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RESEARCH ARTICLE

A board game ludography analysis for Game-Based Learning in Astronomy, Astrophysics and Space Science

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Abstract

Space exploration and astronomical objects are extensively used in modern board games. These games can be an entertaining way to present educational contents on Astrophysics-related topics, by acknowledging the importance and beauty of Space. However, careful consideration of mechanics, messages, and themes is required to achieve this goal. We present a classification system for the presence of Astronomy, Astrophysics, and Space Science in the 2000 most popular modern board games, where games are categorised according to their complexity and actual scientific contents. This initial mapping defines a potential Astronomy, Astrophysics and Space Science ludography, i.e. a set of board games for STEM educators to create learning activities about such topics, using easily attainable commercial products.

Keywords: Physics Education; Board Game; Game-Based Learning; Serious Games; Astrophysics; Space Science

1 Introduction

In recent years, many board games have been used to deliver educational contents and experiences, as Bell et al. (2009) and Bayeck (2020) among others underlined. According to Swertz (2019), we can define Game Media Literacy (GML) as the set of educational processes specific to games, including learning in games, learning about games, learning by game design and learning from games (for example, see McGonigal (2011)).

Whether they are professionally designed or developed by academics and educators, they can address students and the public about a wide range of technical topics. Just to give some examples, these games span from climate changes and environmental issues (Illingworth et al., 2019; Parekh et al., 2021) to the appreciation of plants (Friedersdorff et al., 2019), including literary disciplines as persuasive writing (Barab et al., 2012). Games immerse participants in their topics and require players to make decisions according to their knowledge, observations, and experiences (Schell, 2008). As educational tools, board games allow learning in a positive environment, forming new interactions with others, and allowing experimentation and exploration of an educational topic with the possibility of failing within a safe environment. Moreover, games can increase learning outcomes and positive emotions associated with the addressed topic (Chen et al., 2020), leading to higher engagement and participation. These properties are even more important when it comes to STEM disciplines (Science, Technology, Engineering, and Mathematics), which in general can cause estrangement or perhaps even negative emotions (Li and Tsai, 2013). Board games create also democratic access to learning since players create their own learning experience by freely playing within the well-defined game structure (Klopfer et al., 2009). We believe that a clear and immersive play experience is necessary to address an effective learning outcome, that will emerge as the result of a playful cumulative process (Petsche, 2011).

Indeed, considering games to be just a tool of information delivery is to miss their much more powerful ability to create emotions and experiences, which lead to reflectiveness, memorization, and growth in their participants. Games are also a natural habitat for approaching complexity, making it evident and affordable, being systems entirely readable and operable by players (Babini et al., 2021). Furthermore, (Gee, 2003) argued that in games players are keen to face difficulties, usually dreaded and avoided by students.

Games vary on a broad spectrum of design production, from the ones expressly designed for commercial uses to those developed by academics and researchers to convey their work. Relying upon the many benefits of using games in learning contexts, many researchers developed board games about several topics, such as physics (Cardinot et al., 2022) or evolution (Coil et al., 2017) and with different aims, such as promoting healthy nutrition (Amaro et al., 2006) or scientific careers (Murray et al., 2022).

In addition to that, games range from purely pedagogical tools - with little or no focus on play experience or game mechanics - to games that use themes and concepts as settings and frames, not aiming at delivering educational contents. In this context, a lot of scientific reviews and pedagogical studies have been conducted, to analyse the pros and cons of using games as educational tools (Randel et al., 1992; Laukenmann et al., 2003; Giannakos, 2013; Jabbar and Felicia, 2015; Lean et al., 2018).

In this context, the National Working Group on Creative Learning, Tinkering and Games of the Italian National Institute for Astrophysics (INAF) aims to go beyond the sole engagement or literacy promotion in Astronomy, Astrophysics, and Space Science (AASS, from here on). We focus on scientific citizenship, i.e. promoting the understanding of the scientific and technological research processes as a fundamental step towards democracy. In this framework, one of the tools we use is the application of game studies and Game-Based Learning (GBL) activities in educational environments.

Engaging with practitioners and teachers who already use games in their classrooms, we observed various approaches to implement GBL in educational settings. Some approaches involve commercial or educational games, while others revolve around the homemade creation of bespoke games, customised for specific educational purposes.

The challenge of designing tailored educational games lies in finding ways to embed educational purposes in the game without compromising the integrity and fun of the playing experience. The ideal scenario would be to bridge this gap, for example creating games that are both educationally valuable and comparable in quality to entertainment commercial games, thereby optimising the effectiveness and appeal of game-based learning in schools. This idea is precisely the motivation for the development of "Pixel - Picture (of) the Universe" (Inchingolo et al., 2023), a board game created by researchers of the Italian National Institute of Astrophysics (INAF) in collaboration with professional game designers of the GAME Science Research Center (GSRC). We envisioned the game design around specific literacy goals and foundational educational values. In this game, players manage an observation centre to study the Universe at different resolutions, facing scientific concepts integrated into the gameplay.

We are aware that teachers hardly have the time, the opportunity, and the expertise to design a game from scratch even when this option is attractive for them (Garris et al., 2002; Cardinot et al., 2022). Whitton (2012) suggested several possible solutions to this problem, such as including in the lesson playful techniques that proved to improve learning, or allowing the learners to be game creators themselves. Generally, this approach is less used because it requires in-depth knowledge of game design and GBL techniques that teachers do not possess.

Another attractive option is to build tools to help teachers and educators reinterpret the most significant commercial games from an educational perspective. Successful commercial games offer advantages over home-built games: they are playable, playful, available, popular, and have a professional look and feel. There are examples of commercial games that employ game design approaches to use mechanisms that directly evoke and support the educational message they seek to deliver. *Catan* [Kosmos 1995] is one of the most famous semi-collaborative strategic games in which players try to build settlements, cities, and roads, managing and trading limited resources. The mechanics of this game were recently adapted to describe the consequences of climate change and global warming (Illingworth et al., 2019) and are very interesting for educational purposes. In *Power Grid* [2F-Spiele 2004], players build energy factories to supply cities with power, creating a national supply network. Again, the mechanics of resource management and resource market for the energy factories of this game can be used in educational activities about climate change and energy consumption. In *Genotype: a Mendelian genetic game* [Genius Games 2021], players compete to collect experimental data on pea plants (their phenotype) and try to understand how these are determined by their genetic makeup (the genotype). The relationship between genotype and phenotype and the nature of genetic inheritance is at the game's heart**.** For this reason, this game can be used in educational contests for biology and genetic classes. These and similar commercial games can be easily implemented in game-based learning activities, with tailored analysis tools, as suggested by Ligabue and Farné (2020).

The difficulty in using commercial games is that they may not cover desired topics, or their scientific contents may be poor, not declared, or even not well-known by producers, making it difficult to find the right game for an effective educational activity. Moreover, teachers do not always have adequate expertise in AASS or the necessary game experience to choose the appropriate board game for their activities among the more than 100,000 games available in the market. In addition to that, according to our analysis, the literature lacks an exhaustive collection of commercial board games that can be used for GBL activities.

The goal of this work is to respond to this need for a guide of commercial board games that can be used for AASS GBL activities. Fulfilling an exhaustive and conclusive list would be very ambitious and perhaps not even possible, even because new board games related to these topics are released yearly. In this work, we present a board game ludography obtained by analyzing the most famous board games available in the market at the time of this publication, and selecting the ones that can be functional as central tools in educational activities for AASS disciplines and may help STEM educators find the right game for their GBL activity. We considered games in which the educational message is not necessarily explicit but perhaps unveiled by the game design and mechanics. In addition to that, this work also presents a method to analyse any board game and choose the most suitable ones for AASS GBL activities.

Figure 1. Astronomy, Astrophysics and Space Science (AASS) in board games. (a) *The search for Planet X*, in which players manage an observatory for the investigation of a hypothetical Planet X in the Solar System. (b) *Terraforming Mars*, where players assume the roles of corporations preparing Mars for human colonisation. (c) *Stellar*, in which players are stargazers, calibrating telescopes to observe celestial objects of several types. (d) *First Martians*, in which the players are part of a team of researchers on Mars that has to face specific missions.

The paper is structured as follows: Sec. 2 describes the characteristics we selected to study how board games can be related to AASS topics according to theme, mechanics, and contents. Sec. 3 explains how we converted these characteristics in a binary marker framework and describes the analysis method we used to argue if the considered games are suitable for AASS GBL activities. We present the results of this analysis in Sec. 4, while Sec. 5 summarizes the process and the results and gives some suggestions for AASS and STEM GBL activities using the results of our analysis..

2 Astronomy, Astrophysics and Space Science in contemporary board games

The ultimate goal of this analysis is to provide a tool to guide educators and teachers in selecting the most appropriate board games for their educational purposes. We believe that only a teacher, or possibly the students themselves under the teacher's guidance, can make the most appropriate choice. For some educators, it might be important to understand the various characteristics of each game. These include the balance between reality and fiction, the accuracy and coherence of the game's graphical and textual representations, how closely the game mechanics mirror Astrophysics processes, and what type of literacy the game aims to develop. By considering these factors, teachers can more effectively choose games that not only engage students but also complement their educational objectives.

In modern games, AASS are generally introduced as a theme. This means the game is set in Space; the player could be on a spaceship settling on Mars or in an adventurous quest among exoplanets. In principle, this could be achieved simply using appropriate illustrations and graphics. Some games dig deeper into the discipline using sophisticated and complex play elements, introducing tailored game mechanics or appropriate data contents, and matching the discipline and the game dynamics.

Table 1. The 25 binary *markers* we used to classify how a board game presents AASS *characteristics*, grouped in Reality vs Fiction (R), Space (S) and Time (T) coordinate, IAU topics (A), game mechanics (M), and game data (D).

Characteristic	Marker	Description
Reality vs Fiction	[R1] Science is real	The science presented in the game is based on actual scientific contents.
	[R2] Science is fiction	The science presented in the game is not based on actual scientific contents and includes fictional aspects (such as alien life, superluminal travel,...).
	[R3] Technology is real	The technology presented in the game is based on currently achieved technologies.
	[R4] Technology is realistic	The technology presented in the game is based on technologies currently under development and study.
	[R5] Technology is fiction	The technology presented in the game is too far to be achieved at present or includes fictional aspects.
Space coordinates	[S1] Earth	The game setting is on Earth or its satellite, the Moon.
	[S2] Rest of the Solar System	The game setting is in The Solar System.
	[S3] Universe	The game setting is in the rest of the Universe.
Time coordinates	[T1] Present	The game time setting is a real or realistic present.
	[T2] Past	The game time setting is an explicitly declared past.
	[T3] Future	The game time setting is the future.
AASS topics	[A1] Fundamental Astronomy and Astrophysics	The game presents fundamental contents of Astronomy and Astrophysics, like celestial body evolution, plasma physics, high-energy physics,...
	[A2] Facilities, Technologies and Data Science	The game presents technologies, systems, and processes to study the cosmos, like telescopes, research facilities, mechanisms for data visualization,...
	[A3] Sun and Solar System	The game presents objects of our Solar System, like planets, satellites, comets, etc.
	[A4] Exoplanets and Astrobiology	The game presents planets external to our Solar System, also related to the occurrence of conditions favourable to the development of life.
	[A5] Stars and Stellar Physics	The game presents elements of stellar life, as birth, evolution, and final stages, like Pulsars, black holes, etc.
	[A6] Interstellar Matter and Local Universe	The game presents components and processes of our Galaxy, the Milky Way, and our Local Universe (i.e. $< 4 \times 10^{20}$ *km*).
	[A7] Galaxies and Cosmology	The game presents cosmic components and processes beyond our Galaxy, like galaxy evolution, and the early stages of the Universe.
	[A8] Space exploration and rocket science	The game presents Historical and technological aspects of Space exploration, like Spaceships, Space travel, rockets, artificial satellites, etc.
Game mechanics	[M1] Astrophysics	Game mechanics implement Astrophysics contents, like stellar evolution and gravitational force.
	[M2] Space technology	Game mechanics implement technological development and Space exploration technologies, like rocket science, Space travel, and telescope usage.
	[M3] Research methods	Game mechanics implement elements of research processes and methodologies, like interdisciplinary collaboration, observations, and publications.
Game data	[D1] Contents	Scientific contents are correct and up-to-date.
	[D2] Terminology	Scientific terminology is semantically correct.
	[D3] Community	Research community is represented.

To represent this plurality of approaches, we created a framework of binary *markers* referred to specific *characteristics*, reported in Tab. 1 and discussed in the following. To develop our analysis system we took inspiration from Friedersdorff et al. (2019), in which the presence of plant elements in several board games is classified under three main characteristics: theme, game mechanics, and contents.

Following the same approach, we decided to study the presence of AASS *characteristics* in the game themes, mechanics, and contents. In particular, we decided to focus our analysis on addressing the level of fairness in the representation of Science and Technology, the place and time in which the game is set, the addressed AASS topics, the implemented game mechanics, and the correctness of represented contents (data). We are going to describe these *characteristics* in sections 2.1, 2.2, 2.3, and 2.4.

2.1 Real Science vs sci-fi

The first *characteristic* we want to address is the presence of authentic AASS scientific and technological elements in the studied games and distinguish these games from the scientific fiction (sci-fi) ones. For example, *Terraforming Mars* [Fryx Games, 2016], where players assume the roles of various corporations in preparing Mars for human colonisation, presents legitimate scientific and technological elements in the game or technology that is currently under development or study. On the contrary, *Gaia Project* [Feuerland Spiele, 2017], where the players take on the role of various civilisations for the colonisation of different planetary systems, is dominated by sci-fi elements. For this reason, we create five different *markers*:

1. Science is real (R1): The science presented in the game is based on actual scientific contents.
2. Science is fiction (R2): The science presented in the game is not based on actual scientific contents and includes fictional characteristics (such as alien life, superluminal travel, etc.).
3. Technology is real (R3): The technology presented in the game is based on current achieved technologies.
4. Technology is realistic (R4): The technology presented in the game is based on technologies currently under development and study.
5. Technology is fiction (R5): The technology presented in the game is too far to be achieved at present or includes fictional characteristics.

As we will exploit in detail in Sec. 3, we limit our analysis to

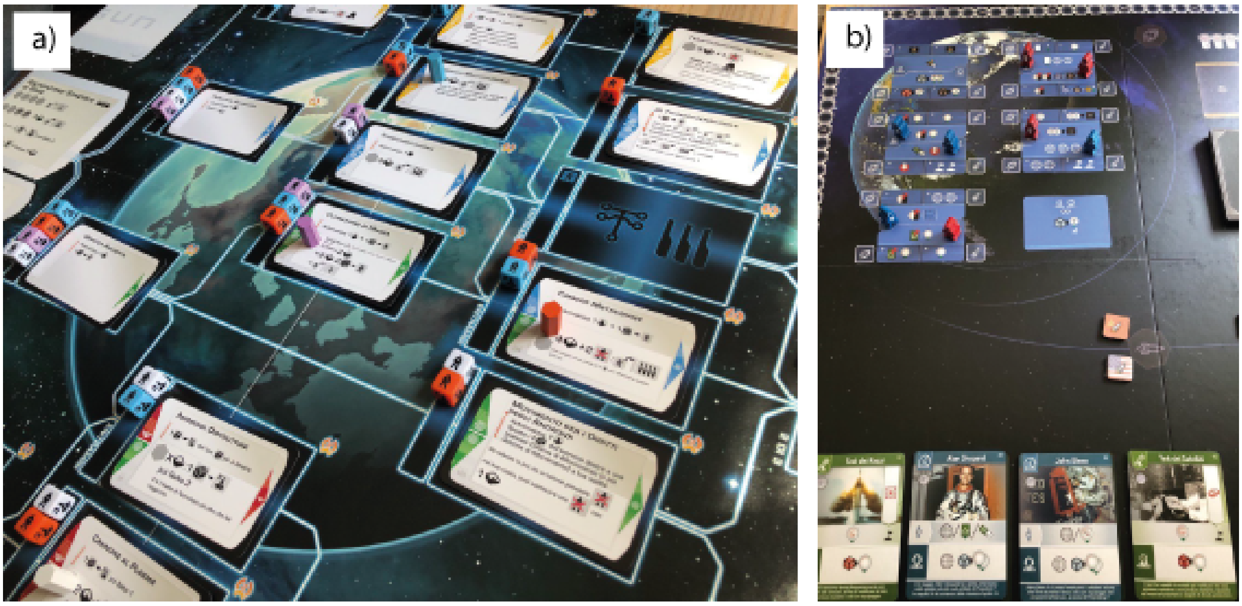

Figure 2. Different examples of technology development for Space exploration in (a) *Beyond the Sun*, in which players compete on a technology tree for technology development, and (b) *One small step*, in which players use a mechanics of workers placements to do actions and develop specific technology cards.

commercial board games classified as "Science is real". Regarding technology, we catalogue the games according to all three classifiers: real, realistic or fiction.

2.2 Space as a theme

A narrative often characterizes many modern board games, in the storytelling, the aesthetics, and the atmosphere the game simulates (Woods, 2012). These themes can be very diverse, from exploring Outer Space to navigating the Seven Seas as Pirates and everything in between. For example, in *Mission: Red Planet* [Fantasy Flight Games, 2015], the players take on the role of heads of mining corporations to conquer Martian soil. However, the *steampunk* mechanics and actions in the game are completely unrelated to actual scientific content or technology.

To better distinguish the games by theme, we classify them using a space-time set of coordinates of the game and catalogue the different AASS topics based on the International Astronomical Union (IAU) divisions. We will motivate this choice in Sec. 2.2.

We distinguish three different time frames for the game theme: Present (T1), Past (T2) and Future (T3). Simultaneously, we set three different Space regions: Earth and its satellite, the Moon (S1), the rest of the Solar System (S2) like Mars and other bodies, and the rest of the Universe (S3).

AASS topics

The mission of the International Astronomical Union (IAU) is to promote and safeguard Astronomy in all its aspects (including research, communication, education, and development) through international cooperation[1]. As a global standard for astronomers and astrophysicists, we used IAU Divisions [2] to catalogue game themes. We use IAU Divisions to have an internationally recognisable classification of AASS topics, aiming at creating a tool that can be used by the global community of researchers and educators in AASS to find suitable games for their GBL activities. In particular, we created the following topics based on IAU Divisions:

1. Fundamental Astronomy and Astrophysics (A1), which combines IAU Division A - Fundamental Astronomy - and D - High Energy Phenomena and Fundamental Physics;
2. Facilities, Technologies and Data Science (A2) - corresponding to IAU Division B;
3. Sun and Solar System (A3) - corresponding to IAU Division E and the themes of Division F regarding our Solar System;
4. Exoplanets and Astrobiology (A4) - corresponding to the rest of IAU Division F;
5. Stars and Stellar Physics (A5) - corresponding to IAU Division G;
6. Interstellar Matter and Local Universe (A6) - corresponding to IAU Division H;
7. Galaxies and Cosmology (A7) - corresponding to IAU Division J.
8. Space Exploration and Rocket Science (A8).

The "Space Exploration and Rocket Science" *marker* is added to focus on games with a strong presence of these aspects. Even if these aspects could have been connected to the Space industry or engineering-related technologies instead of being grouped with IAU AASS topics, we decided to include them here because they are very interesting in terms of introducing young people to AASS disciplines. An example is *Rocketmen* [PHALANX, 2021], where the players take on the role of Space industries in colonising the Solar System.

2.3 Space as mechanics

Besides its theme and narrative, a game is strongly characterized by its mechanics: the way it is played, for example, moving pawns, rolling dice, or placing cards, or with a combination of all these actions, combined to create richer experiences that can support the narrative of the game (Woods, 2012). For educational purposes, the presence of AASS *characteristics* integrated into the mechanics of a game is a perfect tool to trigger specific skills in players resulting in a deeper and longer-term effect. For example, *The search for Planet X* [Foxtrot Games 2020] simulates the management of an observatory to find a hypothetical

1 https://www.iau.org/administration/about/
2 https://www.iau.org/science/scientific_bodies/divisions/

Planet X in the Solar System. The game incorporates observation time as the primary resource in its mechanics, allowing the players to manage it as they like to get generic or more detailed information on their research.

In this work, we focus our analysis on three different characterizations of mechanics implementation that represent three central features related to AASS. The first is the introduction of disciplinary aspects in the game mechanics (M1). It could be, for example, the process of stellar evolution or the presence of fundamental forces in the game. An example is *High frontier 4 All* [Ion Game Design 2020], in which a player can travel across the Solar System. This game introduces Lagrange Points, stable points in the trajectories of rockets under the influence of two massive orbiting bodies, like the Earth and the Moon.

The second recurrent game mechanic introduces technological development and space exploration technologies (M2), like rocket science, space travel, and telescope usage. The aforementioned *High Frontier 4 All* and *The search for Planet X* are examples of games with these mechanics.

The third game mechanics family is the research processes, methodologies, and the scientific community's behaviour (M3); it may include scientific collaboration, observations, and publications. An example is *First Martians: Adventures on the Red Planet* [Portal Games 2017], in which the players take on the role of a team of researchers on Mars to solve specific missions, like food sustainability or developing construction materials.

2.4 Space as data

The relation between a game and the represented science is also in the data of the game like labels, card descriptions, and images. For our analysis, We include these elements in the game data *characteristic*. For this *characteristic*, we focus our attention on three *markers*: the correctness of the scientific content (D1), the scientific terminology (D2), and the representation of the research community (D3).

The correctness of the scientific contents is intended as the correct use of AASS scientific and technological elements in the game, like round-shaped and not sparky planets, stars not represented as pentagrams, and similar. An example is *SpaceCorps 2025-2300AD* [GMT Games 2018], in which the elements of the Solar Systems are accurately described and represented in the game data.

The correctness of scientific terminology is the appropriate use of labels and names in the game. For example, the correct use of the term *Solar sail* as propulsion mechanism in*High Frontier* or, on the contrary, the misuse of the term *sylvanite* for the martian regolith in *Mission: red planet*.

The last *characteristic* we consider is the representation of the research community in the game, in terms of the presence of researchers and technicians, correctness with historical data, and minorities and gender-balanced representation. An example is *One Small Step* [Academy Games 2020], in which the players take on the role of researchers and engineers of the USA and USSR during the Cold War Space Rush, using historical names of male and female representatives of the period.

This study aims to use the different *characteristics* outlined in this section to identify the representation of AASS in modern board games. To do so, we create a binary classification framework of *markers* based on these *characteristics* and analyze a restricted list of commercially and significantly successful games using these *markers*, as we are going to describe in 3. This *marker* framework analysis system is intended as an instrument to help educators make conscious and fruitful choices of games for their GBL activities on AASS themes and contents, providing learning experiences both enjoyable and enriching for students.

3 Methods

3.1 Binary markers

According to how the *characteristics* introduced in Sec.2 are implemented in the games, we create a list of 25 binary *markers* to evaluate the presence of AASS as themes, mechanics and data in a selection of board games. These *markers* are outlined in Tab. 1.

The overall aim of these *markers* is to identify games with a fair representation of science and technology about AASS topics.

To distinguish between games that represent authentic AASS scientific and technological contents and games that make use of sci-fi elements (Sec. 2.1), we introduce the R1 to R5 *markers*. In this way, we want to pinpoint games that give a realistic view of AASS, providing meaningful educational tools for GBL activities.

Concerning the theme (Sec. 2.2), we used the IAU Divisions to catalogue the various AASS topics addressed in the games using the *markers* A1 to A8. We also considered the space-time coordinates in which the game is set with the *markers* S1 to S3 and T1 to T3.

Regarding AASS *characteristics* in game mechanics (Sec. 2.3), we focus our research on three different aspects: the Science, the Technology, and the representation of the research methods (*markers* M1 to M3). Similarly, for the game data (2.4), we focus on the correct representation of contents and terminology, and also of the human community (*markers* D1 to D3).

We want to underline that evaluating also the presence of the human community helps to identify board games suitable for GBL orienteering activities, showing how the AASS research environment works, reinstating its complexity and humanity.

3.2 Analysis method

The analysis method is illustrated in Fig. 3. First, we selected a list of 2016 games as the initial sample of analysis, using the website BoardGameGeek (BGG, https://boardgamegeek.com/) as described further in this section. We named this initial sample "BGG top 2000". Since we are interested in games connected with AASS, we skim this initial list to select only the games that present at least one of the [A1-A8] AASS topic *markers* we introduced in Sec. 2.2. We called this selection the "Space sample". The result of this selection is a list of 116 games that correspond to the $\sim$ 5.8% of the initial selection. Subsequently, we focus our attention only on games in which science is real, filtering the "Space sample" using the results of the application of the [R1] binary *marker* "Science is real". The result of this filtering is a sample of 32 games ($\sim$ 1.6% of the initial selection) called "Science sample". As a last step, we analyze all the "Science sample" games, using all the binary *markers* presented in Sec. 2, together with evaluation of the complexity of the games (2, described in the following), the indicated player age, and duration. To properly evaluate the presence of AASS *characteristics* in commercial board games, each of us played all the "Science sample" games independently with other people, compiled the evaluation of the binary *marker* framework and then discussed together the results of the analysis to converge.

As aforementioned, we started our analysis by selecting more than 2000 games based on BGG. BGG is a universal crowd-sourced centralised repository for board gaming knowledge. BGG creates automatically a ranking for all the board games presented in their archive, based on the votes given by their users all around the world[3]. Since this website is constantly

3 The rank is created using a crowd-sourced mean user rating with corrections made to remove bias for more recent games or games with a low number of user votes. More details on the algorithm used can be found on

Table 2. The four complexity categories according to the BGG weight rating.

BGG weight	Game complexity	Description
1 to <2	Casual	A game suitable as a hobby, for people with no direct interest in board gaming. A game with little or no formation requirements, accessible to all players' levels.
2 to <3	Lightweight	An entry-level game for enthusiast or hobbyist gamers, that might be seen as complex by someone with little experience in board games. It might introduce some of the more complex elements of board gaming and require some formation to learn to play.
3 to <4	Medium weight	A sophisticated and detailed game with potentially rich and exhaustive rules and playing strategies, that would require a significant investment of time to learn to play, likely not suitable for non-expert gamers.
4-5	Heavyweight	A complex, deep, and detailed game suitable only for expert board gamers. The game may be enduring and require a considerable time investment to learn how to play efficiently.

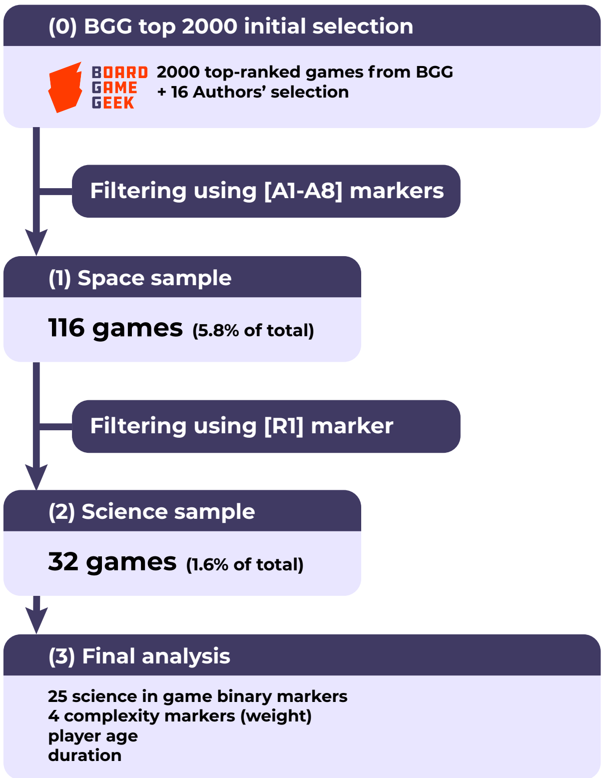

Figure 3. Flowchart of the analysis method: (0) selection of the initial sample "BGG top 2000", (1) filtering by the [A1-A8] AASS topic binary *markers* to create the "Space sample", (2) filtering by the "Science is real" [R1] binary *marker* to create the "Science sample", (3) analysis of the "Science sample" using the complete set of binary *markers*, the complexity value, player age, and duration of the game.

updated with new games released every week, we decided to focus our analysis primarily on games chosen from the top 2000-rated titles on BoardGameGeek (BGG) as of 17th February 2022 (the date when we started our analysis), corresponding to titles with a rank above 6 over 10. Subsequently, we added 16 board games that we tested and valued for their pertinence with the project and were not included in the original top 2000 ranking of BGG. These titles are marked with (*) in Tab. 3. We acknowledge the initial selection made for this work is not exhaustive of all the board games released so far. However, this selection represents a good estimate of board games much popular within the gamers community and for this reason still available in the market for educators to procure. We are currently monitoring the market releases to pinpoint new board games that can be included in future analysis.

Before discussing the results of this analysis, we want to introduce here the concept of "game complexity". This parameter describes how difficult the game is to play and understand. In BGG this concept is represented by the "weight" parameter, a number that spans from 1 (light games) to 5 (heavy games). The weight parameter in BGG is a crowd-based evaluation of the game that takes into account the difficulty of the rulebook, how much formation and training is needed to understand the game and its rules, the global time needed to play the game, how much strategic/analytical time is required to plan action, how much technical skill (math, reading ahead moves, etc) is necessary in the game, and how many times do you need to play before you feel like you "got" the game.

Table 2 defines how we group these weights for our analysis in four binary *markers*, i.e. *Casual*, *Lightweight*, *Medium Weight*, and *Heavyweight*, based on the BGG weight groups.

For example, *The Crew: quest for planet nine* [KOSMOS, 2019], in which you play a trick-taking card game to advance in space exploration, is a casual game (weight 1.99) due to the simplicity of its rules and actions and its relatively short duration of 20 minutes. On the contrary, the aforementioned *High Frontier 4 all* [ION games, 2020] is a heavyweight game (weight=4.82) since has a long and complex rulebook and requires a lot of math skills to play.

4 Results

In this section, we collect the results of the analysis on the "Science sample" guided by our *marker* framework, to understand how the "Science sample" games can be used in GBL activities connected to AASS and in which contexts. We remind that, by the construction of the sample, all the games have the R1 ("Science is real") binary *marker* and not the R2 ("Science is fiction") one.

the web page: https://boardgamegeek.com/wiki/page/BoardGameGeek_FAQ#toc13.

First, we present the results of the game themes (Sec. 2.2) using the space-time binary *markers* (T1-T3, S1-S3) and the AASS topic *markers* (A1-A8). We remark that by selection, all the games in the "Science Sample" have at least one binary *marker* A1-A8 flagged.

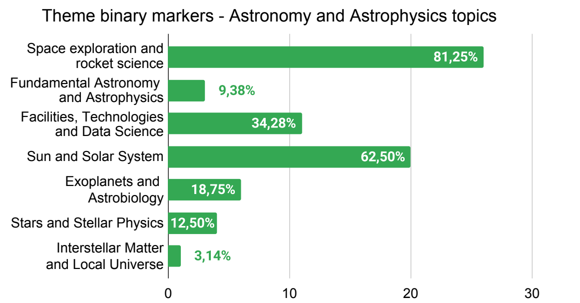

Figure 4. Distribution of the AASS topic binary *markers* in the "Science sample" games, with the absolute value (x-axis) and the corresponding percentage of the considered sample.

Figure 4 shows the distribution of the AASS binary *markers* A1-A8, introduced in Sec. 2.2. The most represented topic binary *marker* in our sample is "Space exploration and rocket science" (A8) with ~ 81%, followed by "Sun and Solar System" with ~ 63% (A3) and "Facilities, Technologies and Data Science" (A2) with ~ 34%.

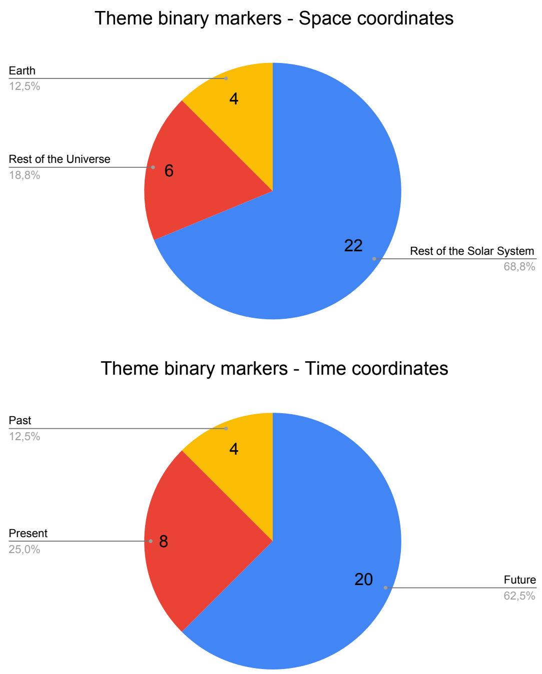

Figure 5. Distribution of the Space (top) and Time (bottom) coordinates binary *markers* in the "Science sample" games.

Figure 5 shows the distribution of the Space (S1-S3) and Time (T1-T3) coordinates binary *markers*. We observe that the majority of the "Science sample" games are settled in the Solar System - Earth excluded (S2 with ~ 69%) and take place in the future (T3 with ~ 63%).

We can conclude that there is a tendency in commercial board games inherent to AASS to theme with space exploration and, in particular, the exploration of the Solar System. Space exploration is currently a hot topic in mass culture (for example, with the hype connected to possible future moon landings with the Artemis projects or the participation in the Space industry of private companies like SpaceX, BlueOrigin, and Virgin). For this reason, we are not surprised to observe that most commercial board games are set in the future, as a tendency to "anticipate" through the board games the emotions and experiences of upcoming Space exploration.

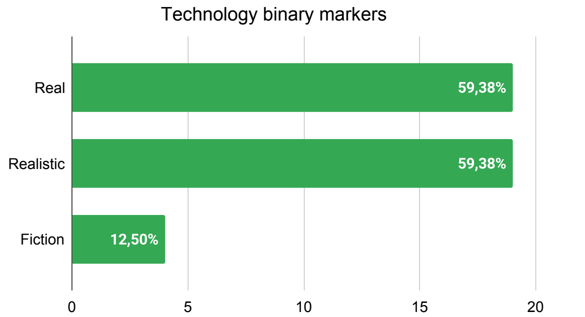

Figure 6. Distribution of the technology binary *markers* (R3-R5) in the "Science sample" games, with the absolute value (x-axis) and the corresponding percentage of the "Science Sample".

This interpretation is also corroborated by the analysis of the technology *markers* in the "Science sample" games since ~ 94% of games show at least one technology binary *marker* (R3-R5) (Sec. 2.1). In particular, ~ 59% of the "Science sample" games use real (R3) or realistic (R4) technology.

This result suggests that modern game designers are well aware of up-to-date technologies used in AASS environments, limiting their necessity to insert sci-fi technologies in their space exploration games (only ~ 13% of games).

We also analysed the "Science sample" game mechanics and data according to how these characteristics reflect three aspects of the AASS research: the scientific aspects, the technological aspects, and the human aspects.

As shown in Fig. 7, the ~ 78% of the "Science sample" games present at least one of the three mechanics *markers* (M1-M3) we defined. In particular, the most implemented mechanic is "Space technology" (M2) with ~ 66% of the selected games.

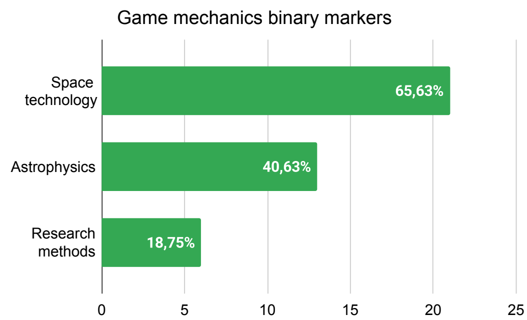

Figure 7. Distribution of the game mechanics binary *markers* (M1-M3) in the "Science sample" games, with the absolute value (x-axis) and the corresponding percentage of the "Science Sample".

We can conclude that the majority of the "Science sample" games are not limited to the use of Space elements for their theme, but also implement specific AASS concepts in their mechanics. In particular, consistently with what we observed in the theme analysis, the most implemented game mechanics

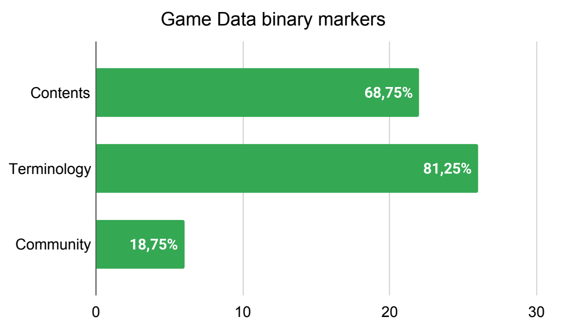

Figure 8. Distribution of the game data binary *markers* in the "Science sample" games, with the absolute value (x-axis) and the corresponding percentage of the "Science Sample".

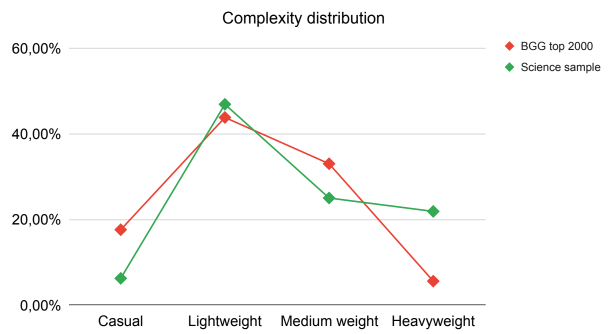

Figure 9. Normalized complexity distribution of the "Science sample" (green)and BGG top 2000 games (red).

concern the development and usage of space technology for exploration.

This is an important result in terms of GBL activities in AASS and STEM, since board game mechanics are crucial to fostering more effective learning processes, allowing players to engage deeper with the research processes, in particular with AASS ones, thus also stimulating specific scientific citizenship skills (Squire and Jenkins, 2003).

We also analysed the "Science sample" to assess the correctness of scientific contents, terminology, and the representation of the research community (*markers* D1-D3). We observe that the ~ 81% of the selected games show at least one of these *markers*.

Following these results, we point out that in the majority of the commercial games, AASS *characteristics* are not implemented as mere themes (the 100% of our "Science sample" by construction), but they are strongly implemented in both game mechanics (~ 94%) and contents (~ 81%).

As reported in Fig. 8 "Science sample" games present correct and up-to-date scientific contents (D1 with ~ 69%), and semantically correct terminology (D2 with 81%). This result is in agreement with what we observed before and supports our custom of using commercial board games for GBL activities since there is a high percentage of games that discuss actual AASS with the correct terminology.

Summarizing the results so far, we can conclude that games in the "Science sample" are good candidates for GBL activities about the Solar System, both from the astronomical point of view and to stimulate interest in exploring this part of our Universe.

From the analysis of research methods and community in both mechanics and data (respectively M3 and D3 markers), we observed that research methods are present only in the ~ 19% of the game mechanics; similarly, the research community is represented in only the ~ 19% of the game data.

We conclude that research methods and research community are not much represented in top commercial games, showing a lack of interest in portraying how the research world works, despite an adequate interest in properly representing AASS scientific and technological contents.

We strongly believe that representing the research community and processes in board games is a powerful tool to effectively and engagingly show how Science and Technology work, helping humanise the research and foster in this way interest in STEM disciplines (Li and Tsai, 2013). Due to this lack in commercial board games, as a research group in GBL education, we are designing new board games in collaboration with professional game designers, aiming to fairly depict our research environments (Inchingolo et al., 2023).

To help educators choose the right board game for their GBL activities for AASS topics, the analysis of themes, mechanics, and

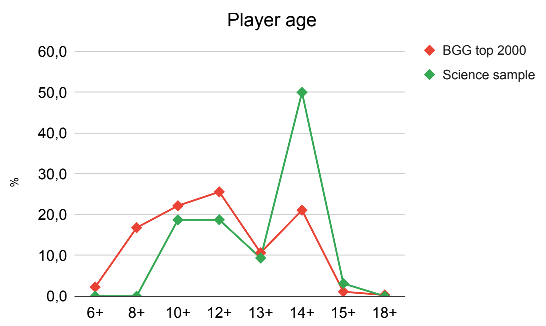

Figure 10. Normalized suggested player age distribution for the "Science sample" (green) and BGG top 2000 (red) games.

contents is not sufficient. While the previous results tell us that commercial board games are good candidates for GBL activities about the Solar System and Space exploration, we need more details on game complexity, duration, and player age to better argue their usability in educational contexts and properly design the GBL activity for the right target.

Figure 9 shows the normalized complexity distributions for the "Science sample" games (green line) and the BGG top 2000 games (red line). The majority of the "Science sample" games are lightweight (green line peaked at ~ 45%), consistently with the complete BGG top 2000 sample. This means they present a level of complexity that may require some explanations for neophytes but are entry-level games for enthusiasts and hobby players. However, we observe an abundance of ~ 16% heavyweight games in our "Science sample" compared to the BGG top 2000 distribution. This result suggests a tendency of some AASS commercial board games that use real science elements to be heavyweight, i.e. not easily accessible for neophytes, requiring more time to be studied, understood, and played.

Fig. 10 shows the normalized suggested player age distribution for both the "Science sample" games (green line) and the BGG top 2000 games (red line).

The BGG top 2000 games distribution has a broad span between "8+" and "14+" with a peak at "12+" suggested player age. Instead, the games in our "Science sample" mostly suggest playing ages of "14+" (50%). Moreover, we observe that no game in the "Science sample" targets a player age of less than 10 years old. We conclude that there is a lack of top-rated board games that use actual AASS and target primary school children. Instead, there is a tendency to develop games with actual AASS content targeting teenagers in secondary schools. This result oriented the kind of GBL activities we can do with "Science sample" games: since the lack of games for "8+" players, we cannot use these games to design GBL activities for primary

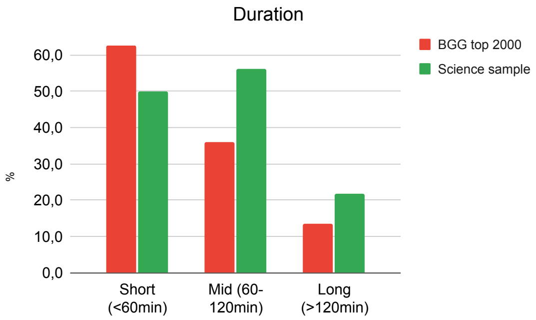

Figure 11. Game duration distribution for both the "Science sample" games (green) and the BGG top 2000 games (red).

schools. Instead, market games are strongly recommended for GBL activities in the middle ("10+" and "12+" games) and high schools (games with suggested playing ages "14+" or more). We notice a drop in both the distributions of suggested player age at the value "13+". We argue that this may be due to the tendency of the producers to use even numbers instead of odd numbers to indicate the lower limit of the suggested player age: few games expressly report a suggested player age of "13+" on the box. Indeed, for the few "13+" games in the BGG top 2000 list, the community of gamers sometimes suggests "12+" or "14+". For consistency in our analysis, we decided to maintain the value indicated by the producers, resulting in the pinpointed drop in the graph.

Figure 11 displays the normalized duration distribution for both the "Science sample" and the BGG top 2000 (red) games divided into Short - (less than 60 minutes), middle (between 60 minutes and 120 minutes), and long (more than 120 minutes) time range. If the game time range covers two or more of our partitions, we mark the game in all of them. As an example, *High frontier 4 all* has a time range of 30-240 minutes, so we insert it in all our time range partitions.

While the majority of BGG top 2000 games last less than 60 minutes (Short range), the majority of the "Science sample" games last way more than 60 minutes (Middle and Long ranges).

In general, to design GBL activities Short and middle-range games are preferable. This is mainly due to the organization of educational environments (schools, libraries, and more), that do not consent game sessions longer than 2 hours on average, including the game setting and preparation. On the other hand, organizing multiple sessions during which to resume the game is not suitable, due to the limited time that educators and teachers can or are willing to dedicate to GBL activities. Our results suggest that designing effective GBL activities using games in the "Space sample" may be challenging. Nevertheless, we promote the use of our "Science sample" games to design tailored GBL activities even if this may result in more difficult planning and time management since they prove to be very valuable in terms of contents and mechanics. We recommend that educators personally study and test each chosen game with the appropriate target group before designing the GBL activity, to understand how they can properly modify the game duration. Using this approach, the students play only a part of the game during the activity, and educators have the time to explain the rules of the game, assist the students while they play, and debrief with them at the end.

4.1 Possible limits of the analysis results

We report here some of the potential limits of our analysis method, and how they could have affected the results of this work.

First of all, we acknowledge the potential bias introduced by using the BGG ranking list and complexity values for getting the initial sample of games. The biases could lie in the fact that both these parameters are crowd-sourced. In particular, making these choices implies an intrinsic bias about the age and type of the target of the top-ranked games, since most BGG community users are young adults with deep knowledge and passion for board games regardless of their educational purpose. This bias may be the reason why the "Science sample" resulted in only the ~ 1.6% of the initial BGG top 2000 game selection. However, this was the initial purpose of this work, evaluating enjoyable commercial board games that could be used as educational tools, so we expect a low percentage of these titles in the top-rated commercial games. Anyhow, we tried to mitigate this bias by adding to our analysis some personally selected games that were already used as GBL tools by our network of AASS educators and experts. In addition to that, concerning the complexity value of the game, it is not defined taking into account our target of both educators and students. We recommend therefore to carefully study and personally test with appropriate target groups any selected board game before deciding to use it for a dedicated GBL activity.

Another possible bias is connected to the filtering of the initial sample to obtain the "Space" and "Science" samples. We could not possibly play all the 2000 initially selected games, and our filtering for the presence of AASS topics as a theme and for real representation of the Science is based on the public description and info of the games. We acknowledge that in this way we could have missed some games that have interesting AASS mechanics and data not declared by the producers. This could be a sign that market trends do not consider "appealing" to include scientific content in their game descriptions. Anyhow, we present this analysis as our best efforts and recognise that other groups of board gamers might argue over some of our decisions. We will welcome any possible comment or discussion about this specific issue.

5 Conclusion and Future Work

In this work, we analyzed more than 2000 board games to see their usability as educational tools for game-based learning (GBL) activities for Astronomy, Astrophysics and Space Science (AASS) in schools and other educational environments. We collected an initial sample with the top 2000 games according to Board Game Geek (BGG) ranking and added an Authors' selection of 16 games. We developed a system of 25 binary *markers* in which we evaluated the presence of AASS *characteristics* in our selection of board games as theme, mechanics, and data, discriminating games in which Science and Technology are real or sci-fi. Using this *marker* framework, we filtered the initial selection of games to obtain a sample of games with at least one binary *marker* in one of the 8 IAU AASS topics. We obtained a subset of 116 board games (~ 5.8%) from the initial list, naming this the "Space sample".

Then, we further restricted our sample by selecting the games that use actual space science, leaving behind any sci-fi game. In this way, we reduced our study to 32 games (~ 1.6% of BGG top 2000). We named this final selection the "Science sample". The complete list of these games is available in Appendix A.

In the end, we classified the "Science sample" using the complete set of binary *markers*, the complexity value, player age, and duration of the game.

From this analysis, we observed that the dominant theme in the "Science sample" is Space exploration (~ 81% of the sample) of the Solar System (~ 69%) that takes place in the future (~ 63%).

Since Space exploration is the dominant theme, there is a high presence of technology in these games (~ 94%), and most of this technology is real or realistic (~ 59% of the "Science sample").

We noticed that the presence of AASS themes is also well correlated with the implementation of AASS within the mechanics and the data of our "Science sample" games. In general, the ~ 78% of the games in the sample implemented correct scientific mechanics. In particular, the ~ 66% of the "Science sample" games implements Space exploration technologies as mechanics. Similarly, the majority of the games implement correct scientific contents (~ 69%) and terminology (~ 81%) in game data.

From this analysis, we concluded that the "Science sample" games have good scientific correctness in the game data and deep implementation of Space science elements in their game mechanics, particularly related to Space exploration of the Solar System. We recommended the usage of these games for GBL activities about the Solar System, both from the astronomical point of view and referring to Space exploration.

To better address the creation of GBL activities using the "Science sample" games, we also analysed their complexity, duration and target age. We found that "Science Sample" games are in general more complex than the average complexity distribution of the BGG top 2000 initial sample. In particular, there is an abundance of ~ 16% of heavyweight games compared to BGG top 2000 distribution. This result reflects also that "Science sample" games target mostly ages above 14 years old (50%, compared to the ~ 20% of BGG top 2000), and no games of this sample target children (8+ years).

This result opens further investigation to design board games suited for primary school children that can address actual AASS in their mechanics and data. Meanwhile, we suggest using the 10+ and 12+ "Science sample" games to design GBL activities for middle school teenagers, and the 14+ more complex games for high school GBL activities.

Similarly, the complexity of the games affects their duration: "Science sample" has longer games (more than 60 minutes) compared to the BGG top 2000 distribution (containing games with less than 60 minutes of playtime).

This result makes more challenging the planning of GBL activities in education environments when usually the time available for the entire session is around 2 hours due to school constraints. Nevertheless, we recommended educators to test the selected "Science sample" game for their GBL activity and reduce its playtime up to 60 minutes to leave time for discussion during the educational activity.

As a downside, we found a relative absence of representation of the research community in the "Science sample" games (~ 19%). Portraying the research community in a game is crucial to designing AASS GBL activities, showing how the research environment works, humanizing it to improve deeper scientific citizenship and also addressing the gender gap in STEM disciplines.

To help make up for this lack, our research group - in collaboration with professional game designers - created *PIXEL - Picture (of) the Universe*, a board game in which players manage an observatory and the researcher team, to study Space bodies while improving image resolutions (Inchingolo et al., 2023). In particular, we implemented in this game several professionals, like theoreticians, experts in observations, engineers, and project managers, to show the different roles in a research group.

In conclusion, we created a AASS board game ludography of 32 board games corresponding to the "Science sample" analysed in this work and reported in Tab. 3. This list can be easily extended by analysing new-released board games using the marker framework presented in this work. These games can be used for GBL activities about AASS topics. In particular, we suggest using this ludography to create educational activities around Space Exploration and the solar System with middle and high school students.

In future work, we will exploit the creation of GBL activities using a selection of the "Science sample" games, and we will test proper analysis tools to evaluate their efficiency[4].

6 Declarations

6.1 List of abbreviations

BGG - Board Game Geek
GSRC - GAME Science Research Center
IAU - International Astronomy Union
INAF - Istituto Nazionale di Astrofisica, National Institute for Astrophysics
AASS - Astronomy, Astrophysics, and Space Science

6.2 Ethical Approval (optional)

Not applicable

6.3 Consent for publication

Not applicable

6.4 Competing Interests

The author(s) declare that they have no competing interests

6.5 Funding

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6.6 Author's Contributions

Giannandrea Inchingolo - Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Resources, Writing - original Draft, Writing - review& editing; Rachele Toniolo - Investigation, Writing - review& editing; Stefania Varano - Conceptualization, Investigation, Supervision, Writing - review& editing; Alessandra Zanazzi - Funding Acquisition, Writing - review& editing; Andrea Ligabue - Investigation, Resources, Writing - review& editing; Sara Ricciardi - Conceptualization, Funding Acquisition, Investigation, Methodology, Supervision, Writing - review& editing;

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4 In the website `https://play.inaf.it/ludografia/` you can find detailed reviews of a selection of games from the "Science sample" and their usage in educational activities.

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A APPENDIX - Science sample games

In Tab. 3, we list all the selected games in the "Science sample" used in the analysis of this work with details on the reference age, number of players, duration, and the list of the binary *markers* we used for this analysis according to 1. By construction, all the games in the "Science sample" have the R1 ("Science is real") binary *marker* and not the R2 ("Science is fiction") one, so we omitted these two *markers* in Tab. 3 for clarity of reading. To summarize and ease the reading of this table and make it usable by practitioners and educators for their choices when designing GBL activities, we report here some notes, referring to the definitions we used in the paper (Tab. 1 and Sec. 2). The "Age" column indicates the appropriate target age declared by producers; the "Duration" column indicates the time duration declared by producers; the "Weight" column indicates the game complexity in a 0-5 scale, as described in Tab. 2); *markers* R3 to R5 indicate whether the represented technology is real, realistic, or fiction; *markers* S1 to S3 indicate where the action takes place (Earth, Solar System or the rest of the Universe); *markers* T1 to T3 indicate when the action takes place (past, present or future); *markers* A1 to A8 indicate what scientific contents are reported in the game, according to the IAU classification; *markers* M1 to M3 indicate whether the mechanics implement Astrophysics, Space Technologies and/or Research methods; *markers* D1 to D3 indicate whether the game materials and features use correct contents, terminology and/or representation of the scientific community. According to this table, for example, the game "Dawn on Titan" can be used for roughly 1 hour GBL activities about Sun and Solar System and Space Exploration in middle school classes, also implementing game mechanics for introducing Astrophysics and game features accurate in terminology and semantically correct, while the game "The search for Planet X" can be chosen for roughly 1,5 hour GBL activities in high schools, about Fundamental Astronomy and Astrophysics, Facilities, Technologies, Data Science and the Sun and the Solar System, with mechanics implementing astrophysics aspects and research methods and game features and materials implementing semantically correct and up-to-date data. Besides the suggestions retrievable from the table, we highly recommend testing the games personally and with the appropriate target to design effective and aware GBL activities.

Table 3. Complete list of the "Science sample" games selected for the analysis of this work, with details on the reference age, number of players, duration, and the list of the binary *markers* we used for this analysis according to Tab. 1. The (*) titles are the ones added by the authors and not originally present in the top-2000 ranking in BGG.

Title	Age	Players	Duration	Weight	R3	R4	R5	S1	S2	S3	T1	T2	T3	A1	A2	A3	A4	A5	A6	A7	A8	M1	M2	M3	D1	D2	D3
1969(*)	10+	2-5	90 min	2,32	X			X				X									X		X	X	X	X	X
Apollo XIII(*)	13+	2-4	45-75	2,67	X			X				X									X				X	X	
Aster(*)	12+	2-4	45-90	4,00				X			X			X			X					X			X	X	
Beyond the Sun	14+	2-4	60-120	3,10	X	X				X			X		X		X				X		X		X	X	
Cosmogenesis(*)	12+	2-4	60	2,62						X	X			X			X	X				X			X	X	
Dawn on Titan	10+	1-4	30	2,50	X				X				X			X					X	X			X	X	
Eminent Domain	10+	2-4	45	2,51		X				X			X				X				X		X			X	
First Martians(*)	14+	1-4	60-90	4,15	X	X			X				X		X	X					X		X	X	X	X	X
Ganymede	14+	2-4	20-40	2,32		X			X				X			X					X						
High Frontier	12+	2-5	180	4,34	X	X			X		X					X					X	X	X		X	X	
High Frontier 3rd ed.	14+	1-5	120-240	4,72	X	X			X				X			X					X	X	X		X	X	
High Frontier 4 all	14+	1-5	30-240	4,82	X	X			X		X					X					X	X	X		X	X	
Kepler 3042	14+	1-4	60-120	3,43			X			X			X				X		X		X	X	X		X	X	
Leaving Earth	15+	1-5	60-180	3,72	X				X			X			X	X					X		X	X	X	X	
On Mars	14+	1-4	90-150	4,66	X	X			X				X		X	X					X		X	X	X	X	X
One small step(*)	14+	2-4	90-120	3,13	X				X			X									X		X	X	X	X	X
Pocket Mars(*)	10+	1-4	15-30	2,33		X			X				X		X						X		X				
Project Mars(*)	14+	2-4	50-75	2,20		X			X		X					X					X						
Pulsar 2849	14+	2-4	60-90	3,25			X			X			X				X	X			X						
Rocketmen(*)	14+	1-4	30-90	2,59	X	X			X		X				X	X					X		X		X	X	
SpaceCorp: 2025-2300AD	12+	1-4	60-240	2,92	X	X			X				X		X	X					X	X	X	X	X	X	
Star realms	12+	2	20	1,94			X			X			X								X						
Starship Interstellar	14+	1-4	90-120	3,00	X	X			X				X			X		X			X	X	X	X	X	X	X
Stellar Horizons(*)	14+	1-7	120-240	4,03	X	X			X				X			X					X	X	X	X	X	X	
Terraforming Mars	12+	1-5	120	3,25	X	X			X				X		X	X	X				X	X	X	X	X	X	X
Terraforming Mars: Ares expedition	14+	1-4	45-60	2,91	X	X			X				X		X	X					X	X	X	X		X	
The Artemis Project	13+	1-5	60-75	2,81		X			X				X		X	X							X		X	X	
The crew: quest for planet nine	10+	2-5	20	1,99	X				X		X										X				X	X	
The Expanse Board Game	14+	2-4	60	2,77			X		X				X			X					X		X			X	
The search for planet X	13+	1-4	60	2,33	X			X			X			X	X	X						X		X	X	X	
Titan	14+	2-4	60-120	3,50		X			X				X			X										X	
Welcome to the Moon	10+	1-6	25-30	2,39		X			X				X			X					X		X				