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RESEARCH ARTICLE

A social semiotic analysis of university level astronomy teaching resources

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Abstract

The use of representations in astronomy education has been a subject of investigation spanning across educational levels and with various content-specific topics. Within astronomy education research, a major focus can be identified; the use of different types of visualizations (from planetaria to textbook images and drawings) and their usefulness in the astronomy classroom. However, in order to construct and communicate its knowledge, the discipline of astronomy relies not only on visualizations, but also other resources, including mathematics, written language and code. Therefore, there is a need for astronomy education researchers and practitioners to analyse the use of all the different resources that together constitute complex, multifaceted disciplinary knowledge about the universe. This is our goal with this paper; to present a social semiotic perspective of teaching and learning astronomy at the university level, through the use of representations. For this purpose, we catalogued representations (semiotic resources) from lecture notes and textbooks used in six higher education astronomy courses, and using thematic analysis divided them into nine different categories (semiotic systems), on the basis of their fundamental differences in representing knowledge. Using the notion of affordance, we analysed what each of these systems tends to accomplish for disciplinary meaning making. Finally, we discuss the implications of using the framework of social semiotics as a lens to better understand teaching and learning in astronomy, and how it can give access to new insights and perspectives that would not otherwise be foregrounded.

Keywords: Representations - Higher Education – Social Semiotics – Astronomy - Cosmology

1 Introduction

1.1 1.1 Background

The discipline of astronomy constructs and mediates its knowledge using a wide range of meaning-making resources. The work of an astronomer involves different tasks that range from manipulating mathematical equations, writing code, to creating and interpreting different types of visual representations, such as graphs, diagrams, images, etc. This is also reflected in the practices of astronomy education; in lectures and textbooks for astronomy courses, students encounter a variety of different representations and face the challenge of interpreting and using them in an appropriate disciplinary manner. It comes as no surprise, therefore, that in the Astronomy Education Research (AER) literature, we can find a great number of studies about different representations and how they can be leveraged to teach astronomy more effectively (e.g., Carsten-Conner et al., 2015; Yu et al., 2015) (see section 1.2 for details). While these works do not have a specific content focus, one main trend in research work about representations in AER can be highlighted: a focus on the educational aspects of visualizations of astronomical objects (e.g., images, video simulations, planetaria, etc.) (Galano et al., 2018; Trump and Lawler, 2022; Yu et al., 2015). The study of visualizations ranges between different disciplinary content, mostly regarding the Earth and Moon and other phenomena within our solar system (Bekaert et al., 2022; Li, 2022; Wilhelm et al., 2018; Yu et al., 2015, 2016). However, more recently, a num-

ber of studies regarding large-scale concepts have also surfaced in the literature (Nolan et al., 2021; Salimpour et al., 2021a,b). Moreover, research on the use of representations in AER has traditionally focused on the teaching and learning of astronomy at the school level (Carsten-Conner et al., 2015; Galano et al., 2018; Peña and Gil Quílez, 2001; Salimpour et al., 2021a; Testa et al., 2014). It is only recently that work regarding university level astronomy has started to appear (Airey and Eriksson, 2019; Eriksson et al., 2014b; Eriksson, 2019; Nolan et al., 2021; Salimpour and Fitzgerald, 2022b; Trump and Lawler, 2022; Ubben et al., 2022; Yu et al., 2015).

What is noticeable in all this work, however, is that regardless of the content knowledge to be communicated, or the educational level of interest, the main focus has been on visualization. This means that other representational formats that have been of great interest in other Discipline Based Education Research (DBER) fields, such as mathematics or written language, remain relatively underexplored in the AER literature. We suggest that this issue can potentially be tackled by adopting the theoretical perspective of social semiotics. Social semiotics is a framework that is used to study "the development and reproduction of specialized systems of meaning making in particular sections of society" (Airey and Linder, 2017, p.95). In recent years, it has been used in physics and astronomy education research as a lens to explore teaching and learning in those disciplines.

In this paper, our aim is to use a social semiotic perspective to explore representation use in higher education astronomy. For this purpose, we present a literature review of representations and social semiotics in AER, followed by a brief discussion of the reasoning for using this framework. For the empirical part of our study, we systematically documented the range of representations used in higher education astronomy at both undergraduate and postgraduate levels. Our focus was specifically on representations that deal with larger-scale structures and phenomena outside the solar system, typically found in courses on Cosmology or Galaxy Evolution and Formation. Using our social semiotic approach, we catalogued a range of representations and categorized them across different representational formats. By presenting some exemplar cases from our data collection, we demonstrate how social semiotics can serve as a useful framework for astronomy education researchers and practitioners, providing valuable insights that might not otherwise be foregrounded.

Our research questions are as follows:

RQ1: What is the range of semiotic systems used in astronomy education at the university level?

RQ2: How are the identified systems used for meaning making?

1.2 Literature Review

Social Semiotics in Astronomy Education Research

In this section of our literature review, we outline some work that highlights the use of the social semiotics framework in the context of AER. Some of the papers in this section focus on the disciplinary aspects of meaning making in astronomy, and their consequences for teaching and learning. Eriksson et al. (2014b) examined the development of students' three dimensional awareness, in a study involving students across educational levels. They conclude that as students progress through their education, their ability to discern aspects of three-dimensionality also develops. Eriksson et al. (2014a) also argued for different levels of disciplinary discernment (identification, explanation, appreciation and evaluation) by examining university students and lecturers engaging with a three-dimensional space-travel simulation. In a later study, this concept of disciplinary discernment was synthesized with concepts such as disciplinary knowledge and extrapolating three dimensionality, as the foundations of the competency of reading the sky (Eriksson, 2019). These competencies are used to characterize the process of learning astronomy and the underlying challenges students face when accessing the discipline. In similar fashion, Airey & Eriksson (2019) analyzed the meaning making functions of Hertzsprung-Russell diagrams and identified potential barriers to student understanding of such diagrammatic representations (idiosyncratic historical development, omission or overloading of features and students' own expectations). In conclusion, they also present an alternative version of the diagram that addresses some of its counter-intuitive features and therefore is more apt for educational use (Airey and Eriksson, 2019). Finally, in a broader study about different kinds of visualizations in cosmology education, Salimpour, Tytler et al. (2021b) analyzed different visual representations across all educational levels (from public outreach to higher education). The study led to a framework for the description of different layers with which audiences engage with representations (Dimension – Features – Translation – Interrogation), intended to be a guide for educators and textbook authors to further support the interpretation of visual representations in cosmology. Shifting the focus from disciplinary aspects of meaning making, other studies have used the social semiotics framework to explore student meaning making with representations in astronomy. Salimpour, Fitzgerald et al. (2021a) discussed the advantages of using a web-based interface to analyze and visualize Big Data in a high school classroom and how the process of students creating Big Data visualizations can facilitate their experience of science as practice. Using social semiotics along with an embodied cognition perspective, Euler et al. (2019) studied how students engage with various meaning-making resources in a non-disciplinary manner when they reason about physical phenomena (using binary star dynamics as the topic for their case study). Other researchers have also examined student engagement with a range of visual systems (e.g., drawing, images). Testa et al. (2016), for instance, analyzed student difficulties when interpreting images and simulations. After performing a semiotic analysis of representations, they interviewed students to understand the kinds of difficulties they face when interpreting them. Tytler et al. (2020) analyzed student drawings and how they contribute, under certain conditions, to their reasoning and learning. The process of students moving meaning across semiotic systems (transduction) has also been explored, as Prain & Tytler (2024) identified elements in teacher-student interaction that can enable transduction and how they can inform the design of science inquiry in the classroom. Furthermore, the social semiotic perspective has also been adopted to bring cultural aspects of astronomy into the discussion. Salimpour & Fitzgerald (2022a) explored the cultural aspect of meaning making in astronomy, and its relationship to disciplinary meaning making. In an attempt to bridge the two together, they designed a framework for bringing cultural aspects into the teaching and learning of astronomy, considering the wide range of its cultural diversity. Overall, in our overview of research that adopts a social semiotic perspective in AER, we can see that the nuances and theoretical notions of social semiotics have enabled authors to examine various aspects of astronomy teaching and learning; from better understanding disciplinary meaning making to identifying students' challenges or bringing cultural aspects into the classroom. In a similar manner, our goal with this paper is to contribute to this agenda, by highlighting the insights provided from our semiotic analysis of astronomy representations at the university level.

Representations in Astronomy Education Research

In DBER, representations are traditionally analysed as part of the problem-solving category. However, in AER we can find work with representations spanning a number of research top-

ics, from the use of planetarium visualizations in order to teach specific astronomical phenomena (Trump and Lawler, 2022; Yu et al., 2015, 2016) to exploring students' conceptions and mental models of astronomical objects (Ubben et al., 2022). While in other disciplines, and especially in Physics Education Research, there is a focus on coordinating multiple representational systems (e.g., mathematics or graphs), AER researchers have mainly focused on visualizations, aiming to examine how different ways of visualizing astronomical objects and phenomena can help develop students' competence in spatial thinking. This is a particularly complex task for Astronomy educators and it begins from the problem of extrapolating the dynamics of a three-dimensional universe from a two dimensional sky and its visualizations Eriksson (2014); Eriksson et al. (2014b). Hence, the US National Research Council (2012) has argued that the relationships between astronomy knowledge, visualization and spatial thinking should be an active area of investigation in AER.

For this reason, within AER, visualizations have been studied from various perspectives. We will now provide some examples of the range of this branch of AER literature. Researchers have studied the challenges students face when reasoning with visualizations regarding the phases of the moon (Subramaniam and Padalkar, 2009) or the difficulties they have adopting scientifically correct 3D models of the Earth and Moon, even when they are presented with them (Vosniadou and Brewer, 1992). Beyond difficulties and challenges, a study by Ivarsson et al. (2002) has shown that developing three-dimensional thinking is indeed achievable even at a very young age.

In a study about the utilization of the "AHaH" (Appreciating Hubble at Hyper-speed) virtual tool (Nolan et al., 2021), the authors showcased how using a visualization for traversing the Hubble Ultra Deep Field in three dimensions at speeds higher than the speed of light and with the option of different geometries, can help facilitate learning about the effects of a relativistically expanding Universe and support students in developing an intuitive understanding of such concepts.

Several authors have tried to deal with the challenges of visualizations and discerning three-dimensionality by looking at the use of planetaria in astronomy education and leveraging the advantage of adding a third dimension by presenting objects on a curved screen. In studies with elementary school students, it has been shown that planetarium use can support the connection between knowledge about observed patterns and orbits, with non-observable patterns such as the Earth's orbit. This can also help with visualizing concepts such as the speed of planetary orbits (Carsten-Conner et al., 2015). Trump and Lawler (2022) explored the use of planetaria in introductory astronomy courses, with results showing that planetaria are mostly used for teaching aspects of the night sky in an unscripted manner. Other studies with undergraduate students have indicated that using immersive planetarium visualizations in teaching the solar system or the seasons and moon cycles can be superior to non-immersive classroom visualizations (Yu et al., 2015, 2016). Persson and Eriksson (2016) have also showcased how 3D visualizations can be reproduced in a classroom setting using planetarium software and provide examples of its use for teaching solar and planetary motion and HR-diagrams.

Besides three-dimensional planetarium visualizations, the use of images has also been of interest to authors in astronomy education. Testa et al. (2014) pointed out that the use of images in Astronomy textbooks poses difficulties for students across educational levels (middle, upper secondary and undergraduate students) because they internally represent phenomena in a geometrically inadequate way. Moreover, as pointed out by Galano et al. (2018), these difficulties are also related to the interference of some of the image's features with relevant factors that are crucial in identifying underlying depicted structures and phenomena. Another study (Peña and Gil Quílez, 2001) showed that images sometimes do not provide sufficient information to engage students and lead to successful knowledge transduction to other representational formats such as written language or diagrams.

Analyzing the literature presented in this section, which we believe to be indicative of the work done with representations in AER, we can see that researchers have explored the use of representations in many different contexts and across many educational levels and content specific topics. There is a very prominent focus on analyzing and developing the use of different kinds of visualizations for astronomy education, spanning from diagrammatic representations to planetarium projections and 3D video simulations. This is often connected to the goal of developing students' competence in spatial thinking, which has been marked as very important for astronomy. However, we also identify a lack of work regarding the use of non-visual systems of meaning making, such as mathematics, code or written language and how they are used in astronomy education in order to facilitate the teaching and learning of disciplinary knowledge.

2 Why Social Semiotics?

Constructing and sharing meaning within a social group always involves the use of a variety of semiotic resources. Semiotic resources can either be physiological (e.g. gestures, speech, facial expressions) or technological (e.g. sketches, images) and are placed in the space between people when they engage in any kind of meaning making process. In the physics education research literature, the term representations drawn from cognitive psychology is often used as an alternative to semiotic resources (Airey and Linder, 2017). The representations framing, interests itself in objects or phenomena and how these are represented. The potential problems with this approach are threefold. First, in such a framing it is easy to make the mistake that representations only have one meaning: "Here is the thing and here is its representation". In reality semiotic resources have a wide range of possible meanings depending on the specific situation—put simply, they are flexible resources for meaning making. Our second reason for choosing social semiotics is that it allows us to include meaning making resources that would not be included in a representations approach, such as experimental apparatus. As shown in our data analysis section, this approach allowed us to categorize all the available resources into different semiotic systems and to include some that would have been otherwise overlooked (code, for example). Finally, because cognitive psychology views representations in terms of input, there is a tendency to focus on the two main input channels—visual and auditory and categorize representations accordingly. Using social semiotics enables us to distinguish between for example mathematics, graphs, and diagrams—systems that would otherwise all be considered part of a visual classification. In this way, our focus can both be more fine-grained and shift from a preoccupation with the use of visualizations in astronomy education to an analysis that includes other semiotic systems that have not been as extensively explored within AER such as mathematics.

Different types of semiotic resources construct and represent meaning in different, often complementary ways. For example, if we compare a piece of written language with a mathematics equation or an image describing the same process, we notice different aspects of meaning being foregrounded in each case. The term semiotic systems has been used to categorize these fundamentally different classes of semiotic resources (see for example, Martinec, 2000). Some examples of semiotic systems that are often used in scientific disciplines are mathematics, graphs, diagrams and written language. Thus, the terms semiotic resource and semiotic system are particularly useful for our analysis.

2.1 Affordances

The idea that different semiotic systems represent meanings in fundamentally different ways raises an important follow-up question: are some meanings better represented in one semiotic system than another? Here, the concept of affordance has been used to describe how semiotic systems are "by nature" better at certain types of meaning making—we say that different semiotic systems have different affordances (Kress et al., 2001).

The term disciplinary affordance (Fredlund et al., 2014) has been used to describe a general agreement within a scientific discipline regarding the disciplinary meaning or usefulness of a particular semiotic resource, whereas pedagogical affordance on the other hand, refers to the aptness of a semiotic resource to be used for teaching and learning a scientific concept (Airey, 2015). The question for education therefore becomes one of how to leverage the disciplinary and pedagogical affordances of the semiotic resources available, and how these can best be coordinated to facilitate students' holistic access to disciplinary knowledge (Airey and Linder, 2017).

The notion of affordance is central to our work; it allows us to see how the meaning making functions of each semiotic system used in astronomy are leveraged in an educational setting, and how they all work together in order to make disciplinary knowledge accessible to students.

3 Method

3.1 Data Collection

Our data for this study consists of different semiotic resources collected from lecture notes and textbooks from two undergraduate (UG) and four postgraduate (PG) astronomy courses that took place during the autumn semester 2022 and spring and autumn semesters 2023 at two research intensive universities in Sweden.

The courses were selected on the basis of covering all levels of higher education astronomy, both for undergraduate and postgraduate students. Additionally, we selected courses that mainly focused on teaching concepts and phenomena that diverged from the ones that are more traditionally explored in physics and astronomy education (Sun, Earth and Moon, the Solar System); hence, we also included courses such as cosmology, multi-messenger astrophysics, and observational astrophysics. The data were collected by the first author cataloguing semiotic resources from lecture notes and textbooks (whenever they were used) for all courses, and by actively observing the lectures and taking notes of how the different representations were used together for the teaching and learning of the relevant concepts.

3.2 Data Analysis

i) Categorization into semiotic systems For this part of our research question, we categorized the range of resources in our dataset, based on the semiotic system to which they belong. To achieve this goal, our methodology consisted of stages described by thematic analysis (Braun and Clarke, 2006), where new themes emerge in the process of exploring and collecting a dataset. Initially, the tentative categorization started while collecting data from each course individually. Then, as new data were introduced, we tried to fit them into our pre-existing categories. Whenever this was deemed impossible, new categories were added. This process was repeated until we completed our data collection. Let us illustrate this with an example: our study started by analysing material from lecture notes and textbooks from course (v) – astrophysics and cosmology. After dividing this material in a few categories, we moved to the next course (course (iii) – cosmology) where new semiotic systems emerged – video simulations and code. This informed our initial categorization with new categories. We continued this process until we finalized our categorization into nine different semiotic systems, which we then refined and used to categorize our whole dataset.

ii) Analysing meaning making For the second research question, we analysed the meaning making functions of semiotic resources in each system based on the theoretical concepts described in section 2. Focusing on the concept of affordance, we identified the most prominent meaning making functions played by the resources in each system. To achieve this, we performed a semiotic analysis of the available resources and how they were used in lectures. This meant analysing resources according to their representational structures, and how they organise their different elements for communication (e.g., Kress and van Leeuwen, 2006; Testa et al., 2016). In this way, we were able to provide a description of each system's main affordances and how they were leveraged for educational purposes.

4 Findings

4.1 Affordances of semiotic systems in astronomy at the university level.

First, we will present an overview of our findings regarding the range of semiotic systems presented to undergraduate and postgraduate students in astronomy in Figure 1. After documenting all the resources from the courses described in the previous section, we coded them into nine distinct categories. From our analysis, the following semiotic systems were identified: **graphs, mathematics, images, diagrams, maps, written language, code, video simulations** and **hybrid**.

At this point, we will present the details of our categorization for each semiotic system individually, along with a description of their affordances for meaning making.

i) Graphs

Under this category, we included the "traditional" format of a graph with two axes and either a plotted theoretical line (theoretical graphs), data with error bars, or a combination of both a theoretical line and data. Moreover, as a special subcategory of this system, we included graphs that, although labeled as "diagrams" (HR diagrams, spacetime diagrams) by the discipline, use the traditional format of graphs with axes and plotted data or theoretical lines. The following affordances were documented:

- Graphs are often used in conjunction with written language and mathematical symbolism, to reveal information about what is depicted. At the same time, most of the meaning is made by the line shape, that reveals the dynamic relationships between the depicted elements.
- Plotting a combination of a theoretical lines along with data seems to achieve the most for meaning making with graphs; it reveals detailed information about the processes of a physical system, even when differences are smaller and hard to notice (Figure 2a).
- Graphs that are labeled as "diagrams" by the discipline utilize the same elements and structures as the rest. However, the distinction here is that disciplinary meaning does not solely rely on the shape of a line, but in identifying different regions within the graph that signify different physical processes and groupings of plotted data (Figure 2b).

ii) Mathematics

Within the category of mathematics, we included every form of algebraic expression that we identified, mostly equations or inequalities. Because of its usefulness in unpacking information

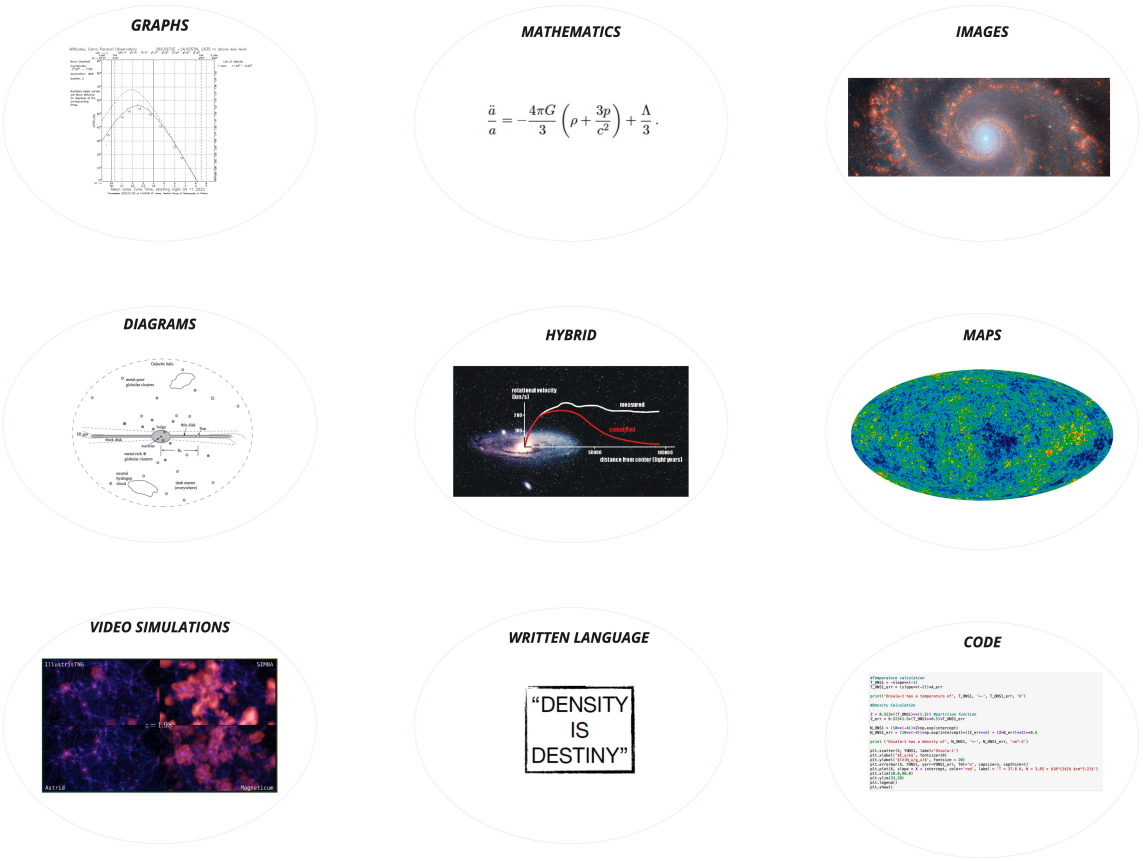

Figure 1. Overview of the range of semiotic systems used in astronomy at the university level, based on our data collection. Nine semiotic systems were identified: graphs, mathematics, images, diagrams, hybrid, maps, video simulations, written language and code.

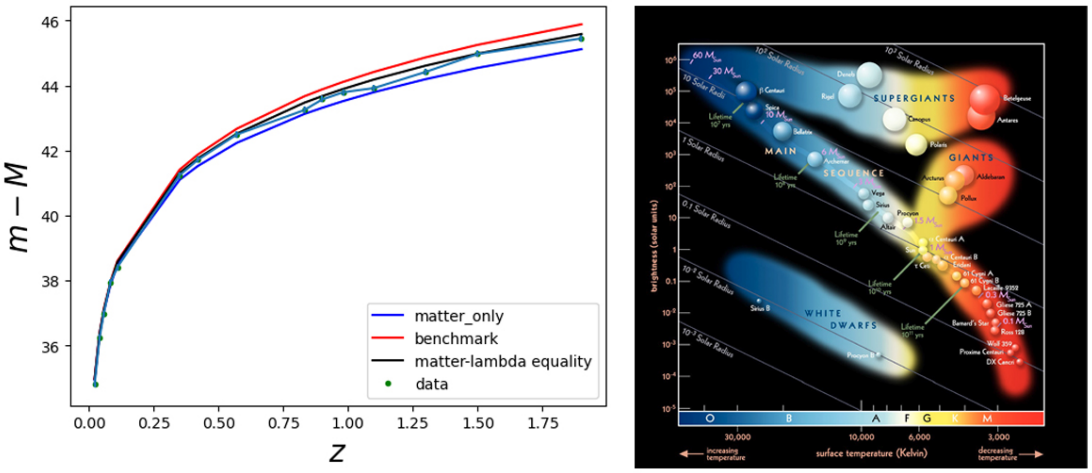

Figure 2. Examples of graphs: a) Left: Data plotted along with theoretical lines. Notice how plotting the data and all three theoretical lines makes it easier to infer which model better fits the data. b) Right: The Hertzsprung-Russel (H-R) diagram where different regions signify stars at different phases of their life cycle (Credits: ESO).

about the dynamics of physical processes, mathematics is one of the two systems we identified that were coordinated with almost every other semiotic system (the other being written language). For example, the shape of a graph line would be accompanied with a mathematical expression to specify the relationships between physical parameters of a system.

As a standalone system (when not accompanying other resources), the main function of mathematics was the calculation of a specific parameter by rearranging and combining equations. This would often happen by relying on what Tuminaro and Redish (2007) have described as "plug and chug" (rearranging an equation into a form, that was then used to "plug in" different known parameters and extract numerical results). Sometimes, the final forms of the equations would be used to engage in some kind of scientific argument (i.e., which parameter is more dominant).

iii) Images

For the category of images, we catalogued realistic-looking depictions of either astronomical objects or other contexts (people, places, objects) that served as teaching tools for the courses.

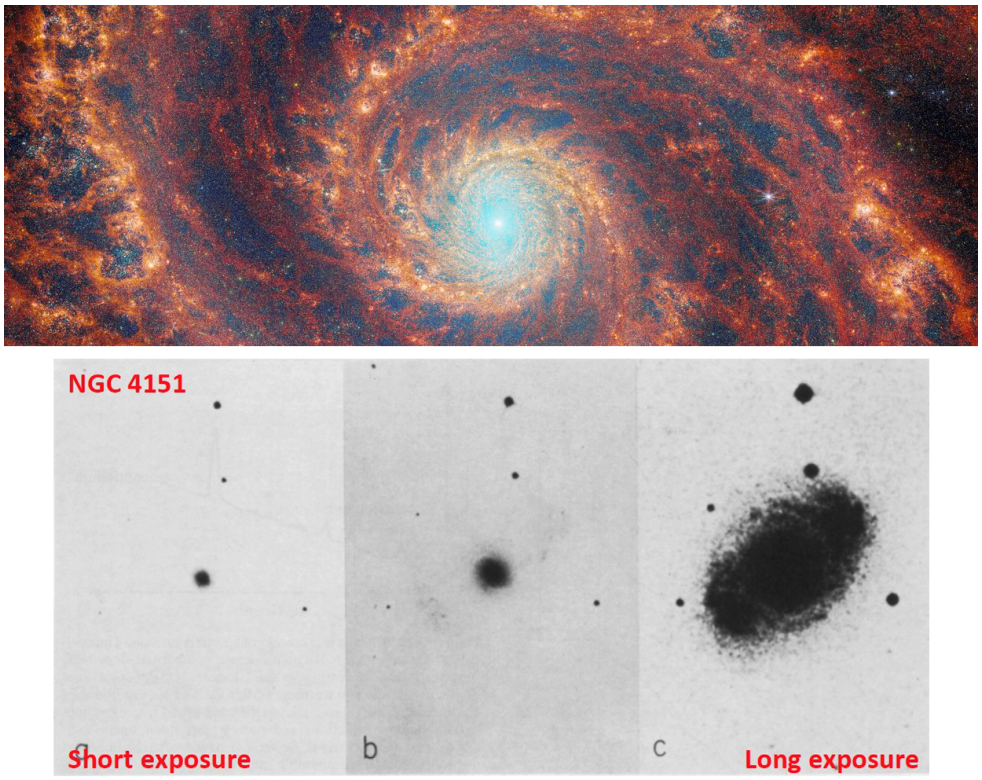

Figure 3. a) Top: A composite image of the M51 galaxy taken by James Webb's Mid-InfraRed instrument (MIRI) and Near-InfraRed Camera. Credits: ESA/Webb, NASA & CSA, A. Adamo (Stockholm University) and the FEAST JWST team: https://esawebb.org/images/potm2308a/ and b) Bottom: A variation of three images of the galaxy NGC 4151 taken at different exposure times (Morgan, 1968).

In general terms, we included photographs that attempted to depict their contents as "real-looking" rather than abstract representations of physical objects and phenomena.

In terms of meaning making, we identify two functionally different subcategories; images of astronomical objects that were mainly created for science outreach purposes, and images that are used for scientific purposes within the discipline of astronomy:

- Images used in science outreach (Figure 3a) seem to have a twofold function. On the one hand, elements such as colour, contrast and cropping are used to indicate important disciplinary information about the object depicted. At the same time, these elements are also used to aesthetically engage students; they direct their attention towards an important scientific discovery, encapsulating a sense of grandeur and mystery stemming from the importance of capturing detailed views of astronomical objects at large distances. It is important to note here, that, more often than not, these images were presented to students as standalone entities and not coordinated with other systems such as written language or mathematics, that are usually used to further unpack information.
- Images used for science purposes within astronomy (Figure 3b) functioned quite differently. The use of colour and texture is more limited, aimed at revealing information about structures rather than aesthetically engaging the audience. These images were often coordinated with written language to further unpack important information.

iv) Diagrams

Diagrams form the most diverse category that emerged from our data, including several kinds of abstract visualizations of processes and phenomena, that differed a lot in their function and form. This category includes diagrams that are more highly abstracted, aiming to explain a specific concept such as homogeneity, isotropy (figure 4) or spacetime geometry. Their affordances are usually leveraged by combining different elements (arrows, curves, dots) and contrasting them in size or direction. Due to their abstract nature, they were often (but not always) combined with other semiotic systems to unpack details about what is depicted.

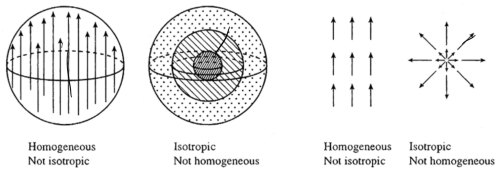

Figure 4. Diagram depicting the different combinations between a homogenous and isotropic universe. Credits: James Schombert, University of Oregon.

v) Hybrid

Under the category "hybrid" we included semiotic resources that do not belong to one semiotic system alone. These are resources that combine two or more semiotic systems to construct a single representation that works as a standalone. Considering that almost all visual semiotic systems include the use of written language and mathematics alongside a visual representation, for this category we only included representations that use two or more visual systems simultaneously (Figure 5).

Our motivation for using semiotic hybrids is that by combining different semiotic systems, information that would not otherwise be noticeable is revealed. See for example, how in figure 5, new information is revealed in a profound way; the image makes it possible to see that the part where the mea-

sured and calculated curves diverge is beyond the visible limits of the galaxy, thus providing the opportunity to introduce new meaning, which in this case is the existence of the galaxy's dark matter halo beyond that limit. This semiotic hybrid accomplishes its work by combining the graph's affordances for revealing information more explicitly (labels, line shapes) with the image's affordances for revealing structures (colour).

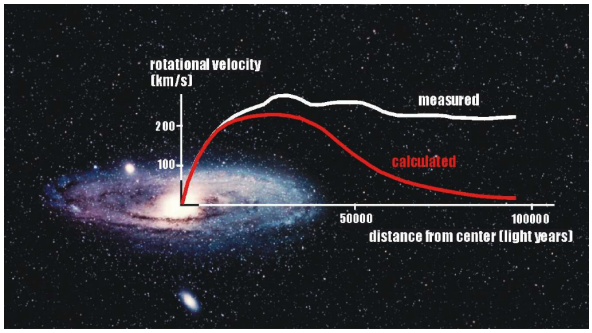

Figure 5. A galaxy's rotation curve embedded onto an image of a galaxy. Credits: SuperCDMS group (Queens University)

vi) Maps

In the category of maps, we included visualizations of spatial distribution of different objects in the sky. Semiotically, maps share a lot of similarities with diagrams. They are also an abstracted way of visualizing information and utilize some of the same elements, for example the use of colour or texture to contrast different regions of the diagram in order to assign them particular disciplinary meanings. However, considering their intended meaning making, maps have a major difference from all the visualizations in the category of diagrams; maps are intended to display a realistic depiction of how structures are distributed within a – larger or narrower – field of view. This aspect alone creates a need for their affordances to be leveraged differently and this is why we chose to categorize them as separate from diagrams.

Given their abstract nature, information about what is depicted is often not fully unpacked with this type of visualization (figure 6a). However, they are partially revealed by adding different elements to the map, such as a set of coordinates or a colour scale (figure 6b & c). In many cases, this was also achieved by presenting variations of the same field of view in different wavelengths and contrasting the differences between what is depicted (figure 6d & e). It is also noticeable that maps were often presented with an elliptical shape, resembling a map of the Earth's surface.

vii) Video simulations

Under this category we included video animations of physical processes (e.g., a merger of two neutron stars, universe expansion), cosmological simulations and videos that showcasing processes of data collection with various instruments.

Video simulations, although not found extensively in our dataset, can potentially be very useful for leveraging the affordances of visual semiotic systems even further. The element of change in time that is unique in animations results in them having further meaning-making capacities especially when coordinated with other semiotic systems. For example, the screenshot in figure 7 originates from a simulation of the data collection process of the CMB photons by the Planck satellite. It depicts the full process of the whole sky survey that ends in the 2D CMB map we described above, thus establishing what is actually depicted.

viii) Written language

For this category, we considered both large pieces of written language found mainly in textbooks, more condensed pieces

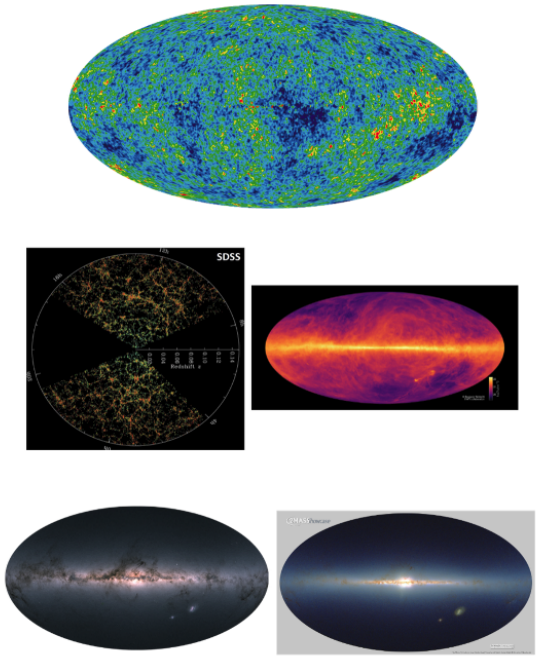

Figure 6. Top: a) A map of the Cosmic Microwave Background (CMB) temperature fluctuations. Credits: NASA / WMAP Science Team. https://map.gsfc.nasa.gov/media/121238/index.html Middle: b) The SDSS map of galaxy distribution in the Universe, with coordinates and a redshift scale added (left). Credits: M. Blanton and SDSS https://www.sdss4.org/science/orangepie/ and c) a sky survey with a colour scale added (right). Credits: Benjamin Winkel and HPI4I collaboration https://astro.uni-bonn.de/~bwinkel/research.html. Bottom: 2D Visualizations of sky surveys in different wavelengths, highlighting different structures. The image on the left (d) is taken in optical wavelengths (Copyright: ESA/Gaia/DPAC, CC BY-SA 3.0 IGO, acknowledgement: A.Moitinho) whereas the image on the right (e) is in infrared light (Credits: 2MASS/J. Carpenter, M. Skrutskie, R. Hurt).

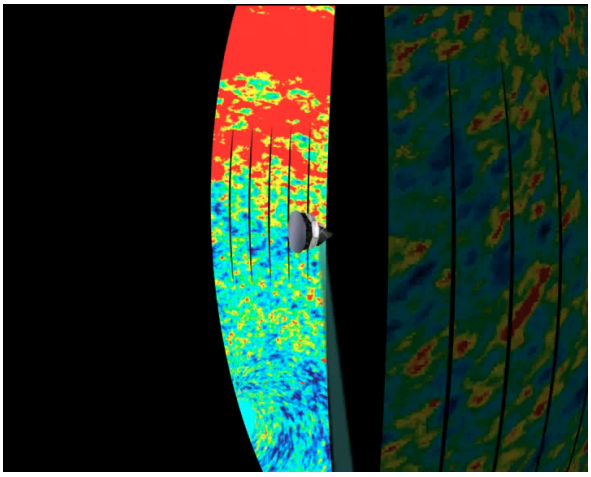

Figure 7. Screenshot from a video simulation that visualized the whole sky survey for CMB photons by the Planck satellite. Credits: ESA/Planck Science team.

found in lecture notes and also written language that is used to complement and unpack other semiotic resources. Along with mathematics, it is the system that is coordinated the most with other semiotic systems, as its affordances are very useful in unpacking information that is not present but can be inferred from other semiotic resources.

The affordances of language as a semiotic system have been well explored in the relevant literature, and we found them to be

```
#Temperature calculation
T_ONS1 = -slope**(-1)
T_ONS1_err = (slope**(-2))*A_err

print('Onsala-1 has a temperature of', T_ONS1, '+-', T_ONS1_err, 'K')

#Density Calculation

Z = 0.523*((T_ONS1)**(1.5)) #partition function
Z_err = 0.523*1.5*(T_ONS1**0.5)*T_ONS1_err

N_ONS1 = (10**(-4))*Z*np.exp(intercept)
N_ONS1_err = (10**(-4))*np.exp(intercept)*((Z_err**2) + (Z*B_err)**2)**0.5

print ('Onsala-1 has a density of', N_ONS1, '+-', N_ONS1_err, 'cm^-2')

plt.scatter(X, YONS1, label='Onsala-1')
plt.xlabel('$E_u/k$', fontsize=20)
plt.ylabel('$ln(N_u/g_u)$', fontsize = 20)
plt.errorbar(X, YONS1, yerr=YONS1_err, fmt='o', capsize=3, capthick=1)
plt.plot(X, slope * X + intercept, color='red', label = 'T = 37.6 K, N = 3.85 x $10^{14}$ $cm^{-2}$')
plt.xlim(10.0,90.0)
plt.ylim(33,39)
plt.legend()
plt.show()
```

Figure 8. Code for calculating Temperature and Density from data from molecular clouds observations and subsequently plotting a population diagram.

reflected in our dataset as well. Here are a few examples:

- Written language is mainly used to reveal information about the "participants" of the meaning making context: what objects are involved in specific process, which processes take place, what concepts are used to describe them. Written language is very good at this kind of meaning making and its affordances are highly leveraged that way.
- Bold, italics and font sizes were used to direct the reader's attention to important information regarding the topic discussed and its relevant aspects.
- Bullet point texts were often used in lecture notes to provide algorithmic-style instructions about performing a certain task. In this case, written language was often coordinated with mathematics.
- In some cases, written language was used to reveal information that moved out of pure astronomy and stepped into the realm of history of science and epistemology.
- Standalone texts in textbooks, especially in topics that explore the time evolution of the universe (big bang nucleosynthesis, last scattering surface), tend to adopt a narrative, almost story-telling style.
- Finally, in some cases, words such as adjectives, adverbs or catchphrases were used to "set the tone" and guide the reader towards a certain perspective of the topic being discussed.

ix) Code

Finally, code was identified as a semiotic system in its own right. Although it could be framed as a combination of a particular style of written language and mathematics, we believe that the way code combines these two systems makes it deviate radically from its constituent parts (written language and mathematics) to form a new semiotic system with its own particular affordances. In this category, we included code from Python scripts that were used in the courses we examined for our study.

Code was mainly used to either transduce meaning from one semiotic system to another (e.g. plotting a graph from numerical data) or to transform one semiotic resource to a different form without changing the system of representation (e.g., data reduction with astronomical images to create a science frame). What is interesting here is that these final products play an important part in assessing the validity of code (whether the task was adequately performed); this was often performed by comparing the produced resource with the theoretically expected form and subsequently checking the code itself for possible errors.

5 Discussion

5.1 The social semiotic perspective

We will now discuss our findings with regards to our overall purpose and aim. For the purposes of the study, we documented, categorised and analysed hundreds of semiotic resources and their meaning making functions. Why was that useful? And, most importantly, how can astronomy education researchers and practitioners gain new insights from our analysis? These are the kinds of questions we want to address here.

For example, due to social semiotics, we collected and analysed our data with the idea that anything can be a meaning making resource. This allowed us to steer our focus away from the very well researched and reoccurring topic of using various types of visualizations in astronomy education. Expanding on that, we looked at the whole range of semiotic systems and analysed what is not traditionally looked at within AER – written language, mathematics and code. Our analysis shows that meaning making with these semiotic systems is quite prominent in the teaching and learning of astronomy at the university level, thus their functions and overall educational use cannot be disregarded.

Another aspect of social semiotics that informed our study theoretically is the concept of affordance, and the notion that each semiotic system has its own affordances for meaning making. Armed with this hypothesis, we were able to analyse the resources in our data in greater detail. For example, this allowed us to further explore differences between graphs, diagrams and maps and the kinds of meaning making they are used to form. Consequently, this becomes an important aspect when it comes to understanding teaching and learning in astronomy. Having described our overview of the range of semiotic systems that exist and their affordances, we can now work towards identifying how to coordinate these resources in order to make disciplinary knowledge accessible to students.

5.2 Looking for what is hidden

In our findings section, we presented a detailed discussion of how different semiotic systems are used for meaning making in astronomy. We did this by discussing examples of how the affor-

dances of particular resources were leveraged successfully and the disciplinary meaning that was made available to students. However, it is not usually the case that meaning making is so straightforward. More often than not, meaning remains hidden and inaccessible to students, due to: omission or, conversely, information overload, the idiosyncratic character of representations, students' own alternative conceptions, etc. (Airey and Eriksson, 2019). Disciplinary meaning making is also complicated by the existence of multiple meaning potentials in a semiotic resource. This means that a resource might not only afford the intended disciplinary meaning, but other meanings as well. This makes noticing the disciplinary meaning at hand harder for students, who may simply be focusing on other aspects than those we intend. Adopting a social semiotic perspective can be very useful in uncovering these "hidden" aspects of meaning making "lurking in the background". Identifying specific aspects of meaning making and making them more explicitly noticeable to students can do a lot for disciplinary teaching and learning; hence, we believe that here lies another advantage of our social semiotic perspective. Below we illustrate this benefit with some examples that occurred in our data. These examples can also serve as directions for further research work:

- We identified that the use of mathematics was not restricted to simply manipulating equations for numerical calculation. We also identified an aspect of scientific reasoning, related to introducing new terms into an equation and connected with the questions of interest and the agenda of the discipline. In another study, we have explored even further how equations are manipulated for reasoning and how these affordances can be leveraged when using mathematics in physics and astronomy education (Kapodistrias and Airey, 2024).
- Our findings regarding the use of astronomical imagery reveal that their affordances are leveraged in two ways: their aesthetic features are used to raise students' interest and engagement and to mediate disciplinary knowledge at the same time. In an upcoming study, we aim to explore how these two different aspects of image use can facilitate or obstruct meaning making with images in Astronomy Education, and how other systems can be coordinated with them to mediate knowledge in a more effective way.
- Finally, we identified examples where semiotic resources were very dense in "appresent aspects" – aspects that disciplinary experts have learnt to perceive even though they are not directly visible in a particular representation (Marton and Booth, 1997). In order for students to learn to notice such appresent aspects it is crucial that they first experience them as present in the resources used. This raises the question of how such semiotic resources can be unpacked for students. Such resources need to be transformed or coordinated with others in order to make the appresent aspects explicit. In upcoming work, we aim to explore these ideas by examining a central resource that appeared numerous times in our data: the CMB map (figure 6a). This resource provides great potential for this type of work, as it is dense with disciplinary meaning, but most of this meaning is appresent.

6 Summary & Conclusions

Our aim in this paper has been to explore two research questions: what is the range of semiotic systems used in university level astronomy education (RQ1) and how these systems are used for meaning making (RQ2).

For **RQ1**, through our documentation and analysis of the representations used in lecture notes and textbooks, we identified nine distinct semiotic systems: **graphs, mathematics, images, diagrams, maps, written language, code, video simulations** and **hybrid**. Each of these semiotic systems was identified as a distinct representational format, that posits different affordances for meaning making.

For **RQ2**, we highlighted some exemplar representations in each identified system and analyzed their affordances for meaning making. In an attempt to synthesize these results, we can highlight the following:

- Visual semiotic systems (graphs, diagrams, images, maps, video simulations) utilize different elements (e.g., colour, shapes, contrast, cropping) to highlight objects and physical processes. However, meaning about what is depicted is often made by coordination with other semiotic systems like written language or mathematics. In some cases, when visual semiotic systems are used standalone, this information remains hidden.
- Non-visual semiotic systems (mathematics, written language) are prominent and highly important in university astronomy education. They posit affordances that cannot be leveraged by visualizations (e.g., revealing information about the participants of the meaning making context or the dynamics of physical processes); hence, they are often used in conjunction with visual semiotic systems to facilitate meaning making.
- Using hybrid systems of visualization (e.g., a graph over an image) may be useful for unpacking information that would not otherwise be available.
- Code is identified as a distinct semiotic system, despite being a hybrid between written language and mathematics. This is because code posits its own affordances for meaning making, due to its capability to transduce meaning from one semiotic system to another (e.g., from numerical data to a graph) or to transform semiotic resources within the same system (e.g., from raw images to a science frame).

In summary, in this study we have highlighted the complex processes of meaning making in the highly multimodal discipline of astronomy and how using a social semiotic perspective can helps us better understand those processes and their consequences in the teaching and learning of the discipline. In our view, the challenge of learning astronomy for a student lies in becoming fluent in using a set of semiotic resources and developing the ability to move meaning fluently across semiotic systems. Teaching astronomy then, becomes a question of working out which semiotic systems need to be coordinated, in which particular ways in order for their affordances to be leveraged so as to make disciplinary learning possible.

7 Declarations

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7.3 Competing Interests

The authors declare that they have no competing interests.

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