an estrangement mutually brought about by both factions, and its depth is masked by a very superficial open-mindedness to interdisciplinarity.[23] Scientists either do not care for art, or do not feel the need for a specialist to appreciate art, and scholars from the humanities rely on relations or chance colleagues for their scientific expertise. Both factions also seem to have an inherent assumption that their point of approaching science does not work for the other faction; i.e., scientists assume that the humanities’ self-descriptive philosophies are ‘epiphenomenal on art and culture, and therefore dispensable’, while those in the humanities are assumedly content with the descriptions of science from its philosophy and sociology.[24] Snow illustrated this with a very simple test- asking a scholar to explain the second Law of Thermodynamics, and if they had read any work of Shakespeare. It turned out that almost no one in the humanities read unpopularized science, and not many scientists read literature from the humanities. The “Two Cultures” view might be a very stark one, given how much literature there can be found in its defence. However, authors Bullot, Seely, and Davies disagreed with Snow’s fundamentally pessimistic assertions, while discussing the various interactions of art and science in the history of ideas to prove that progress in both thrives on their co-dependence on each other.[25] Elkins takes a similar approach, by systematically identifying three ways in which he can bring a methodological difference in subjects that intersect in the study of sciences and humanities. [26]

Finally, one of the main motives for this thesis is the fact that not much has been written about exoplanet visualisations in the humanities. Looking at these images from the lens of Visual Culture raises several questions about their nature, their purposes, and the pedagogical implications of their mediums.

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[22] C.P. Snow, *The Two Cultures: And A Second Look: An Expanded Version of The Two Cultures and the Scientific Revolution*, London, Cambridge University Press, 1964, p. 10
[23] Elkins, *Six Stories from the End of Representation*, p. 1
[24] Ibid. p.2
[25] N. Bullot, W. Seeley, & S. Davies, ‘Art and science: a philosophical sketch of their historical complexity and co-dependence’ (in press), *Journal of Aesthetics & Art Criticism*. November 2017, pp. 453-463
[26] Elkins, *Six Stories from the End of Representation*, pp. 13-19

Disposition of thesis

The first chapter *Looking Up and Beyond* discusses the evolution of thought in the astronomical sciences; acting primarily as a historical background of popular scientific thought that eventually inspired the modern-day field of exoplanet research. Theories about the nature of our solar system and the Universe beyond it will be examined, starting from the rather astounding cave paintings in Lascaux that record the star cluster Pleiades to the Earth-centric beliefs that Aristotle and Ptolemy famously advocated, which inspired the landmark theories of heliocentrism by Copernicus, changing the way we understood the Universe. The speculations of Plural Worlds- planets like the Earth around other stars- are addressed next, showcasing the depths of human imagination and their yearning for the company of living creatures beyond Earth. The second part of the chapter includes a section introducing the scientific gaze and ways of looking and moves on to the historical developments of viewing technologies (telescopes, spectrometry, the Doppler Effect) that are crucial in astronomical studies in general, and exoplanet research and visualisation in particular.

The second chapter, *The Science behind the tools of Visualisation* begins with an introduction to the methods and technology that aid the discovery of exoplanets, the types of exoplanets that have been found so far, and more details about the TRAPPIST-1 System, whose visualisations serve as the main empirical material for this thesis. Through various examples, this chapter ends with a description of modern technological tools used for scientific visualisation. This is followed by a brief discussion of some modern software applications developed to showcase visualisations, and how they help in the understanding and dissemination of scientific research, ending with a focus on *OpenSpace*, highlighting the work done by their team in the field of exoplanet visualisation.

The final, and in my view, the most crucial chapter, *About Exoplanet Visualisations* contains a critical analysis of the visuality of exoplanet images and a discussion of the significance of these images in popular science and the role they play in the general understanding of space research and discovery. This will be done with the help of Pauwels' theoretical framework, that illustrates how scientific visualisations can be seen as consisting of referents and further looks into aspects of encoding/decoding data for production, the role of mediums in production, and the contexts of dissemination. The chapter ends with a section addressing the big debate of the visual culture of science and arts, the nature of their symbiotic relationship, and its development in the foreseeable future.

Chapter 1: Looking Up and Beyond

Space visualisations started out as an attempt to map the skies, to find patterns in the twinkling stars in the night, to learn more about the spinning ball of water and rock that was our home. This chapter starts out with a brief overview of scientific discoveries that changed the way we look at the sky from Earth and everything that lay beyond our own atmosphere. These events span over hundreds of years, and that does not, by any means, imply that nothing else of importance happened in the intervening years. It is through these discoveries that we see how our view of the Earth and the Universe changed over the years.

In the early 17th century, religion was very closely intertwined with the speculations of what existed outside our Solar System, and the extent of it. Shipping voyages routinely discovered new foreign lands on the Earth. As our fascination with the foreign grew, astronomers and philosophers discussed the possibility of discovering new worlds and alien species, after all, if God created life on Earth, he surely might have created life elsewhere in the Universe too.

Visualising the Universe

Mankind's ambition to gaze deeper into space continued to facilitate the most marvellous inventions, along with great strides in the philosophies that eventually evolved into scientific studies. Cultures around the world have had different theories about their worldviews. Ancient Hindu scriptures speak of the Earth being an egg, or simply a world supported on the backs of a snake, tortoise, and six elephants. While ancient Greeks, Sumerians, Babylonians, Egyptians, and Vikings might have believed that the Earth is flat, observations from navigation and eclipses cemented Earth's spherical nature very early on, as we can see in records dating back to 340 BC.[27]

[27] S. Hawking, *The Illustrated A Brief History of Time*, New York: Bantam Books, 1996, p. 3

There has been a strange pattern of dots recurrent in art throughout the history of planet Earth. The number of dots differs, but their arrangement remains distinctly consistent as six dots arranged in lines of two and four. This fascinating motif has been seen in the art of communities across the world, little-known to each other; as holes pierced in a gourd rattle of a Navajo tribe, in a painting on a Siberian shaman's drum, in cave paintings in Lascaux, and even in a modern-day car manufacturer's logo (Subaru).[28] This group of six or seven dots corresponds to one of the most distinctive features of the Earthly night sky: the Pleiades, more popularly known as the "seven sisters". They are also a distinguishing part of the constellation Taurus, sitting abov celestial bull.

Figure 2. In the "Salle de Taureaux": the Aurochs (no 18; Ruspoli, 1986). Above the animal's back a strange figure, a cluster of six floating points can be seen.

German astronomer Rappenglueck talks about the Aurochs in the cave drawings of Lascaux, particularly about the painting of a bull directly above it, stating evidence from anthropology that societies throughout history might have used the Pleiades as a calendar.[29] Stars revolve around the north and south celestial poles each night, and the Earth's orbit around the Sun means they also have an annual cycle- different stars and constellations rise or set (become visible over the horizon at dawn or dusk) at specific times of the year. As a distinctive star cluster close to the ecliptic (the Sun's path through the sky), the Pleiades mark the seasons remarkably well.

Our palaeolithic ancestors wondered about their place in the world and made observations that were significant to them. In their art lies their understanding of how their world worked, their animal motifs reflected how they had come to learn that even though their surroundings changed almost daily, there was a pattern of changing seasons and changing sky patterns. They might not have known the scientific basis for their observations,

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[28] J. Marchant, *The Human Cosmos: Civilization and the Stars*, Penguin Publishing Group, 2021. p 5.

[29] M. Rappenglück, *The Pleiades in the "Salle des Taureaux", grotte de Lascaux. Does a rock picture in the cave of Lascaux show the open star cluster of the Pleiades at the Magdalénien era (ca 15.300 BC,* 1997, pp. 217-225, ResearchGate [online database], (Accessed 07 May 2022)

but the paintings we see ensure that they made sense of their surroundings to aid their survival and consequent evolution.

All aboard Earth, our celestial chariot in the heavens

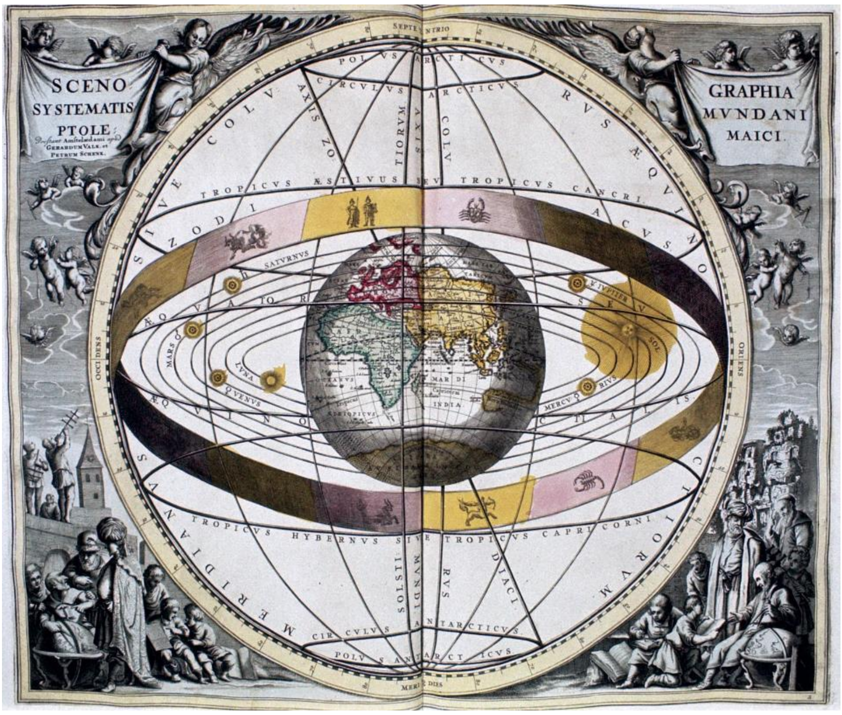

Figure 3. Ptolemaic diagram of a geocentric system, from the star atlas Harmonia Macrocosmica by the cartographer Andreas Cellarius, 1660.

Humanity’s urge to visualise the known world to better understand it first came into play when astronomers like Aristotle and Ptolemy elaborated on the idea that the Earth stood at the centre of the universe, with the Sun, Moon, and other known planets orbiting it. Ptolemy’s cosmological model, inspired by Aristotle’s works, put various heavenly bodies elegantly into place around the Earth in seven concentric orbits or *celestial spheres*,(fig.3) with the fixed stars as we could see them in the last sphere, beyond which lay the mysteries of the Universe yet unknown to human eyes. This simple system of circular objects around the Earth had become greatly qualified by epicycles (secondary orbits born around the major orbits) and eccentrics (off-centre and mobile centres of revolution). The crucial splendour of the Ptolemaic system was progressively shrouded by tactics designed to justify an elegant appearance, omitting essential facts while adding irrelevant details in the process. Looking back, this system was very close to collapsing under the weight of its own elaboration.[30] This model raised as many questions as it answered, but it became a foothold to a theory that has since been proven true and used as a basis of our search for life like ours, on a planet like ours.

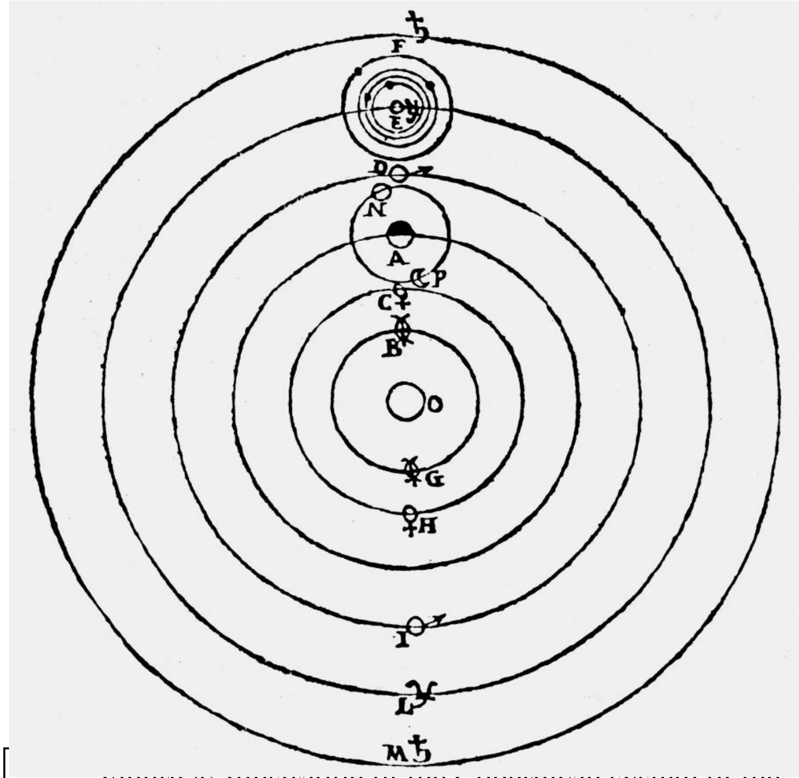

Figure 4: Illustration of the Copernican system of the universe from Galileo's *Dialogo sopra i due massimi sistemi del mondo, ptolemaico e copernicano* (Dialogue Concerning the Two Chief World Systems, Ptolemaic & Copernican), 1632.

It was these issues that inspired Polish priest Nicholas Copernicus to circulate his theory of heliocentrism anonymously in 1514 (because the idea of the Earth not being at the centre of the Universe was considered heretical at the time). Copernicus felt that one could not find harmony and proportion in the body of the Universe that could match the ideal human being created by God, something that was also found in the Vitruvian Man created by Leonardo DaVinci based on the ideas of ancient the Roman architect Vitruvius. Copernicus' ground-breaking act, which art historian Martin Kemp describes as an 'act of genius' was to

[30] M. Kemp, *Seen|Unseen: Art, Science, and Intuition from Leonardo to the Hubble Telescope*, Oxford University Press, 2006, p 22.

see the Universe from a new perspective.[31] His work accomplished the use of Ptolemy's principle of harmonic simplicity to reinstate perfection in a new form while discarding the fixed notion that everything revolved around the fulcrum of privilege that was planet Earth. This is illustrated in the very perfectly circular orbits in his model, which modern science has since disproved. On immediate reception, Copernicus' heliocentric system was considered a possible model of the Universe in a mathematical-and-aesthetical sense, not as a literal description, even though Copernicus meant it as a very real idea. This meant that the controversial nature of this idea in terms of its heretical implications was recognised very slowly. It eventually came to the forefront when it was realized that Copernicus' work had changed the position of the observer on God's celestial vehicle created for mankind's journey through life as they knew it.

This is how we roll

Almost a century later, astronomers Galileo Galilei and Johannes Kepler publicly stated that their discoveries and predictions of planetary movement echoed the Copernican theory of heliocentrism- that the Sun was the focal body around which the other known planets revolved harmoniously. Kepler, for one, was very appreciative of Copernicus' work, even though he modified it by suggesting that planets moved not in circles but elliptical orbits, grudgingly rejecting the aesthetically pleasing but inaccurate circular model conceived by Copernicus. The Ptolemaic theory of geocentrism received its death blow in 1609 when Galilei observed the night sky with a telescope (newly invented in the 1600s) and found small satellites orbiting Jupiter, implying that not everything revolved around Earth as Ptolemy had postulated. [32] The heliocentric model was further cemented in 1687 when Newton published his very significant work *Philosophiae Naturalis Principia Mathematica.* In this volume, he theorised not only how bodies moved in time and space, but also the complex mathematics involved in analysing those movements. So, we see that as scientific discoveries expanded, the notion of Earth being at the centre of the universe was thwarted. Earth might have been unique to support life on it, but that did not make it the focal point of the universe. This perspective is what fuelled mankind's motivation to further understand its place relative to the rest of the Universe.

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[31] Ibid. p. 23
[32] Hawking, *The Illustrated A Brief History of Time*, pp. 6-7

The possibility of Plural Worlds

There is a lot to say in an entailing discussion of the creation and the limits of the universe. The subject of the creation has been long debated in theology and philosophy, much earlier than they were discussed in astronomical sciences. In both these fields, these discussions do not lead to an adequate result, because we are yet to fully understand the workings of the universe. As the debates on the nature and extent of the universe gathered speed, with various theories floating around in the realms of theologists, philosophers, and astronomers, it was only natural for notions of plural worlds or cosmic pluralism (existence of other worlds like Earth elsewhere in the universe) to develop. This conversation usually went hand-in-hand with the speculations of the possibility of life elsewhere in the universe.

The Greek Aristotelian believers did not like the idea of creation because of its heavy reliance on divine intervention, and thus thought that the world around humans had existed forever and would continue to do so.[33] Opposing Aristotle's regard for Earth being the only planet unique enough to support life, atomists like Democritus and Epicurus sided with the notion of plural worlds.[34] Other medieval thinkers later added their views to this debate but continued hitting roadblocks with concerns about the ideas' effects on the Christian doctrine. While the atomists' debate does not lack in richness or depth, this text will not discuss it in further detail because the overall purpose of this thesis leads this story further onwards in history.

In unity, we move: on Giordano Bruno

In the year 1584, the discussion of plural worlds was reimagined in the Copernican light by Giordano Bruno. He was a former Dominican monk who decided to abandon his order to spread his radical ideas on moral and natural philosophy, and a part of the latter was the belief in the existence of infinite worlds like Earth. Despite his espousal, Bruno's ideas of an infinite universe with many other Earths were not derived from Copernicus' views.

[33] Hawking, p. 13

[34] H. Aldersey-Williams, 'The Uncertain Heavens: Christiaan Huygens' Ideas of Extraterrestrials', in *The Public Domain Review*, [online journal], October 2011 < https://publicdomainreview.org/essay/the-uncertain-heavens > (Accessed on 19 May 2022).

In his work *De l' infinito universe e mondi* (On the Infinite Universe and Worlds), he reveals a universe that was 'infinite, homogeneous, and filled with innumerable celestial bodies.'[35] Earth, a standard one of these bodies, was deemed a star, and 'the other worlds are those whose brilliant shining surfaces are distinctly visible to us, and they are all placed at certain intervals from one another.'[36] They all had a nature basically like our planet Earth's and were composed of the same four Aristotelian elements- air, water, fire, and earth. He further refined the differentiation between planets and stars, by stating that 'there are two sorts of bright bodies, fiery bodies which give their own primary light, and aqueous or crystalline bodies which give reflected or secondary light.'[37] Fire was the dominant element in some bodies; in others, water.[38] Reflecting Copernican principles, the fiery bodies like the sun were fixed and the tellurial bodies like Earth were in motion, and both could possibly harbour inhabitants.[39] He did not, however, elaborate on how the motions occurred, stating that they were 'divinely animated creatures' guided by an 'internal principle that was their own soul'.[40] Bruno's ideas of the nature and movements of innumerable bodies in an infinite universe were based on an overarching concept of unity, a metaphysical term applied to a physical universe. Where one might think this concept was a derivative of Copernican principles, it was written as a reaction opposing the more ancient ideas of Aristotle, to highlight how limited his vision was. Bruno considered himself a unique mind to be able to work out the unity of the universe, how 'the greatness of the Divine power and the perfection of Nature' lay in the existence of infinite individual worlds.[41] While this thesis will not delve any deeper into the metaphysics in Bruno's other works, the main thing to note is, as historian Stephen Dick writes,

> Thus, there was irony in Bruno's passionate espousal of a doctrine of infinite worlds, for its basis was the same metaphysical principle of unity that Plato and Aristotle had used to argue for a single world. For Plato unity meant perfection; for Aristotle it meant a single centre on

[35] S.J. Dick, *Plurality of Worlds: The Extraterrestrial Life Debate from Democritus to Kant*, Cambridge, New York, Melbourne, Cambridge University Press, 1982, p. 65
[36] D.W. Singer, *Giordano Bruno: His Life and Thought with annotated translation of his work On the Infinite Universe and Worlds*, New York, 1950, pp. 370-1 in Ibid., p. 65
[37] Ibid., p. 310
[38] Ibid., p. 314
[39] Ibid., p. 306
[40] Ibid., p. 266, p. 362
[41] Ibid., p. 66

which a whole system of physics could be based. In his philosophy of infinite worlds Bruno transcended both views.[42]

Bruno was influenced by the discoveries of Copernicus, transformed by the arguments of Lucretius, and inspired by Aristotle's ideas to formulate a concept of unity across the Universe, in which other worlds functioned like Earth. Bruno however, met a cruel fate in the end. He was executed by the Roman Inquisition by being burnt at the stake in February 1660. However, his cosmological beliefs were not the reason for this end (although they did not help his case); rather his 'denial of the Divinity of Christ' was his primary offence.[43] Bruno's work went on to inspire Johannes Kepler's empirical observations of the Moon and other planets closer to Earth, even though he did not completely ascribe to Bruno's theories of Infinite Worlds.

Fontenelle and Huygens

One of the earliest and major expositions of the idea of cosmic pluralism was *Conversations on the Plurality of Worlds* by philosopher Bernard le Bovier de Fontenelle in 1686. In this work, Fontenelle explained the heliocentric model of cosmic bodies accompanied by Cartesian physics and went on to explore the possibilities of extra-terrestrial life in the universe.[44] His treatise also helped to bring popular scientific theories to the general reader because it was written in French, the language of the common people, unlike other scientific work of the time that was published in Latin. Fontenelle understood the inherent danger (of heresy) that his writing and thoughts posed. He made it clear that even though it used some true philosophical arguments as a foundation, *Conversations* was meant to be read like any other novel, as a series of dialogue about a new idea.[45]

Another work of interest to this discussion is *Cosmotheoros* written by Dutch astronomer Christiaan Huygens in 1698.[46] This treatise is remarkably similar to Fontenelle's *Entriens*, written twelve years earlier. Both were written by authors deeply engaged with the cultural and intellectual scenes of Paris, both were obviously influenced by heliocentrism

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[42] Dick, *Plurality of Worlds*, p. 67
[43] Ibid., p. 69
[44]BB. Fontenelle, *Conversations on the Plurality of Worlds*, Berkeley: University of California Press, 1990. Internet resource.
[45] Dick, p. 123
[46] The full title is *Kosmotheoros, sive, de terries coelestibus earumque ornatu conjecturae* [Cosmotheoros, or, Conjectures concerning the Celestial Earths and their Adornments], Ibid., p. 127

and, to some degree, the Cartesian vortices theory. Both emphasized the possibility of life on other planets and eventually took the reader into a universe of many stars and planetary systems.[47] However, Fontenelle was still a young spokesman of science, while Huygens was nearing the end of his scientific career as a greatly accomplished observational astronomer. His contributions to astronomy included studies of the motions of motion and gravity, the invention of the pendulum clock, a proposed wave theory of light, and mastering the art of making telescopes and using them to make wonderous astronomical discoveries. Considering the backgrounds of the writers, therefore, the differences between the above-mentioned works are just as important as their similarities. Huygens felt *Entriens* could be improved, and unlike Fontenelle's influence from Cartesian's vortices, *Cosmotheoros* relied much more upon Huygens' observational experiences.[48] His interest in the habitable nature of other planets in our solar system developed in the early 1680s and *Cosmotheoros* was finally published after his death in 1689 with the help of his brother Constantine. It consisted of two parts; the first was a discussion of the physical and metaphysical nature of possible inhabitants on other planets using the Copernican theories as a 'chief argument'. [49] He asserted that other planets must have plant and animal life 'because such life manifests better Divine providence', otherwise they would not match Earth in Beauty and Dignity, something that '"no Reason will permit."'[50] The second part of the text examined the plurality of worlds and established that the generalised principles in the first part were dependent on the habitability of planets. The text further discussed the nature of other planets in our solar system, and other astronomical phenomena that might be visible in each of them including the motions of satellites or 'deemed planets' like the Moon. [51]

The importance of this text is reflected primarily in two points. The first is his assertions about the nature and possibility of life on the Moon. Huygens disproved Kepler's and Fontenelle's speculations of the Moon supporting an atmosphere and containing water with his observations of lunar spots on its surface.[52] The second vital point of this text is the analysis of the nature of the other distant planets of our solar system in comparison to Earth. He felt that showing similarities between them and Earth could increase the chances of life like Earth's to exist on them. He deduced how much light each planet might receive from the

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[47] Ibid., p. 128
[48] Ibid., p. 128.
[49] *Celestial Worlds Discover'd*, p.11; *Ouevres*, vol XXI, p. 689 in Dick, p. 130.
[50] Ibid., p. 21; Ibid., p. 701, in Ibid.
[51] Dick, p. 131.
[52] Ibid.

Sun in comparison to Earth and that their possible inhabitants might be adapted to such conditions.[53] He speculated much more upon the nature of life on Mars, Jupiter, and Saturn than on Mercury and Venus. He reasoned that the movement of clouds on Jupiter might mean that there were continuous changes in its environment- like the changing weather conditions on Earth. Describing the astronomy of the multiple satellites orbiting these planets was also thrilling for him.[54] Using observations of our solar system, *Cosmotheoros* ends with the assertion that because it was increasingly correct that the other fixed stars noted by astronomers were suns, they might also support planets as the Sun does.

Newton's postulation of the universal law of gravity in 1687 led to a newfound clarity in our knowledge of the motion of heavenly bodies. His theory asserted that each body in the universe was attracted to every other body around it by a force that increased in strength with the mass of the body and their proximity to each other. It was also the force that caused things to fall to the earth. He also used this theory to explain the Moon's elliptical orbit around the Earth, and the other planets' similar orbits around the Sun. The heliocentric model also cast aside Ptolemy's *celestial spheres* analogy and the idea that there was a natural boundary of the universe.

Gazing into space: the advent of viewing technology

Objectivity in artistic delineations

This section entails a discussion of what it means to have an objective gaze towards scientific images and how this gaze has evolved over the years to formulate current scientific representations. In *Objectivity*, Daston and Gallison steer the reader through the epistemological aspects of scientific imaging, while raising questions about the methodology considered universal in a particular historical era of science as it confronts its objects. The book reads as a fascinating account of the changing scientific gaze on atlases as it culminates into a framework that helps scholars understand how scientific objectivity and personal subjectivity go hand-in-hand; and that scientific imagery can depict truth-to-nature, mechanical objectivity, and trained judgement in different degrees according to the intents

[53] Ibid.
[54] Dick, pp. 131-132.

and purpose of the images. However, due to the limited scope of this thesis, I will only be delving into a pertinent visual example from this book.

> Scientific objectivity has a history. Objectivity has not always defined science. Nor is objectivity the same as truth or certainty, and it is younger than both. Objectivity preserves the artifact or variation that would have been erased in the name of truth; it scruples to filter out the noise that undermines certainty. To be objective is to aspire to knowledge that bears no trace of the knower - knowledge unmarked by prejudice or skill, fantasy or judgment, wishing or striving. Objectivity is blind sight, seeing without inference, interpretation or intelligence.[55]

Objectivity has been a highly debated topic with respect to scientific images. It was certainly a struggle for American astronomer Percival Lowell in his endeavour to draw the canals on the surface of Mars. He compromised and sacrificed a great deal for the sake of objectivity, but his creations did not quite convince a majority of his peers. Lowell's process consisted of taking fifteen minutes to approach each drawing as though he was looking at Mars for the very first time. he only allowed himself to go back in two instances to add the effects of snow that he had missed by accident. The short time span allowed him to remove the pretence to represent every detail that he could possibly see through the telescope. His drawings were an attempt to get 'as nearly as possible impersonal intercomparable representations, -*scientific data, not artistic delineations* [emphasis added].'[56] Lowell prided himself in not submitting to the temptation of making edits or additions to his drawings (apart from the two times mentioned earlier), thus guaranteeing the objectivity of his representations. Where artistic synthesis might have been a proof of truth, Lowell argued that despite being artistic delineations, giving in to the instinct of producing art (in the classical sense of the word) would be the doom of objectivity.

Lowell did go on to capture the surface of Mars on film, a year after he made his sketches. When the photographs were met with criticism on account of being very ambiguous, Lowell afterwards wanted to get them retouched by a neutral party (a scientist friend) so that the canals he was asserting the existence of might be more visible, but his editors protested, stating that the actions would take away from the autographical aspect of the photographs, and would forever carry the mark of being the result of an intervention. Lowell caved and thus sacrificed accuracy, sharpness, colour, and completeness for the sake of mechanical objectivity.

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[55] Daston & Gallison, p. 17.

[56] P. Lowell, foreword to *Drawing Mars,1905*, n.p.: Lowell Observatory, 1906, in Daston and Gallison, p. 180.

Through the looking glass

Many stars are visible from Earth only as pinpricks of light, they are too far away for us to discern their shape or size. Astronomers learnt a great deal from analysing the characteristics of their light, and through evolving technology, they were able to not only distinguish them from each other but also determine the elements they were composed of.

Telescopes were a very recent invention in the early 1600s, created by a Dutch glassmaker, and later modified by astronomers across the world, including Galileo Galilei, Johannes Kepler, and a little later, Christiaan Huygens. They were responsible for the very first visuals of Jupiter, Saturn, and their moons. One of the most important telescopes for locating exoplanets and their system has been named after Kepler. But as with all technology, early telescopes had their own faults. While making stronger lenses, astronomers noticed that images got increasingly distorted, along with blurry colour fringes. Newton realised in the 1660s that this was due to the refracting nature of glass and that these lines were an unbroken band of specific colours. In 1814, German glassmaker Joseph Fraunhofer looked closer into this spectrum of light and saw numerous strong and weak vertical lines- darker than the rest of the spectrum and some almost perfectly black. These came to be known as Fraunhofer lines. He examined and recorded 574 examples of these spectrums, the light from the Sun, the Moon, and some other stars brightly visible in the night sky (Sirius, for example), and noticed that different colours were missing from the light from different kinds of celestial objects but could not fathom the reason for these anomalies.

It was in 1860 that scientists Robert Bunsen and Gustav Kirchhoff built the first spectroscope, which contained a set of lenses, a prism, and a viewing telescope. They used it to investigate flame reactions for various elements and in a momentous challenge, they worked out the relation between these emission lines and the Fraunhofer absorption lines and suggested how it might be used to hunt for elements that made up the Sun. Amateur astronomer William Huggins and chemist W. Allen Miller took their cue and studied other prominent stars, and in 1864 published descriptions of the spectra of over fifty such stars, successfully describing a brilliantly white Sirius, orange-hued Betelgeuse, and pale red Aldebaran. They found that their spectra were not only as packed with lines as the Sun's, but also that the lines coincided with the emission lines of various terrestrial elements like hydrogen, magnesium, iron, and sodium. Huggins continued to study spectrums of celestial objects like nebulae, a nova, and even a passing comet. He would go on to collaborate with his wife Margaret Murray to document the spectra of many planets and stars, extending to the ultraviolet parts with the help of photography. This culminated in the publication of their Grand Atlas of Stellar Spectra. The development of Spectrometry has been very important for exoplanet research as conducted today.

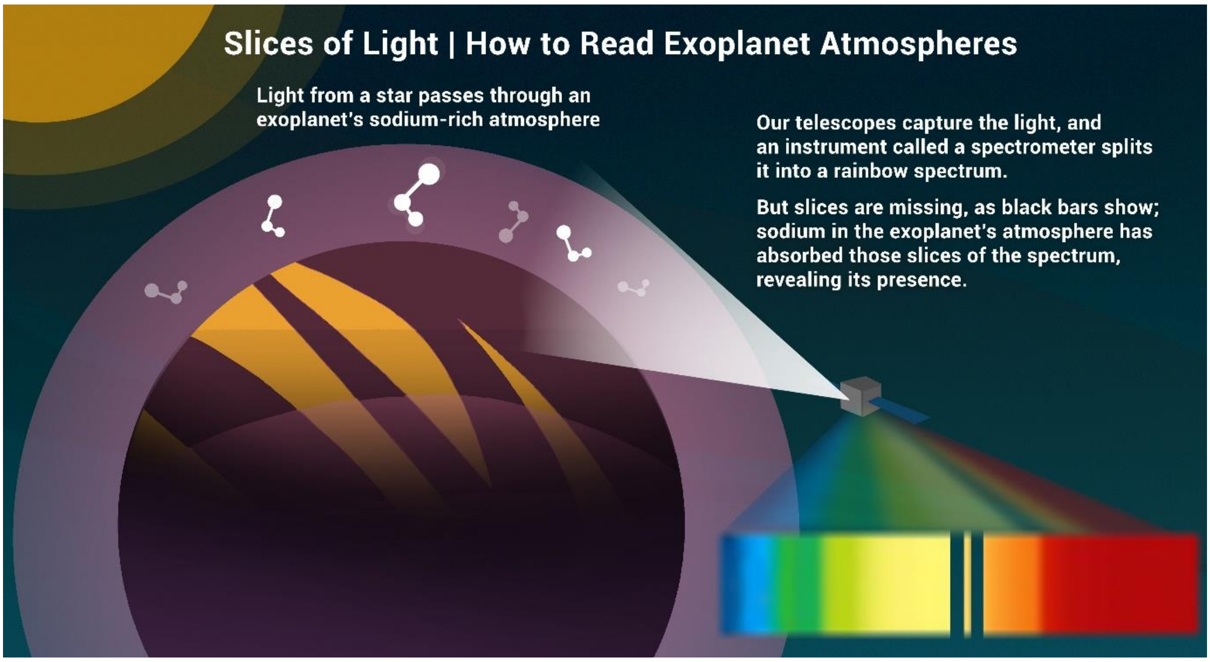

Figure 5. The use of spectrometry in reading exoplanet atmospheres.

Analysing moving bodies in Space- the Doppler Effect

Once the composition of light was understood in such minute detail, scientists tried to observe how the relational motion between the Earth and the moving stars affected the frequency of light and sound waves recorded. A key principle that explained this was the Doppler Effect, named after Austrian physicist Christian Doppler. In 1842 he posited that because the pitch of sound emitted by a moving source increased and then decreased as it passed a stationary observer, the colour of the light from a star should alter according to the star's velocity in relation to Earth.[57] This principle was further enhanced with the study of

[57] 'Christian Doppler', *Encyclopedia Britannica*, 13 Mar. 2022, https://www.britannica.com/biography/Christian-Doppler. Accessed 19 April 2022.

Spectrometry to lead to modern methods of understanding and visualising bodies in the universe.

The nature of the Universe

The picture of the Universe as we know it today is credited to astronomer Edwin Hubble when he demonstrated in 1924 that ours was not the only galaxy in the universe.[58] Prior to that, despite the efforts of astronomer Sir William Herschel to catalogue the positions and distances of a multitude of stars, it was difficult to explore the idea of other galaxies like the Milky Way existing. Hubble studied the amounts of lights emitted by a star to estimate its apparent distance from Earth. He managed to locate and identify nine different galaxies this way, and then went on to make a momentous observation in 1929- that in every direction we looked, distant galaxies around us moved further away from us, implying that the universe was steadily expanding.[59] This also meant that objects in the universe had to be closer together, even at one place at some point in time. This is the observation that led to the very famous Big Bang theory- that there was an event when the universe was infinitesimally small and infinitely dense and that was the event of creation.[60]

These discoveries were a defining moment in space research, for they helped humans to look at the Sun and other stars not as mysterious and glowing heavenly bodies in the sky, but as comprehensible physical objects composed of elements that were 'some of those most closely connected with the constitution of the living organisms of our globe.'[61] Their evidence led to the realisation that these stars were also centres that held and energized systems of worlds that could be potential hubs of extra-terrestrial life.

[58] Hawking, p. 46
[59] Hawking, p. 48
[60] Hawking, p. 14
[61] Marchant, *The Human Cosmos*, p. 173.

Chapter 2: The Science behind the tools of Visualisation

I want to begin this chapter by posing a relevant question borrowed from Steven J. Dick, one that the reader might also ask at this point in the narrative:

> Why should other worlds have become the subject of scientific discourse, when they were neither among the phenomena demanding explanation, nor, by definition, could their existence ever be confirmed by observation?[62]

The motivation for exoplanet research is ultimately to find signs of life elsewhere in the Universe- to know that Earthlings are not alone.[63] Searching for and learning more about exoplanets can help scientists and astrobiologists to study the degree of prevalence of life in other galaxies.

Discovering new worlds

Exoplanet research is a relatively new field compared to general astronomical research. The first big step towards finding exoplanets was the discovery of a planetary disc of dust and gas around a star called Beta Pictoris in 1984. It was taken by the du Pont 2.5- meter telescope at the Las Campanas Observatory in Chile. Eight years later in 1992, two rocky planets were observed orbiting a pulsar (a rapidly rotating dead neutron star emitting electromagnetic radiation) but were deemed unfit to host possible organic life because of the radiation they received. In October 1995, the first exoplanet was found very closely orbiting a main-sequence star 51 Pegasi. The first transiting exoplanet 51 Pegasi b was observed by an independent research team in 1999, paving the way for astronomers to analyse the atmosphere of the planet for carbon, oxygen, nitrogen, and water. This, along with the discovery of the first multi-planet system in the Upsilon Andromedae galaxy solidified our scientific prowess in discovering exoplanets and their compositions to an extent.

As there are new exoplanets being discovered on a continuous basis, the scientific tools and techniques used for studying and visualising them are also evolving as we speak.

[62] Dick, p. 7

[63] 'Is there life on other planets?', *Exoplanet Exploration: Planets beyond our Solar System* [website], 2021, <https://exoplanets.nasa.gov/faq/5/is-there-life-on-other-planets/ >, (accessed 21 April 2022).

Currently there are three main observatories and telescopes that are actively looking for exoplanets around other stars in our galaxy. NASA's Hubble Space Telescope was the pioneer in the search for exoplanets and is credited with helping make the earliest exoplanet atmosphere profiles. It has now been in orbit in space for over 30 years.[64] Another important counterpart of the Hubble was the Kepler Space Telescope, which was responsible for the discovery of over 2600 exoplanets by observing the minuscule decreases in starlight as a planet orbited across it. Kepler faced numerous problems with its direction system between 2013-2014 and was eventually decommissioned in 2018. The Spitzer Space Telescope, which was used to study the space through the infrared spectrum of light and helped discover the TRAPPIST-1 System (among others) was also retired in 2020. These two telescopes are especially celebrated in exoplanet research because despite being out of operation, the data they collected is still producing a continuous stream of new information.[65] The more new-age viewing technologies are led by the TESS (Transiting Exoplanet Survey Satellite) and the James Webb Space Telescope. TESS has been following up on the work started by Kepler; 'conducting a grand survey of the skies' searching for stars brighter and closer to Earth (within a range of about 200 light-years), but still difficult to study from Earth-based observatories.[66] The James Webb Space Telescope is the latest science observatory, launched in 2021, with the largest ever primary mirror (21 feet and 4inches).[67] Not only is it going to help astronomers study the compositions of exoplanets better, but also observe the Universe in infrared light to uncover the process of creation of planetary systems like ours.[68]

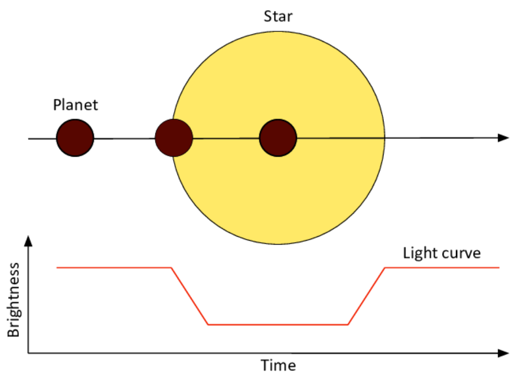

Figure 6. Image showing transit of exoplanet in front of a star from left to right.

How do we find exoplanets?

One of the most common methods for finding a new exoplanet is the Radial Velocity, where a star's gravitational force affects the exoplanet's path, making it wobble slightly. When a

[64] 'Discovery: Missions', *Exoplanet Exploration: Planets beyond our Solar System* [website], 2021, <https://exoplanets.nasa.gov/discovery/missions/#first-planetary-disk-observed> (accessed 07 May 2022).
[65] Ibid.
[66] Corroborating data collected from space telescopes is difficult from Earth-based observatories because our atmosphere is dense and can sometimes hinder accurate observations. Ibid.
[67] Ibid.
[68] Ibid.

telescope is pointed at a star to measure its light, the wobble causes a small split in its light spectrum. These shifts are observed more and based on the intervals, it leads to information about the exoplanet mass.[69]

Another method for looking for exoplanets is Transit Photometry. In this process, the intensity of a star's light is observed. When an exoplanet orbiting the star passes through its light path, a dip in the intensity is noticed. Scientists can measure the amount of light blocked as the exoplanet moves to estimate its size, the length, and direction of its orbit.[70] The Kepler Space Telescope and NASA's TESS with the Spitzer and Hubble Space Telescopes have discovered many exoplanets through this very process.[71]

Accompanying Transit Photometry is a similar process called Transit Spectrometry. As the basic parameters of a potential exoplanet's nature are settled by the methods mentioned above, the light from the star is studied further as the exoplanet continues to orbit it. The light of the star passing through the exoplanet's atmosphere is closely observed, as we know from the discussion of spectrometry in the previous chapter, the colours of the light spectrum reveal the elements present in the exoplanet's atmosphere. [72]

These methods are the most common ones used in the discovery of new exoplanets. Other, more complex processes like Microlensing, Timing, and Astrometry are used to verify these exoplanets' location and nature; after which they are added to the existing databases across the world. These methods are also being fortified by newer techniques like the use of coronagraphs and starshades to make the observation of the light from the exoplanets easier and more efficient. These new techniques will also help in taking the next step in exoplanet exploration- direct imaging.

Characterising Exoplanets

After an exoplanet has been discovered and confirmed, further studies are then used to characterise them. Size and mass are usually the first physical attributes to be studied and determined. Their possible interior and exterior appearances vary according to their

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[69] K. Reidarman, 'Exoplanets: Interactive Visualization of Data and Discovery Method', p. 6.
[70] Ibid., p. 6-7.
[71] 'Discovery: how we find and characterise', *Exoplanet Exploration: Planets beyond our Solar System* [website], 2021, https://exoplanets.nasa.gov/discovery/how-we-find-and-characterize/ (accessed 16 April 2022).
[72] Ibid.

compositions. There are four main groups of classification of exoplanets based on their size and composition:

1. **Terrestrial Planets**: these are planets smaller or almost the same size as Earth, consisting of rock, water, carbon, or silicates. There needs to be more investigation as to whether some might have a gaseous atmosphere, liquid oceans, and/or signs of life.
2. **Neptunian Planets**: as the name suggests, these planets are the size of Neptune or Uranus. They are speculated to have rocky cores with an outer atmosphere composed of a mixture dominated by hydrogen and/or helium. In this category also are planets that are in the size range of Earth and Neptune (mini-Neptunes), unlike any found in our solar system.
3. **Gas Giants**: these are planets that are comparable to or larger in size than Jupiter and Saturn, the largest planets in our solar system.
4. **Super Earths**: these are typical Earth-like terrestrial planets, with or without atmospheres. They are larger in volume than Earth, but lighter in density than even Neptune.

The size of an exoplanet is crucial for determining the nature of the world. Exoplanets bigger than Super-Earths might have thick, gaseous atmospheres because of their large gravitational force. Smaller exoplanets might not have enough gravitational force to hold atmospheric gases and therefore evolve into rocky, terrestrial worlds. [73]

Seven Rocky Worlds

TRAPPIST-1 was one of the first planetary systems to be discovered outside our Solar System. Its ultra-cool red dwarf star was discovered by John Gizis and his team with the Two Micron All-Sky Survey(2MASS) in 1999.[74] Its seven orbiting exoplanets were later discovered by Chile's Transiting Planets and Planetesimals Small Telescope (TRAPPIST) between 2016-2017, thus giving the star and its system their name.[75] The system is located roughly 39 light years away from Earth, near the constellation Aquarius. It is a system much

[73] 'What is an Exoplanet?', *Exoplanet Exploration: Planets beyond our Solar System* [website], 2021, https://exoplanets.nasa.gov/discovery/how-we-find-and-characterize/ (accessed 19 April 2022)
[74] 'Ten Things: All About TRAPPIST-1', *NASA Solar System Exploration*, [website], 2018, https://solarsystem.nasa.gov/news/335/10-things-all-about-trappist-1/ (accessed 27 April 2022)
[75] *About TRAPPIST-1*, [website], http://www.trappist.one/#about (accessed 27 April 2022)

smaller than our Solar System, and thus is much easier to learn more about. Astronomical research on dwarf star systems like these helped current technology on Earth to evolve and eventually graduate to finding possible exoplanets around larger stars.

The star TRAPPIST-1a appears to be much older than the Sun and is likely almost twice as old as our Solar System. It is only somewhat larger than Jupiter, making it 12 times less massive than our Sun. The exoplanets were discovered by Transit Photometry, which meant that their size, mass, densities, and orbital periods were thus determined. Using the temperature of the star and the exoplanets' distances from it, their nature was ascertained to be similar to the Inner Planets in our Solar System. Seven exoplanets are known to orbit TRAPPIST-1a, and they are named in alphabetical order from b to h. Their orbital periods vary in the range of a few to about 20 days. A key characteristic of this system is the distances between the planets and their proximity to the host star. In our Solar System terms, the seven TRAPPIST-1 exoplanets could fit in the distance between the Sun and Mercury, the closest of the Inner Planets. This proximity implies that the exoplanets are likely bombarded with a lot of radiation from the star, thus stripping them of any gases that might make up a very dense atmosphere. They are also expected to be tidally locked to their star (like the moon is to Earth, for instance); meaning that the surface exposed to the star's light and radiations could be significantly different from the opposite side that's always in the dark.[76] Four of the exoplanets are expected to be within the Goldilocks Zone of the star, which makes them suitable candidates for further study of signs of life. The signs of water on these exoplanets are still under discussion because while they are at an ideal distance from their host star, the physical and chemical reactions on their surface might differ according to the nature of the star. Being tidally locked might also imply that water might be present on the shaded side, but unless the radiation from the star reaches that side, the development of life seems unlikely. More about the specific nature of the system will be discussed further when their visualisations are examined.

Understanding the tools of visualisation

As has been established by now, the exoplanets we have discovered by now are too far away to be directly imaged (or *seen*) by our telescopes, but with the help of some of the technology

[76] Being tidally locked means that the duration of each rotation of the body is almost equal to the time taken to revolve around the star; so, the same surface is visible or exposed to the star almost all the time.

described above, enough data can be collected so images of these exoplanets can be created to aid further exploration. There are several different tools that are used to show visualisations of exoplanetary systems. This section will discuss some of them and briefly examine the process behind their creation. The reason behind this is to highlight the differences in visualisations created by different tools.

NASA's Eyes on Exoplanets

Eyes on Exoplanets is a fully rendered, scientifically accurate, 3D immersive application. It allows the user to travel to and take a closer look at over 1000 exoplanets from their extensive database with a simple click of a button. These visualisations are aimed to aid genuine scientific insights and to incite enough interest in the public to engage with scientific discoveries they might otherwise not be able to grasp without a visual representation aid.

About OpenSpace

OpenSpace is an open-source platform used in the development of visualisation of astrophysical and space exploration data. It is targeted towards the creation of visualisations for planetariums and dome theatres, but it supports platforms of a varied nature. The OpenSpace project is a collaborative effort between Linköping University in Sweden, the American Museum of Natural History (AMNH), NASA Goddard's Community Coordinated Modeling Center, New York University's Tandon School of Engineering and University of Utah's Scientific Computing and Imaging Institute. It has been under continuous development since 2014.[77] The software has been developed by astronomers, and space physics researchers in close collaboration with the user and planetarium communities. Being open-sourced and accessible to all for free is a great step towards bringing scientific visualisations into the public sphere.[78]

These are the main reasons why this thesis uses *OpenSpace* as a foundation platform to showcase the visualisations it discusses. While its interface might have a significant learning curve, *OpenSpace* gives accurate representations of data and plenty of adjustable

[77] Reidarman, p. 1.
[78] A. Bock et.al., 'OpenSpace: Changing the Narrative of Public Dissemination in Astronomical Visualization from What to How' *IEEE Computer Graphics and Applications*, vol.38, no. 03, 2018, p. 45

parameters so the user can easily find their way around the objects and systems of their choice. On getting used to the workings, one can use the open-source nature of the code to create scenes and narratives of their choice. A characteristic feature of the program is also that unlike NASA's *Eyes on Exoplanets,* the representations on *OpenSpace* reflect the uncertainties of the currently available data when it comes to exoplanets. While the scenes on *OpenSpace* show numerous exoplanetary systems, it does not render their surfaces with a colour image overlay, so they maybe do not look as eye-catching as those on NASA's *Eyes.* What the scenes do accurately portray, for instance, the variability of exoplanetary orbits. These differences, in my opinion, lay the base for a thought-provoking discussion of the degrees of accuracy of artistic visualisations of exoplanets and how that affects the layperson's opinion and view of such discoveries.

Chapter 3: About exoplanet visualisations

The Space Aesthetic: visualising astronomical phenomena and bodies

Exoplanet visualisations are a way to prove that scientific research is progressing, that newer worlds like and unlike our Earth and its neighbours are being found regularly. Imagining other worlds (exoplanets) has been a key theme in Space Art for over fifty years. One only needs to take a look at the gallery section of the International Association of Astronomical Artists to see the range and evolution of Space Art.[79] Ryan Wyatt notes in his article about exoplanet visualisations, that the trends in art have changed with the developments associated with space exploration- shifting centres from human exploration to robotic journeys: 'transition[ing] from the aspirational ("we will go there") art of the 1950s and 60s to the inspirational ("wouldn't it be nice to be there") art of the 1970s and 80s.'[80] With a context that has evolved from the covers of science fiction novels and posters of science fiction movies, to the more recent stacked telescope images, space art as a genre is thriving. If one looks at images of any exoplanet on NASA's social media pages of their press releases- the images fit so well into the aesthetic of space art that for a layperson they could easily be assumed to be actual photographs. But there is so much more to them than just evoking awestruck reactions from viewers.

While I do not consider exoplanet visualisations strictly a member of the space art collective for the purpose of this thesis, they certainly have a lot in common, and the parallels between them do not go unnoticed. This discussion pertains more to the collaborative aspect between science and art in exoplanet visualisations, and any further digressions must be avoided.

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[79] 'Gallery of Artwork', *International Association of Astronomical Artists*, [website], <https://iaaa.org/artworks_and_news/ >, (Accessed 14 May 2022).
[80] R. Wyatt, 'Visualising Astronomy: Visualising Exoplanets', *CAPjournal*, No.12, May 2012, p. 37.

Images that make sense in a scientific context

To bring the focus back to exoplanet visualisations, let us begin with some questions. Why are the scientific representations of exoplanets worthy of a discussion? What is the significance of being able to produce these representations?

The answer to these questions lies simply in human curiosity and the urge to produce visuals for objects and phenomena that we are too far to see. The process behind their creation is reminiscent of the processes undertaken by Copernicus and Bruno as discussed in Chapter 1. Copernicus postulated his heliocentric model as an idea or a concept that could not be visualised or explained by humans at the time. It was later modified, but it eventually served as scientific fact as we know it today. Bruno also posited that the plural worlds that might exist in the universe would be made of a set of elements similar to those found on Earth. Exoplanet research operates along similar lines today, but with a much wider range of physical and chemical substances.

Exoplanet visualisations may be scientific images instead of being an *original* artwork, (as understood by the art community) but on taking a closer look, they do not fall under the former category entirely. These images are *informed* by scientific data, but they have a highly artistic aspect to them as well. Exoplanet visualisations are not created by simply inputting data into a program and having images pop up (like say, plotting a graph or searching for an image through Google). The data collected by Earth-based and space telescopes needs to be interpreted by artists who are highly knowledgeable in astronomical sciences, who create visualisations by using all the data available to them. The human intervention in this process is crucial in this case because exoplanets are too far away to be imaged directly, and while over 5000 planets have been discovered so far, our knowledge about the detailed workings of these systems remains very limited.[81] This brings us to the significance of visualisations.

The wide range of objects and processes that are represented by scientific illustrations are called referents. The framework categorises these referents into a range that is bound by two broad types:

1. Material/Physical: Visual phenomena that are either directly observable or invisible without technical aid (in this case it is a phenomenon too far from direct view),

[81] *Exoplanet Exploration*, [website], https://exoplanets.nasa.gov/. (Accessed on 13 May 2022.)

2. Mental/Conceptual: Those that are either postulated (black holes, for instance, or phantasmagories like mermaids or unicorns; and constructions like metaphors or abstract concepts.

   In between these categories are non-visual referent phenomena like sound, magnetism, or heat and data-based observations/measurements like temperature, sizes, or amounts.[82]

The specific system that is the object of this study, TRAPPIST-1 has seven planets located very close to a red dwarf star (to compare with our Solar System, this would be seven Earths between the Sun and Mercury.[83] In this dialogue exploring the TRAPPIST-1 system, the star and exoplanets have Material/Physical referent which would be the body itself (exoplanet or star), and the light it emits/reflects that can be translated into visual representations using dedicated means like spectrometry and spectrography. There are also non-visual data-based observation referents for these visualisations like thermal radiation, velocity, orbital distance, size, volume, their physical and chemical nature, that can provide data for further detailing the visualisations. Hence the exoplanet visualisations are a visual representation of not the *physical bodies*, but of the *data about them* that is gathered by observing their various aspects. The relationship between the exoplanets and data is arbitrary and conventional, even though some aspects of the visualisation may be iconic (in that they might resemble the referent). The visualisations are not *depictions* of the real-world phenomena of exoplanets, but rather a 'conceptual translation' of some of their measurable aspects, making them an instance of *observed reality*.[84]

The production of Representations

Every representational process includes a series of complex steps to translate, convert, inscribe, transcribe and/or fabricate the capture and transformation of an initial source (concept or phenomenon) through a decision-chain involving actors (scientists, technicians, artists), devices and their settings. This intricate meaning-making process impacts what is known and used, hidden, or revealed to the viewer. There are various problematics that arise

[82] Pauwels, p. 4.
[83] 'TRAPPIST-1 Compared to Jovian Moons and Inner Solar System- Feb. 2018', *NASA Jet Propulsion Lab, California Institute of Technology: Spitzer Space Telescope*, [website], <https://www.spitzer.caltech.edu/image/ssc2018-04d-trappist-1-compared-to-jovian-moons-and-inner-solar-system-feb-2018>, 2018. (Accessed 25 May 2022).
[84] Pauwels, p. 3.

when considering the ontological relation between the representation and its referents, leading this study to examine the iconicity of the translational processes used to develop exoplanet visualisations. These processes include technology, its cultural impact and the specific norms and values that the technology might embody. These factors have a significant impact on the appearance and purposes fulfilled by the representation, or in this case, exoplanet visualisations. Therefore, the factors examined here, according to the framework, are the Nature of the Technical, Constraints, and Social/Cultural Encoding.

Nature of Technical- Physical Encoding/Transcription

The referents discussed above can be represented in myriad ways, depending on what aspect of exoplanets and their system are being visualised. For starters, one can discuss the translational methods employed in the visual-to-visual part of the process, wherein the light emitted from the TRAPPIST-1a star is analysed to determine its size and (to an extent) its nature. It is known to be a red dwarf star much smaller than our Sun, and a little larger than Jupiter. It emits not only light but a lot of ultraviolet and infrared radiation that impact the environs of the exoplanets orbiting it. Along the same lines, knowing the luminosity of the star's light, the movements of its orbiting planets can be determined by measuring the dips in light intensity every time the exoplanets cross in front of it (see Fig. 8 and 9) resulting in an idea of the number of exoplanets that might orbit the star, their sizes, and the approximate length of their orbits. Further analysis of this light spectrum of the duration of the exoplanet's crossing with the help of spectrometry also shows the elements that might be present on the planet, giving a clue of its physical and chemical nature. All this information together lays the first foundations of the visualisations.

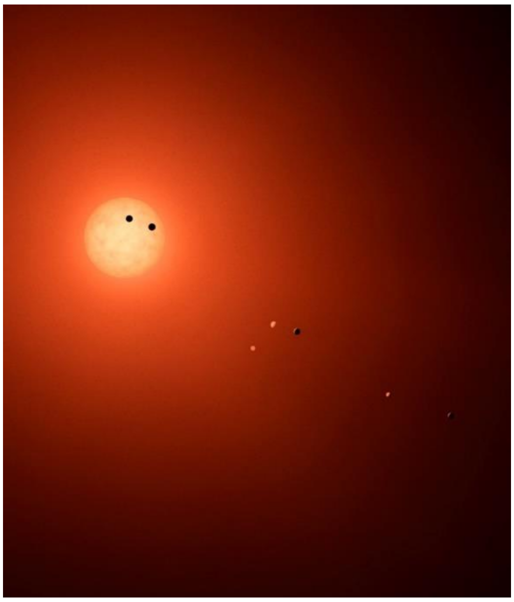

Figure 7. A visualisation of the TRAPPIST-1 system with the exoplanets transiting in front of host star.

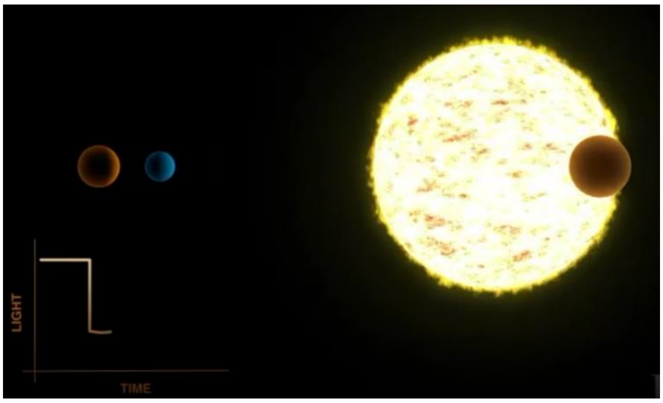

Figure 8. A screenshot demonstrating how transiting exoplanets are noticed by observing the light from a star. The graph in the bottom-left corner shows the dipping value of the data of observed light intensity of the star.

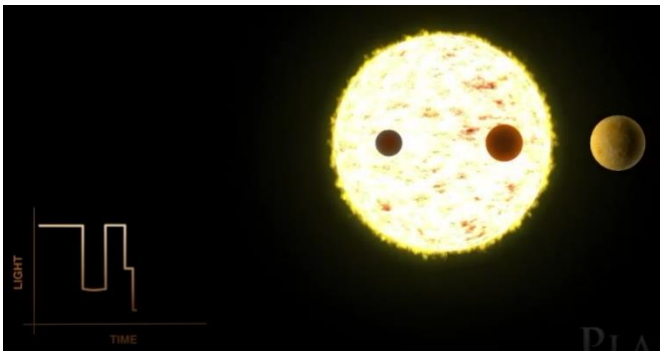

Figure 9. A screenshot of transiting exoplanets, the graph on the bottom-left shows how the dips are observed with two planets of different sizes moving across it.

In a process such as this, where the referents are inaccessible and/or invisible to the unaided human eye, there is a higher reliance on the *machine.* This makes it particularly important that the viewer be aware that they might be looking at 'a*rtifacts of the instrumentation'*, which may be effects generated in the representational process itself or attributed to events that are unexpected or unaccounted for in the data. This is also especially true for exoplanet visualisation where some of the referents might be of an uncertain nature (like orbital angles, lengths) and have aspects of reality that can only be seen through instruments as a representation. Scientists and other viewers should be aware that the visualisations often might have important aspects of the referents that might not be possible to capture, or represent, or could be altogether absent. In exoplanet visualisations, it is good to keep in mind that representations of referents are often based on the constant values of their data, and do not account for margins of error associated with them.

There is then the matter of intentional or non-algorithmic processes (like hand-drawing), which are reflected in the medium used for representations. For scientific purposes, automated and standardised representations created by sophisticated instruments might be considered more suitable, for they also do not rely on personal judgement or skills. In concurrence with Pauwels, who says that ‘in some cases more intentional processes and products may be far more convenient’, I do believe that such is the unique case with images like exoplanetary visualisations.[85] He adds,

> […] intentional processes allow a much swifter combination of different types of signs (iconic, indexical, and symbolic) and levels of significance. Consequently, they may yield a more functional expressive presentation of fact and vision. […] intentional processes may provide a much needed synthesis of features rather than a simple transcript of a particular (snapshot-like) instance of a phenomenon.[86]

The illustration above (fig 7) is a great instance of this thought, for it uses both material and non-visual data-based referents to create a representation that can explain their relationships and help further research to envision the challenges that could be encountered. The representation has an *artwork-like* style, that one could easily mistake it for a painting or digital art, but it explains the expected scale of the exoplanet system, rendering it an iconical representation while showing a practical aspect of the process of observing transit paths by which exoplanets are found.

Scientific illustration is an intriguing instance of a specialisation that has grown by recognising the fact that scientists and artists both, in general, lack the skills to produce life-like renderings of intricate objects and phenomena. Artists skilled in drawing might be largely unaware of some exact purposes that an illustration is supposed to serve; they could make *corrections* in accordance with their personal aesthetic insights or fail to highlight otherwise significant elements of effects. Scientific illustrators are therefore required to be well-competent in the art of illustration as well as the specialised fields of science they work in. They are meant to be fully integrated into the subject matter and concepts that they draw along with the precise scientific and didactic purposes their works need to fulfil.

[85] Pauwels, p.10.
[86] Ibid.

A sneak-peek into the world of a visualisation scientist

The process of visualisation, like any other artistic endeavour, is one replete with revisions. A representation of an exoplanet is modified several times and is often created with multiple options of a similar nature. The changes can be as significant as the colours or textures of cloud formations, or something subtle as the angle and direction of light falling on its surface. The idea behind that is to create a *realistic* visualisation- one that can best explain or represent the data being used to create them. While it is difficult to ascertain their accuracy at this point in time of scientific discovery, history is witness to the fact that humans are quite capable of creating fairly realistic scientific visualisations.

At this stage of the discussion, it would make sense for us to look into the insights of Robert Hurt, one of NASA's visualisation scientists. Along with his colleague, multimedia producer Tim Pyle, they speak about their work and its challenges, in an interview with Pat Brennan for NASA.[87] They worked with the TRAPPIST-1 discovery team to create visualisations for the announcement by NASA and a journal report in *Nature,* visuals that have since been published in other scientific and news media across the world. Hurt talks about the first time he heard about the TRAPPIST-1 system discoveries,

> "I just stopped dead in my tracks, and I just stared at it," Hurt said in an interview. "I was imagining that could be, not our moon, but the next planet over – what it would be like to be in a system where you could look up and see continental features on the next planet."[88]

Hurt the astrophysicist and Pyle the artist both look to each other's specialised opinions for producing accurate visualisations; thus, making a great team. This was the first time they had attempted to visualise multiple Earth-sized exoplanets so close to each other. It gave them a chance to showcase an exploration of the range of possibilities that could be anticipated on Earth-sized exoplanets. Hurt explains further in the interview with Brennan that the visualisations for TRAPPIST-1 exoplanets were made easier by taking inspiration from bodies in our Solar System. TRAPPIST -1b (Fig 11), the closest to the star, was suggested to look like Io, a volcanic moon orbiting Jupiter; while TRAPPIST-1h (Fig 14), the farthest exoplanet, resembled other Jupiter moons like icy Ganymede and Europa.[89]

[87] P. Brennan, 'The Art of Exoplanets', *National Aeronautics and Space Administration*, [website], 2017 <https://www.nasa.gov/feature/jpl/the-art-of-exoplanets>, (Accessed 15 May 2022).
[88] Brennan, *National Aeronautics and Space Administration*.
[89] Ibid.

Producing visualisations for the exoplanets in the habitable zone was a little more challenging because they had to show the possible presence of liquid water on their surfaces in the most correct way they could envision. With the support of data from the discovery team, Hurt depicted TRAPPIST-1c as a dry and rocky world but with ice caps on its shaded side (because as mentioned earlier, the TRAPPIST-1 exoplanets were tidally locked to the star, so one side was almost constantly lit, while the other almost always remained in the shade). He produced a similar visualisation for TRAPPIST-1d, in the habitable zone (see Fig 12). He was told by researchers that TRAPPIST-1d would have a hot dayside lit up by the star, and a cold night-side with ice caps; and in the zones between these regions might be a place where the ice melts to form liquid water. He implemented this into a visualisation that was initially rejected by the scientists, for they felt that the liquid water was too far into the dayside. They reasoned that there were chances of some liquid water also existing on the other, darker side, which Hurt thought would be difficult to show in a visualisation, especially to the layperson. Eventually, there was a compromise- they represented more water on the dayside than might be scientifically expected, but an overall more detailed visualisation.

The aspect of light had to be explored in a different way for the early iterations of the TRAPPIST-1 system visualisations. The data collected by the discovery team's scientists pointed to the initial conclusion that the exoplanets in the red dwarf star's vicinity would appear so red that blue-tinted water might not be noticed at all. Hurt could not understand how to visualise the exoplanets realistically in this scenario, so he planned out an experiment. Brennan writes,

> A colleague provided him with a spectrum of a red dwarf star similar to TRAPPIST-1. He overlaid that with the "responsivity curves" of the human eye, and found that most of the scientists' "red" came from infrared light, invisible to human eyes. Subtract that, and what is left is a more reddish-orange hue that we might see standing on the surface of a TRAPPIST-1 world -- "kind of the same [colour] you would expect to get from a low-wattage light bulb," Hurt said. "And the scientists looked at that and said, 'Oh, ok, great, it's orange.' When the math tells you the answer, there really isn't a lot to argue about."'[90]

The issues discussed above not only provide a background to the reader as they view the images produced by Hurt and Pyle, but they also give an insight into the extent to which

[90] Brennan, *National Aeronautics and Space Administration*.

the producers of visualisations go to ensure a viable representation for their audiences. These insights from Hurt will be brought up again in the discussion moving forward.

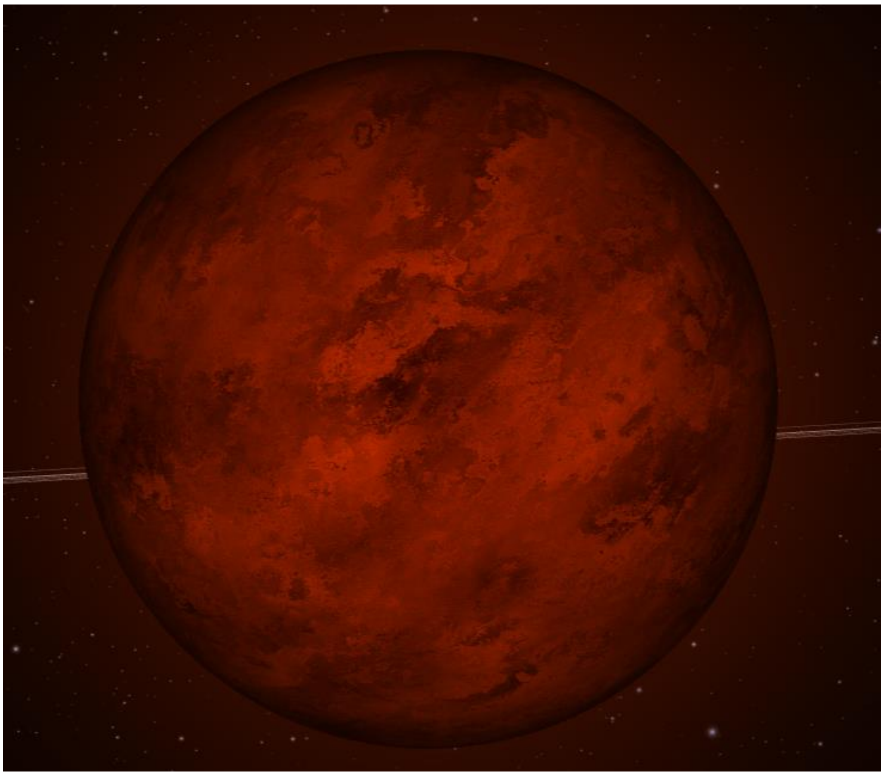

Figure 10: TRAPPIST-1a, a red-dwarf star that hosts one of the most fascinating exoplanet systems in the known Universe. Snapshot from NASA Eyes on Exoplanets

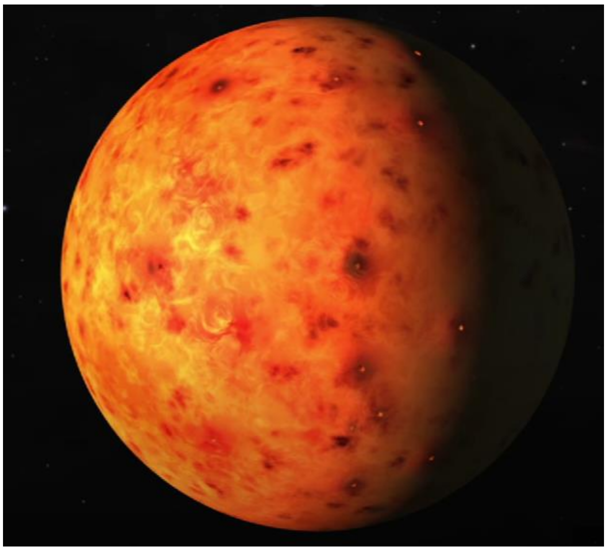

Figure 11. TRAPPIST-1b: an exoplanet resembling Io, one of Jupiter's volcano-ridden moons. Snapshot from *NASA Eyes on Exoplanets.*

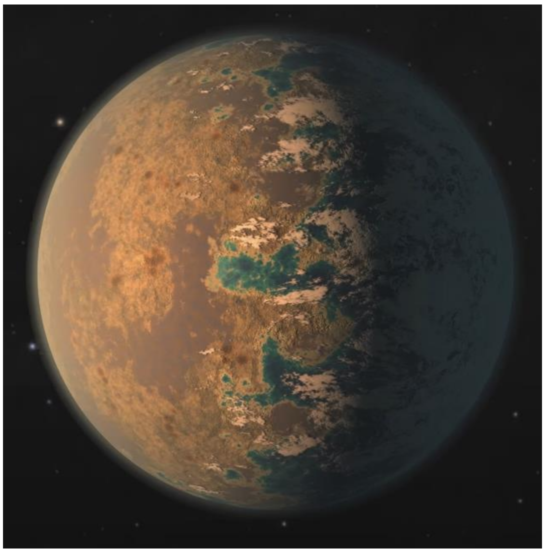

Figure 12. TRAPPIST-1d, the first exoplanet in the habitable zone of the red-dwarf star. Its dayside is dry and rocky with hints of ice caps and possible water in the middle zone. Snapshot from *NASA Eyes on Exoplanets.*

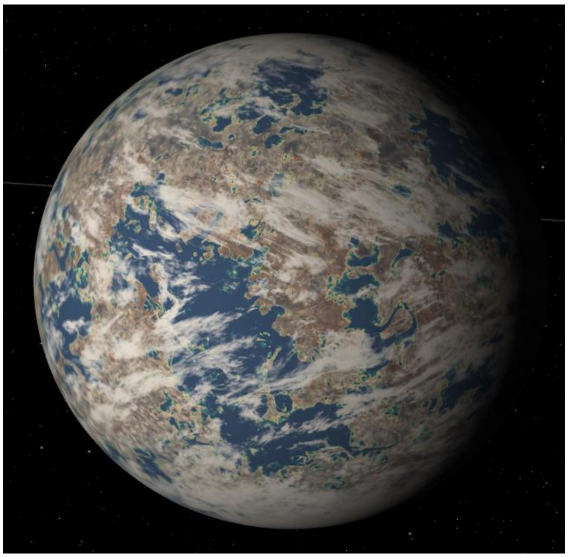

Figure 13. TRAPPIST-1e, the exoplanet most likely to be have traces of iron, and potential of habitability out of all TRAPPIST-1 exoplanets. Snapshot from *NASA Eyes on Exoplanets*

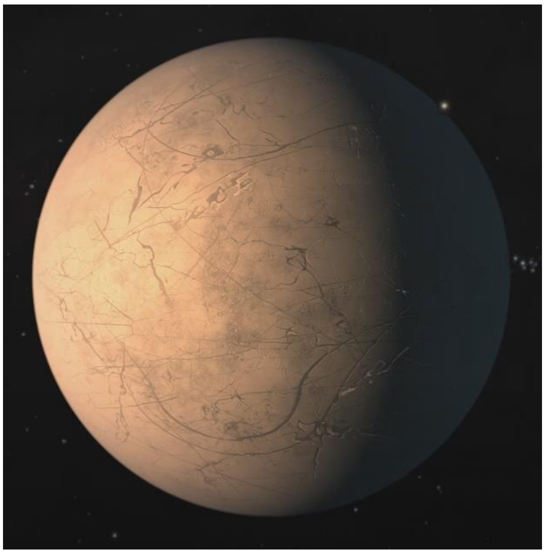

Figure 14. TRAPPIST-1h: an exoplanet modelled after Ganymede, Jupiter's largest moon. Snapshot from *NASA Eyes on Exoplanets*

Impact of medium and execution of exoplanet visualisations

Visualisation is a process aimed to create a visual product- something that can be *seen*- be it a graphical representation, or a computer rendering. The usage of the term representation in this thesis is restricted to Latour's *inscription,* for there is a chance that *representations* might seem ambiguous. However, like Pauwels, I argue that since the visual representation of exoplanets is required to have a material substance which is intersubjectively accessible as a *social object.* The mental images that might be required to make such visualisations have no such material or intersubjective character, though they can be considered as one of the referents for exoplanet representations.

Socio-cultural contexts and impacts

The products of exoplanet visualisation processes generally tend to emanate the characteristics of the end medium and the choices and selections of what is depicted and how, as available in the applications they are viewed in. But while each medium has a fixed number of pre-set characteristics, they also show a variety of ways in which the referents might be represented (mimetically or expressively). This combination of choices of specific formal styles is what Pauwels calls 'the *style of execution*', a phrase I will be borrowing for this narrative [emphasis added].[91] The styles of execution for exoplanet visualisations are determined not just by their medium but also by the conventions dictated by the genre of space images and illustrations, their cultural schemata, the scientific traditions in astronomical studies, the circumstances of their production process, the artists' preferences and idiosyncrasies and very importantly, the specific purpose or user for which the visualisations are made to cater to.

[91] Pauwels, p. 12.

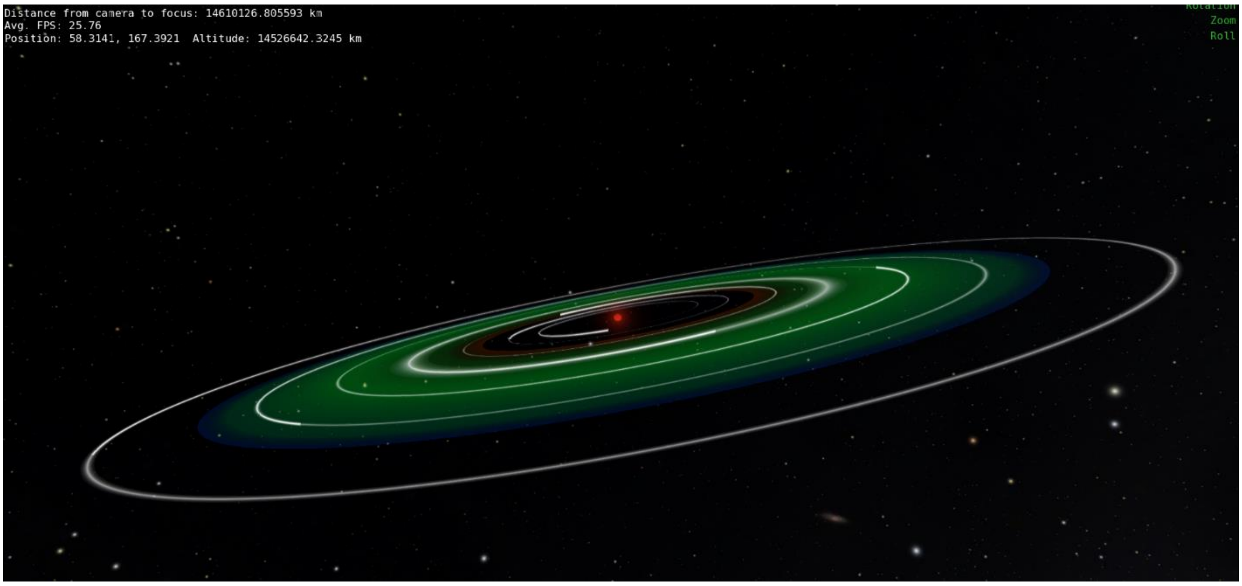

Figure 15. A screengrab from OpenSpace showing a visualisation of the TRAPPIST-1 system after the user flies to it from Earth.

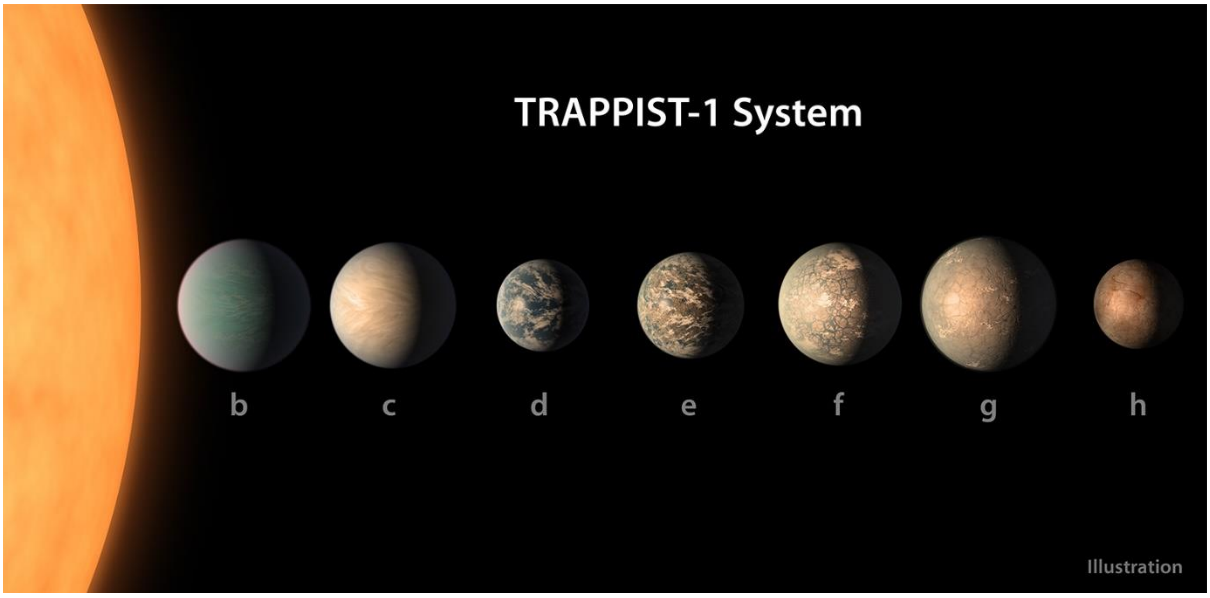

Figure 16. An artist's visualisation of the TRAPPIST-1 exoplanet system, one of the first images showing all the planets, it was used in press releases across the world.

The particular aspect of the different styles of execution makes for a very interesting discussion. Note the images shown above. The first one (Fig 15) is from *OpenSpace*, showing the TRAPPIST 1 system realistically in scale. While this is a 2D image, when visualised on the *OpenSpace* application, one can zoom in and out to see the various bodies more clearly. Not much can be noticed apart from its host red dwarf star and the paths of the exoplanets orbiting it. A similar image (in 2D and 3D) is also available on the *NASA Eyes on Exoplanets* page for TRAPPIST-1, complete with effects of the system revolving in space.[92] The second image (Fig 16) is also from NASA's page with information and images of the TRAPPIST-1 system. Notice how the sizes of exoplanets and their star are different from the previous image. There is much more detail visible on the surfaces of the exoplanets. And then on a slightly lighter note, the third image (Fig 17) is from a poster series *The Exoplanet Travel Bureau* by NASA which explores what it might be like to travel to exoplanet TRAPPIST-1e, the fourth exoplanet in the system.[93] The tone used in the artwork is reminiscent of the art styles used in old posters, creating a nearly instant effect of nostalgia for that era. It is also clear that the artists decided to employ an illustration technique highly inspired by some elements of current popular culture (graphic novels, comic books, etc). Unlike a Lichenstein, the figures are not defined by prominent contours but by intelligent use of the colours. The palette used in each poster can be considered very bold, almost as if fauvism met science-fiction in scenes that encourage the viewers to dream of a future full of scientific wonders. Therefore, given the evident inspiration from the vintage era, emotions play a vital role in these images as well as individual interpretation. The human figures look out from what might be a spacecraft window, the red-blue sky accurately depicts the reddish light from its host star and TRAPPIST 1e's other exoplanet neighbours are visible in the sky like many moons. While it cannot be classified completely under the purview of scientific illustrations, it was an

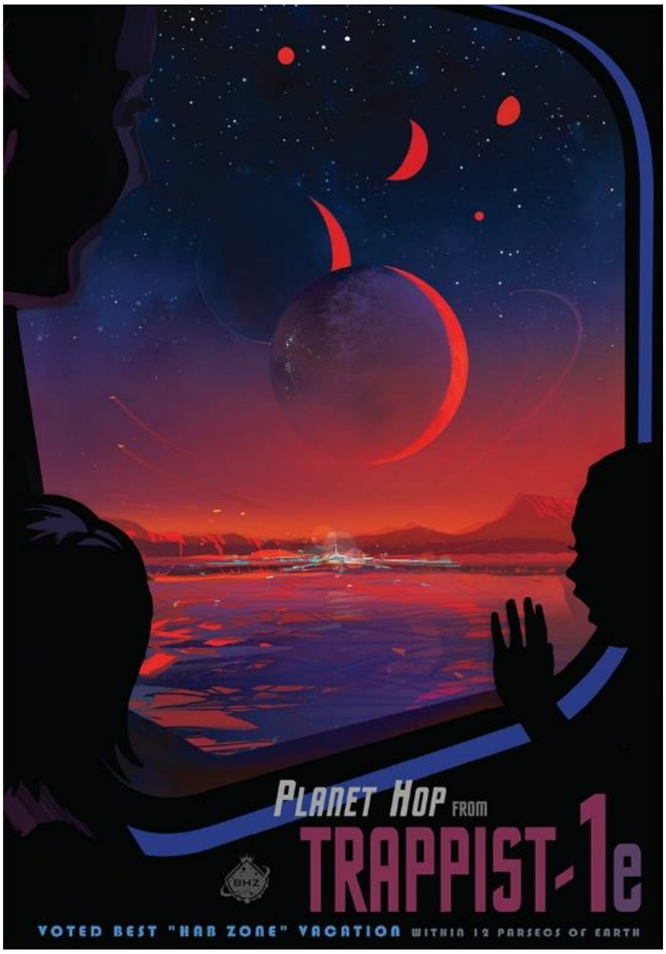

Figure 17. 'Voted Best "Hab Zone" Vacation within 12 parsecs of Earth', A travel poster for the exoplanet TRAPPIST-1e for the NASA Exoplanet Travel Bureau.

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92 'TRAPPIST-1', *NASA Eyes on Exoplanets*, [website], <https://eyes.nasa.gov/apps/exo/#/system/TRAPPIST-1.> (Accessed on 10 May 2022).

93 'Planet hop from TRAPPIST-1e', *Exoplanet Exploration*, [website], 2021, <https://exoplanets.nasa.gov/resources/2159/planet-hop-from-trappist-1e/?layout=magic_shell&travel_bureau=true>, (Accessed 13 May 2022).

initiative to get the general public interested in exoplanet research. There is also an added interactive element to these posters, for the site gives one the option to download a sketch version of it to fill in colours by themselves, according to their imagination.

These three images were created with different socio-cultural contexts in mind. While the first and the second are meant as educational tools for scientists as well as the general public, NASA's visuals are also widely circulated as a kind of *discovery image*; images that are proof of science's capabilities in astronomical research. NASA also takes upon itself the responsibility to generate interest in astronomy and related sciences, and that's an important impact to take into account when viewing its vast database of visualisations and photographs.

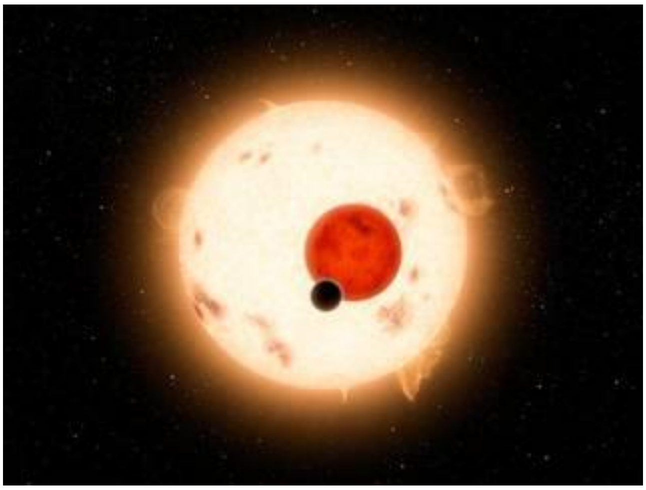

Figure 18. NASA's Kepler mission discovered a world where two suns set over the horizon instead of just one, called Kepler-16b. Robert Hurt created this illustration of the fascinating world.

It is also important to note that with a non-mechanical creative process like hand-drawing or digital drawings there is a chance that the representation might not be *faithful* as a reproduction. This is because, with exoplanet research, scientists cannot ascertain the extent to which their representations can have a general (rule-following) or deviant (exception-like) quality. Since drawing from memory and past observances is key to such visualisations, there is always the chance of perception being coloured by previous knowledge, cultural schemata, and other conventions of the field. This background knowledge of sorts is necessary in order to visualise referents that might be indicated by the exoplanet's data but have not been encountered by direct images so far. An instance of this might be the visualisation of a binary star system (Fig 18), which is rare but not unheard of. Current technology can only recognise exoplanets that might orbit a star, it is much harder to locate and understand the movements of a planet orbiting two stars. In this case visualisations like these come in handy, they act as a kind of sketch or working model to understand novel processes so scientists might be able to further develop techniques to discover such systems and understand them.

Variations in the depicted

There are some evident problems that arise when a representation requires a particular level of abstraction or generalisation, which is an essential facet in the phases of scientific undertakings. This was a problem previously noted in Ptolemy's view of the universe, wherein he omitted glaring problems of his theory's workings to make way for an elegant solution. The variations encountered in data values of referents can easily be mentioned textually or verbally, but in the case of visualisation, the artist needs a definite number. Choices have to be made in such a case to decide which variations can or cannot be easily depicted in visualisations, depending on the importance of the particular referent and the constraints of the medium.

The multidimensional issue of the various kinds of justified and unjustified variations in exoplanet visualisations in combination with the variation that is present within both the existing exoplanets and the variations in the referents used to create visualisations can be defined as what Pauwels states as the 'visual representational latitude'.[94] This latitude is determined by the capacities of the medium used to cope with the observed variations, but more notably by the manner of use of the medium, which includes the offered stylistic options, the scientifically motivated choices, and the liberties the creators have allowed themselves to take. Some detailed variations may also not be necessary to show to a particular audience, and others are important for other groups. For instance, the visualisations made for *NASA Eyes*, and their social media accounts need not show variations of their non-visual data-based referents like mass or volume, but for *OpenSpace* this is much more important because it is an application catering to the need for further research.[95] The requirements simply differ on the visual representational latitude, which should be acknowledged and given *room for manoeuvre*.

The dialogue around the visual representation latitude is thus not just a matter of deciding how variation is expressed, or what is the appropriate level of iconicity or abstraction for a particular purpose. The users of the visualisation also need to be considered. What sort of variation should be expected in reality? Which elements or effects in a particular exoplanet visualisation are driven by a perceived reality, and which others are a result of a specific (intentional or otherwise) choice of the artist, the limitations of the medium

[94] Pauwels, p. 14.
[95] Bock, A. et.al., 'OpenSpace: Changing the Narrative of Public Dissemination in Astronomical Visualization from What to How'.

application in use and the wider context of production? Pauwels advises that one way to convey this information might be via verbal comments (an extended legend or caption) for the viewer- explaining the visualisation they are looking at, any semiotic variations or codes being employed, and the representational claims being made by the representation.[96] An example of this can be seen in the image below (Fig 19). The image consists of three visualisations stacked above each other to illustrate an idea of the size of the TRAPPIST-1 system with reference to our Solar System's Inner Planets (Mercury, Venus, Earth, and Mars) which are similar to the TRAPPIST-1 exoplanets in size and nature, and Jupiter and its moon, because as mentioned above, the TRAPPIST-1 host star is closer to Jupiter in size. To show the true size of the system as visualised, there is a dotted line with the text 'orbits enlarged 25x'. As an added measure, the stars have been kept in scale, which I feel, might confuse the viewer. But if viewed alongside other images of the TRAPPIST-1 system, and background knowledge of our Solar System, this image serves its purpose fairly well.

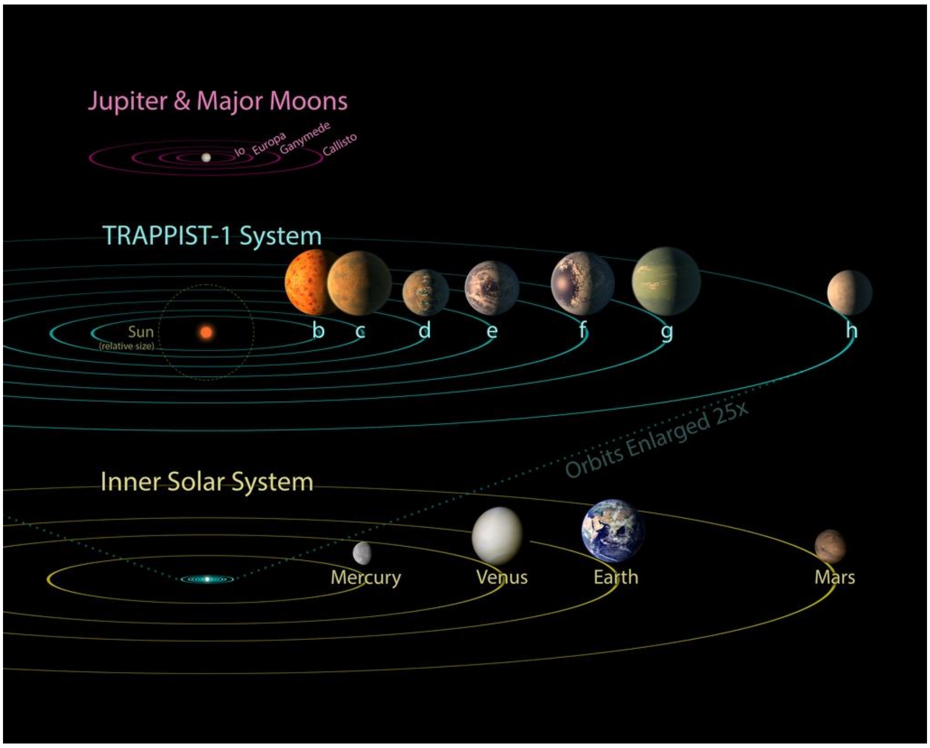

Figure 19. A visualisation showing the comparison of the TRAPPIST-1 system to our inner Solar System, and to Jupiter and its satellite system

[96] Ibid., p. 16.

An additional, and better way of achieving information relay in representations might be to further develop scientific visualisation's visual languages. This might further restrict the ways in which visual elements are employed, as can be seen in the visualisations on *NASA Eyes* but enables a still better visual and unambiguous way of transferring information and expression.

Contexts and uses typified

Representations are required to serve a specific intent, properties that can adequately fulfil certain functions. They are the result of effects and relationships between varied referents (as we have seen above), the end medium/s and the types of usage and claims they carry. These properties though are not only characterised by the medium used, but also by the broader contexts of production and use.

Visual culture scholar WJ.T. Mitchell postulates two factors that the producer of visualisations and their viewers must take into account when attempting to apply visuals with success to a process of communication and cognition. The first, he terms, 'representational commitment', specific techniques that might be more suitable for recording certain referents, and others that might be totally unsuitable.[97] Here, let's recall Hurt's interview with Brennan where he speaks about his experiments that resulted in the TRAPPIST-1 exoplanets being bathed in a red-orange hue from their host star's light. He chose to reserve the bright red light to illustrate the infrared rays produced by the star, and the orangish hues for the exoplanets, thus staying true to the (observed) nature of the different bodies. Mitchell's second requirement is that '[…] a visual representation "must have the correct type of *intentional relationship to its subject matter*"'.[98] This relationship is evident in different ways in the representational work of *NASA's Eyes* and *OpenSpace*, but both try their best to portray information as for their intentions as possible.

These requirements put this discussion into the overall general conversation around the 'long established scientific requirements of *representativity* and *validity*' while emphasising their significance in the visual translation of the visualisations, and varying functionalities of used mediums. This also means that the same medium of representation can

[97] W.J. Mitchell, *The reconfigured eye*, Cambridge, MIT Press, 1992, p.221 in Pauwels, p. 16.
[98] Ibid, italics added by Pauwels in Ibid, p. 17.

be used in a variety of ways and can serve a widely divergent audience. *OpenSpace* serves as an excellent example of this statement. The use of visualisation is considerably determined by the choice of medium, broader prospects of production, style choices, subject selection, and preparation. The multipurpose nature of one kind of representation should still be a guiding principle for its production processes. In the case of exoplanet visualisations, educational and communication purposes can be achieved with highly stylised representations with a focus on the essence of the depicted exoplanet (Figs 11-14) while others like visualisations to help further research in the scientific community might be made with indifference to some referents and highly detailed accounts of a particular data set in a specific context.

For (almost) all intents and purposes

There is a multitude of possible intents and purposes for scientific visualisations in discourse. While one cannot list out *all* of them at the same time (because the purposes inspiring intentions can evolve with the research and success of initial visualisations) the following discussion seeks to debunk and abandon the notion that scientific representations are solely meant to generate and provide objective data purely for cognition. Keeping the above reflections in mind, let's delve into the prospected purposes and intents of produced scientific representations. Referring to Pauwels' framework, the main intentions of a produced representation are to *further the analysis* of its referents, *simplify conceptual developments* and relationships between referents, generally *clarify abstract principles* and to eventually *create a summary and synthesis* of the empirical findings. [99]

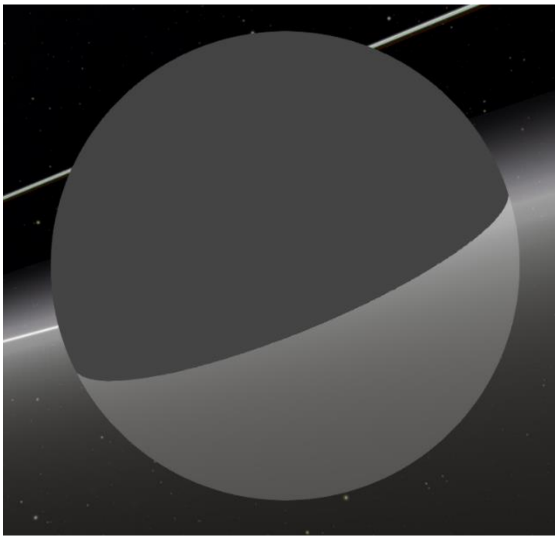

Fig 20. An example of exoplanets as shown on *OpenSpace*. It is a simple sphere with without any rendered details.

In *furthering the analysis* of referents used to visualise a natural phenomenon such as exoplanets, their representations help to understand, compare, describe, document, verify and explore new aspects or relationships between the referents and create

[99] Pauwels, p. 18.

new data for successive phases. An example of this kind of visualisation can be the exoplanets as we see them on OpenSpace (Fig 20). They serve as primary *data* but a visual *intermediary* in the process of a more detailed visualisation.

As exoplanet visualisations have many referents of a mental/conceptual nature, they serve their purpose of *simplifying conceptual developments* very well. They can help in revealing relationships with the referents' material counterparts, thus also helping to *clarify abstract concepts* (Like in Fig 19).

Visualisations of exoplanets as shown (Figs 11-14) can be seen as *creating a summary and synthesis* of their referents' empirical findings. Images such as these can not only be of analytical use but also exhibit results of their conceptual relations and spatial organisations. As evidenced by *OpenSpace* and *NASA Eyes*, exoplanet visualisations synthesised or assembled with purpose can generally facilitate communication and the transfer of knowledge to a diverse audience (ranging from highly specialised to laypersons) through their mediums' adaptability with the audience to mediate experiences. All of these elements are realised in different degrees in both *NASA's Eyes* and *OpenSpace* because both have interactive features that let the user explore by themselves and understand the visualisations, they view by orienting themselves in the environment of outer space. This interactivity is limited in *NASA's Eyes*, to keep it simple for beginners to navigate. In *OpenSpace* the exploration feature is complicated with different controls, making the experience of the user is somewhat like navigating a spacecraft in a simulation or videogame- both fun and slightly terrifying. *NASA's Eyes* also has a comparing feature on its page, which let you compare the host star and the system to our Sun and Solar System respectively. *OpenSpace* again has a much more complex set of parameters that let the user view variations in the referents that we previously discussed and allows changes to views (add or remove bodies and their parameters). Both mediums fulfil the criteria discussed above, in varying degrees. This variation is solely due to the intentions of the visualisations and the contexts in which these tools are used.

The Objectivity of Exoplanet Visualisations

As we have seen the myriad aspects behind the creation, execution, and dissemination of exoplanet visualisations, it would be relevant at this point to summarise this analysis by tying it in with the virtues of Objectivity and Trained Judgement.

Scientific work in the present day is a multitude of coexisting individuals as well as schooling and research traditions. There are new *ways of seeing* cultivated by learning to observe and visualise scientific referents. To reflect on Percival Lowell's endeavours with his sketches of Mars, and Brennan's interview with Robert Hurt, the role of artists has evolved into scientific visualisers and technicians, just like the constraints of Objectivity have relaxed when coupled with Trained Judgement. If we look at the framework Daston and Gallison posited below, exoplanet visualisations fit into the cusp of images made keeping Objectivity and Trained Judgement in mind and while using principles of Truth-to-Nature to whatever extent possible.

Epistemic Virtues	**Truth-to-Nature**	**Mechanical Objectivity**	**Trained Judgement**	**Representational and Presentational Schematisation**
Persona	Sage	Worker	Expert	Combines ethos of 20th century scientist with device orientation of industrial engineer and authorial ambition of artist
Image	Reasoned	Mechanical	Interpreted	Hybrid of simulation, mimesis, manipulation
Practice	Selection Synthesis	Automated Transfer	Pattern recognition	Simultaneity of making and seeing
Ontology	Universals	Particulars	Families	"Nanofactured" goods straddling the divide between natural and artifactual

Table 1: An overview of the covariance of scientific self, image, procedure, and object.

Persona, Image, Practice and Ontology

Daston and Gallison describe the persona of the visualisations as 'worker' and 'expert', with the image itself being 'mechanical' and 'interpreted' when created with objectivity and trained judgement respectively.[100] As we learnt in the discussion of the referents and the productions of their representations, exoplanet visualisations are instances of an *observed reality* with aspects of iconicity and reasoning that make them adhere to the facts of the

[100] Daston & Gallison, p. 371.

phenomena (referents), thus also staying true-to-nature. The interpreted factors include how the referents are translated, converted, transcribed and/or fabricated by expert visualisation scientists from their data into visuals. Hurt also mentions how the course of their work incorporates the above-said actions. The inference, therefore, is that exoplanet visualisations are a representation of a process that makes exoplanets tangible to us on Earth as a simulated hybrid of mimesis and intentional manipulation thanks to the modern scientist working in tandem with engineers and artists.

In practice, objectivity calls for 'automated transfer' along with trained judgement's 'pattern recognition', but here the 'selection synthesis' of truth to nature also plays in.[101] Trained judgement is especially applicable in the role of exoplanet system visualisations in scientific study, for the images are a representation of recurring patterns in the host star's light intensities. But largely, the process of exoplanet visualisation is an exercise in repeated selection synthesis by visualisation scientists to navigate encountered variations and create images for a various contexts and intents. The resulting visualisations as we see them today are thus an exercise of scientists simultaneously *making* and *seeing*. Finally, in the ontological sense, the images are evidently what Daston and Gallison consider '"nanofactured" goods straddling the divide between natural and artifactual', where manipulation by intervention does not take away from the objectivity of the creator/researcher but showcases their specialised view. [102]

[101] Ibid.
[102] Daston & Gallison, p. 371.

Concluding thoughts

This thesis began with the idea of exploring the viewer's understanding of data-informed exoplanet visualisations as seen on popular platforms like *NASA Eyes on Exoplanets*. These visualisation images are a wonderful example of how artistic intervention can work in tandem with scientific study to bring highly technical information to life.

Through the course of this thesis, we have seen the evolution of thought in astronomy as we studied the skies to understand our place in the Universe. As technology developed, so did our ways of looking. In the beginning, artists took personal responsibility for ensuring a scientist's observations were represented in the most accurate and life-like way possible. Then with the camera taking the centre stand, suddenly not just artist, but human intervention was seen as subjective; something hindering the truth as seen on film. Eventually, science and artists found themselves in a new kind of symbiotic relationship, with an added element of technology, for complete reliance on technology left room for errors, and human skill could not be as precise as computers in some cases. With this thesis, I have tried to show how exoplanet visualisations are a testament to this relationship.

This thesis has also investigated the nuances of scientific images in the public eye; how they are created for varied audiences, to inform, educate and incite more interest. Using Pauwels' reflections on Mitchell's thoughts on the role of scientific visualisations, specifically on the requirements that can allow such images to highlight the established fact that scientific visualisations were created for the purpose of communicating knowledge is a very apt summation of this thesis study. The first requirement Mitchell states is that representations must have representational compatibility, in that they fit the particular purpose for which they are created. The second requirement is that the representation's intentional positioning must be true to the abovesaid purpose. These requirements, as we see are fulfilled by the exoplanet visualisations discussed in this thesis, also serve as a reminder of the burden of representativity and validity that is carried by the producers, mediums, and the images themselves.

It was also important to note that the varied functions embodied by some aspects of visual representations could be read or decoded by different receivers in multiple ways (depending on their backgrounds and experiences) some of which might have not been imagined or intended by their producers. Instead of viewing that as a problem, we can justify it as a way of exploring their inter-functionality, and revel in their part of helping to tackle and mitigate possible tensions among a heterogenous collection of actors who play a part in creating, producing, and interpreting scientific visualisations.

By bringing in a perspective of objectivity parallel to the analysis of exoplanet visualisations, I would also like to state how *NASA Eyes* and *OpenSpace* could be essentially regarded as the modern version of scientific atlases, a repository of observed phenomena not fully visible to us (yet); how these visualisations are bringing exoplanets beyond our view to a more tangible existence, making them a more believable reality as compared to the speculations of Plural Worlds by Bruno and Fontenelle. The extent to which the discussed visualisations in this thesis might resemble the TRAPPIST-1 system remains to be seen, as newer technology is swiftly being brought into deployment, such as the James Webb Telescope launched in 2021 with the intention of directly imaging exoplanet systems.

Being a young field of study, exoplanets and their visualisations have an extensive scope of study, one that is only going to grow further. In an early stage, I had conceived the idea of creating an interactive model as a companion to this thesis, as a practical counterpart that could add an element of *learning by doing* to the theoretical analysis undertaken in the last chapter. My failure to complete this undertaking was caused by many factors, like, my lack of knowledge of creating and working with JavaScript code, and *OpenSpace* not yet having features developed to be used to work with instances or actions for someone who might not have the software installed. But should the reader be interested in an interactive experience of their own, they can start with *NASA's Eyes on Exoplanets* as a beginner step or download the *OpenSpace* application (available with full access on the internet) on to their devices for a more immersive feeling. This would also help you understand my experience studying the tools of visualisation. Technology might be openly accessible for everyone to use, but there is still a lot of ground to be covered for seamless collaboration between scientific tools and visual culture. I reflect on this aspiration of mine to show how this thesis can motivate further work and grow into a more collaborative endeavour.

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