ANALYZING STUDENT REASONING IN ASTROBIOLOGY MOOC WRITING

By

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Analyzing Student Reasoning in Astrobiology MOOC Writing

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ABSTRACT

This study examines student understanding and science reasoning within the Coursera MOOC *Astrobiology: Exploring Time and Space*. Using a mixed-methods approach, we quantitatively analyzed the correlation between essay scores and word count, alongside qualitative content analysis of reasoning and thematic patterns in student essays compared to expert writing. The methodology integrated detailed coding of essays, emphasizing factors like planetary characteristics, habitability criteria, and evolutionary potential. Results indicate that students often mirror expert-like reasoning when discussing well-defined scientific concepts such as surface water but tend to speculate more when dealing with uncertain or complex topics such as exoplanetary atmospheres. The study reveals significant differences in the application of scientific reasoning and the depth of content knowledge between students and experts, particularly in the extrapolation of life's potential on exoplanets based on limited empirical data. This research underscores the potential of MOOCs to democratize access to science education, emphasizing the importance of student writing and peer review as learning and assessment tools. By demonstrating the reasoning patterns that contribute to successful learning outcomes, the findings contribute to the understanding of educational engagement in science MOOCs, suggesting that while students are capable of approaching expert reasoning, targeted instructional interventions are necessary to bridge gaps in critical thinking and scientific understanding.

1. INTRODUCTION

As many people turn to online sources for learning, Massive Open Online Courses (MOOCs) offer a no-cost or low-cost, open-access avenue for students to learn from some of the best instructors worldwide. Many MOOCs are non-credit bearing, so they are ideal for those wanting to learn something outside of a traditional academic setting. Courses are moving into the MOOC format or being created especially for the MOOC format (Seidametova 2020). With this movement comes the question of how to assess the knowledge students gain through the multimedia format present in many MOOCs.

Since the 'Year of the MOOC'—2012, MOOCs have evolved from simple recordings of lectures from professors' in-person courses to multimedia, interactive online learning experiences (Pappano 2012; Oakley and Sejnowski 2019). Over the years, MOOCs have grown rapidly to reach 220 million learners and include 19.4 thousand courses in 2021 (Shah 2021). MOOCs have a variety of use cases and students have various reasons for taking them. One example is that MOOCs are important for high school students who can use these courses as a way to explore what college academics might be like for them in the future, while experiencing the learning in a low-stakes environment (Brahimi and Sarirete 2015; Cohen and Magen-Nagar 2016).

Science MOOCs were some of the first to emerge on the scene (Waldrop 2014), though their impact is under-researched (Yıldırım 2022). They are effective for learning in STEM courses, as students usually learn more effectively by practicing a topic multiple times. Students can watch MOOC videos several times before engaging with assessments, building on the idea that repetition of concepts leads to better retention of that concept (Ebbinghaus 1913; Voice and Stirton 2020).

Previous research within another one of our MOOCs - *Astronomy: Exploring Time and Space* (Exploring Time

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and Space)[1], saw a ceiling of 20% in completion rate, which is mirrored in the MOOC of focus for this paper - *Astrobiology: Exploring Other Worlds* (Astrobiology)[2]. Early engagement in the course with assignments that demand greater learner engagement, such as the writing assignments, was a strong predictor of success (Impey et al. 2016).

Our three MOOCs use peer review as the grading method for writing assignments, and this method is a widespread, scalable way to provide feedback and assessment to large numbers of students (Luo et al. 2014). Examining insights learned from our peer reviewed writing assignments, it was determined that the general course population and the population participating in these peer-graded assignments are different (Formanek et al. 2017). Despite issues with inconsistencies that arise through the peer grading process, peer grading is useful to help students develop reflection skills and take responsibility for their own learning. (Sluijsmans 2002; Reinholz 2016).

It was seen in Exploring Time and Space that longer essays received higher peer grades (Formanek et al. 2017), but its reliability hasn't been tested within other courses, and could be investigated in Astrobiology as well (Impey et al. 2024). Within this work, an interesting related point to the work from Formanek et al. (2017) that could be investigated is a comparison of length between essays. We plan to compare student essay lengths grouped by planet to determine if there are any trends, which could be indicative of quality or depth of thinking (Lonka and Mikkonen 1989). Participating in peer-graded assignments is one way for students to demonstrate their engagement with the course, and self-determination and self-efficacy are seen as the main motivational factors influencing course engagement (Ryan and Deci 2000; Formanek et al. 2017; Rabin et al. 2020). It's also a better way to examine student understanding and learning instead of relying only on quizzes that allow students infinite do-overs.

This work aims to analyze the differences and similarities seen in student and expert content reasoning in the Exoplanet Mission Proposal (Week 6) writing assignment from Astrobiology. We extend the expert-novice framework used previously in scientific contexts (Petcovic and Libarkin 2007) to MOOC assessments in §3. This study aims to explore the intricacies of learning and engagement within MOOCs by conducting a comparative analysis of reasoning patterns found in student and expert essays within the Astrobiology MOOC.

The research questions guiding this study are:

1) What is the relationship between score and word count in student essays, and does this relationship change with the choice of planet or the reasoning students utilize?

2) How do the reasoning patterns in student essays compare with those of experts in the field? What linguistic and thematic differences can be identified between student and expert essays?

To address these questions, the study integrates quantitative analysis of essay characteristics and scores with qualitative content analysis, providing a holistic view of learning outcomes.

Section 2 introduces the three MOOCs operated by our research group, details the specifics of the Astrobiology course and the writing assignment that is the focus of this work, and includes a literature review with an emphasis on past research that supports the analysis framework. Section 3 details the process of qualitative analysis for the writing assignments. Section 4 highlights crucial findings from the analyses and from examining strong student reasoning. Finally, Section 5 offers insights on the importance of this work for future MOOC research and design.

2. BACKGROUND

2.1. *Astrobiology: Exploring Other Worlds*

Our research group offers three MOOCs on Coursera covering astronomy-related topics. These include Exploring Time and Space, which delves into the latest in astronomical research; Astrobiology, focusing on the search for life beyond Earth; and *Knowing the Universe: History and Philosophy of Astronomy*[3], our newest course, which examines the philosophical underpinnings of astronomical discoveries.

The MOOCs feature video lectures encapsulating a broad range of astronomy content and a variety of assessment methods.

Out of these three courses, this research will focus on Astrobiology, as the writing assignments in this course are high quality and likely to contain enough explanation to be able to analyze student writing and reasoning.

Astrobiology is a MOOC created for the Coursera platform, and originally launched in April 2019.

The course contains 10 hours of video lectures and textual lectures on topics such as habitability, biology, exoplanets, and the search for extraterrestrial intelli-

[1] https://www.coursera.org/learn/astro

[2] https://www.coursera.org/learn/astrobiology-exploring-other-worlds

[3] https://www.coursera.org/learn/knowing-the-universe/

gence, among others. To assess student progress and the knowledge students gain through the course, there are smaller quizzes covering topics addressed in the video lectures, as well as four writing assignments that are spread through the six weeks of the course particularly in Weeks 2, 3, 5, and 6 (Impey et al. 2023). The grading breakdown for the course quizzes and writing assignments is shown in Table 1.

This paper will examine the fourth writing assignment from Week 6 of the course.

Table 1. Table detailing the percentage breakdown for the assignments and quizzes within Astrobiology: Exploring Other Worlds. The Week 6 assignment, which is the focus of this study, comprises the largest percentage of the student's grade.

Assignment/Quiz	Percentage
Week 1 Quizzes	8%
Week 2 Quizzes	8%
Week 3 Quizzes	8%
Week 4 Quizzes	8%
Week 5 Quizzes	8%
Week 6 Quizzes	8%
Final Project Quizzes	8%
Week 2 Writing Assignment/Peer Review	10%
Week 3 Writing Assignment/Peer Review	10%
Week 5 Writing Assignment/Peer Review	10%
Week 6 Writing Assignment/Peer Review	**14%**

2.2. *Week 6 Writing Assignment*

The Week 6 writing assignment serves as a cumulative assignment allowing students to utilize knowledge from the content they've learned through the entirety of the course. The assignment gives the students autonomy to choose what characteristics of an exoplanet or its host star are valuable to support their argument and are in their opinion valuable to the possibility of there being life and the benefits they could reap from visiting that planet. It also has students create a mock mission proposal, which enables them to connect their thinking to what scientists may actually do. The assignment offers a rich dataset for both statistical and thematic analysis, presenting an opportunity to deeply understand student learning and engagement. The prompt for this assignment is in §A.1.

Table A.2 shows the information given to students about the exoplanet candidates they can choose to write about in their assignments. Once students write their assignment draft, they are given grades from at least three randomly selected peers using an instructor-designed rubric. The content of this rubric is in §A.3. Our peer review process follows that detailed in Robinson (2001). While receiving their grades for the assignment, students also needed to grade 4 of their peers' work or face a decrease in final assignment grade of 20%. Students need to get a 11 out of 15 score or higher as the median of the grades received from their peers to pass the assignment.

2.3. *Literature Review*

MOOCs have emerged as a significant force in the quest to democratize higher education, offering a virtually limitless number of learners affordable and open access to higher education resources (Rambe and Moeti 2017). Initially, the conception of MOOCs was rooted in the vision of breaking down the traditional barriers of higher education, including high costs and limited accessibility, which have been major challenges for personal and social development (Rohs and Ganz 2015). The introduction of MOOCs by George Siemens and Stephen Downes in 2008 marked a pivotal moment in online education, aiming to extend learning opportunities globally (Downes 2008).

Despite the enthusiastic reception and substantial investments from various stakeholders, MOOCs have encountered challenges that question their efficacy in fulfilling their transformative potential. Concerns such as low completion rates and limited engagement in learning forums have highlighted the complexities of online learning at scale (Xing et al. 2019; Tang 2021a,b).

While MOOCs promised unparalleled access to education, their journey has been marred by challenges impacting their effectiveness. The low retention rate, characterized as a scale-efficiency tradeoff, and the minimal participation in discussion forums (Xing et al. 2019) underscore the difficulty of maintaining quality and engagement in such an open and scalable learning environment (Anderson et al. 2014; Brinton et al. 2014; Gillani and Eynon 2014; Brown et al. 2015).

These issues reflect both personal and contextual factors, including learners' motivations, prior knowledge, and the supportiveness of the MOOC environment (Tinto 1975; Hew and Cheung 2014).

Moreover, enhancing learner interaction through discussion boards, social media, and providing structured content can significantly improve engagement (Hew 2016; Tang 2021c; Tang and Xing 2022). A systematic approach to incorporating evidence-based assessment and feedback will also be critical in sustaining learner interest and participation (Prieto-Rodriguez et al. 2016).

The methodologies and impacts of peer and self-grading in educational settings have been extensively explored, revealing nuanced insights into their effectiveness. Jackson et al. (2018) delve into the comparison between peer and self-grading of practice exams, suggesting a critical evaluation of their benefits in fostering deeper understanding and learning autonomy among students. The significant impact of self- and peer-grading on student learning is emphasized by the role in enhancing students' engagement and metacognitive skills (Sadler and Good 2006). In a more focused examination of peer assessment in a MOOC context, Formanek et al. (2017) provide valuable insights into the scalability and applicability of these strategies in large-scale online learning environments, showcasing the potential of peer assessment to facilitate broad learning outcomes. Stefani (1994) further adds to this discussion by comparing the reliabilities of peer, self, and tutor assessments, underscoring the importance of diverse assessment methods in achieving comprehensive and reliable evaluation metrics. Collectively, these studies underscore the benefits of incorporating peer and self-assessment strategies in educational practices, highlighting their capacity to not only improve academic performance but also to cultivate essential skills in critical thinking and self-reflection.

The development and assessment of scientific reasoning skills in diverse educational contexts has garnered significant attention in educational research. Zulkipli et al. (2020) focused on identifying specific scientific reasoning skills among science education students, highlighting the need for targeted instructional strategies. Similarly, Westbrook and Rogers (1994) investigated the progression of these skills in ninth-grade students, emphasizing the foundational stages in early secondary education. On the higher education front, Ding et al. (2016) variations in scientific reasoning skills across different majors and institutions, suggesting that curricular and pedagogical differences significantly impact skill development.

Additionally, Hogan and Fisherkeller (2005) introduces the innovative use of interactive protocols to assess students' scientific reasoning through dialogue. This approach highlights the importance of real-time interactions and adaptive questioning in educational assessments, offering a dynamic method to evaluate and enhance students' understanding and reasoning processes within the context of ongoing dialogue.

Furthermore, the role of massive open online courses (MOOCs) in enhancing scientific reasoning and higher-order thinking has also been extensively studied. Wang et al. (2016) and Otto et al. (2019) both explored how MOOCs can trigger and foster complex cognitive skills like critical thinking, particularly in the context of global challenges such as climate change. Additionally, Pardos and Schneider (2013) provided an overview of the pedagogical frameworks and challenges associated with MOOCs, while Chen et al. (2020) specifically examined how misconceptions can affect student persistence and learning outcomes in these courses. Collectively, these studies underscore the potential of MOOCs to significantly enhance scientific literacy and reasoning across diverse learner populations, although they also highlight the complexities involved in achieving these educational outcomes.

Within this work, we define reasoning as the explanations students and experts use to support their choice of planet or refute the other planet options. This definition is closely related to the definition of reasoning from the Evidence-Based Reasoning Framework outlined in Brown et al. (2010).

Minor linguistic and content-related tests can also be used on the assignments. Within the MOOC realm, content analysis has been used on discussion forums to determine if students are engaging in critical thinking. Some tests used in O'Riordan et al. (2020) will be used in this work as a final comparison point between student and expert writing assignments.

Word count serves as an indicator of the level and intensity of participation and engagement. This is seen to have the strongest correlation in O'Riordan et al. (2020), and we anticipate that a correlation will emerge between the lengths of student essays and the scores they receive, as longer essays may indicate a higher level of engagement and therefore achievement.

By revisiting the foundational promise of MOOCs in light of the challenges and barriers they face, this literature review underscores the need for innovative solutions that align with the educational potential of MOOCs. As MOOCs continue to evolve, it is imperative to adopt a critical and reflective approach to their design and implementation. The pursuit of democratizing education through MOOCs requires a concerted effort to understand and mitigate the factors that hinder their success, thereby ensuring they can truly revolutionize access to higher education globally. Through careful analysis and the application of learner-centered design strategies, there is hope for MOOCs to fulfill their promise as a transformative educational tool.

These methodologies allow for a rigorous examination of differences between student and expert submissions, providing a robust foundation for the subsequent analysis detailed in §3.

3. METHODS

In compliance with ethical standards, the analysis protocol, including data collection and analysis methods, was reviewed and approved by the Institutional Review

Board (IRB) at the University of Arizona. Participants were informed about the study's aims, the voluntary nature of their participation, and the measures in place to ensure their privacy and confidentiality. All data were encrypted and stored securely, with access restricted to the research team.

Eligibility for inclusion was based on the completion of the relevant assignment and the peer grading process, and expressed consent to participate in the study. Participants in this study were drawn from students who successfully completed the Week 6 writing assignment within the designated study period. Experts were contacted and asked to submit writing assignments for comparison. They were given the same instructions and information from that class that was available to students.

The total enrollment in the course stood at 24,129 students as of December 20, 2023. Of these, 1,119 students completed the Week 6 assignment and completed a survey where they agreed to allow their class work to be used for research. The distribution of completed assignments across different hypothetical exoplanets is detailed in Table 2, while Figure 1 visually presents the proportion of assignments corresponding to each exoplanet.

For the qualitative analysis, a sample of 100 student essays was curated from the 1,119 completed assignments. Initial filtering criteria were based on a word count threshold: assignments were required to fall within the 250 to 750-word range as stipulated in the assignment guidelines. Subsequently, assignments were processed through an automated system to identify and eliminate duplicates. These initial steps narrowed the pool to 710 eligible submissions - 289 for Shishen-4, 136 for Maya-186, 127 for Tusi-1250, 111 for Lockyer-2, 34 for Cannon-1, 8 for Rubin-70, and 5 for Samos-270. These eligible submissions underwent a manual duplicate cut, as the automated cut before missed some duplicates or mislabeled the planet the student selected. In the final stage of sample selection, a decision was made to balance the sample equally between the exoplanets that experts had chosen (Shishen-4 and Maya-186) and those they had not (Tusi-1250, Lockyer-2, Cannon-1, Rubin-70, Samos-270). This balanced approach was intended to provide sufficient variety within the student responses. The resulting sample of 100 student essays is listed in Table 2.

For the purposes of this research, an *expert* is someone who has completed a Bachelor's Degree in a physical science. In addition, they are either currently enrolled in or have previously completed a Ph.D. in Astronomy/Astrophysics, Planetary Sciences, or a related discipline. The experts were solicited by the authors, and are all known by at least one of the authors or by former students that worked with the authors. Each expert was given a brief overview of the assignment requirements (word count, time, what their assignment will be used for) in addition to the prompt in §A.1 and Table A.2.

In the qualitative analysis, the application Dedoose[1] was used to organize and tag all student sample members and expert responses. Each assignment was given a descriptor, which included whether the assignment was written by a student or an expert, the word count, the score of the assignment (since the experts were unscored, their score is indicated by N/A), and the planet the assignment chose. Within Dedoose, there is a feature to create codes to tag portions of the assignments. The codes created were based both on the assignment rubric in Section A.3 and patterns seen when reading the expert responses. There were 10 major codes, and each assignment was coded using these major codes, with each code excerpt consisting of a sentence or a few sen-

Table 2. Table showing breakdown of students by planet within the completed Week 6 assignments and the selected sample. The table also shows the breakdown of experts by planet selected.

Candidate	Total Student Assignments (Percentage)	Sample Assignments (Percentage)	Number of Expert Assignments (Percentage)
Shishen-4	450 (40.21%)	34 (34%)	5 (71.43%)
Maya-186	225 (20.11%)	16 (16%)	2 (28.57%)
Tusi-1250	198 (17.69%)	19 (19%)	0 (0%)
Lockyer-2	173 (15.46%)	17 (17%)	0 (0%)
Cannon-1	52 (4.65%)	8 (8%)	0 (0%)
Rubin-70	17 (1.52%)	6 (6%)	0 (0%)
Samos-270	4 (0.36%)	0 (0%)	0 (0%)

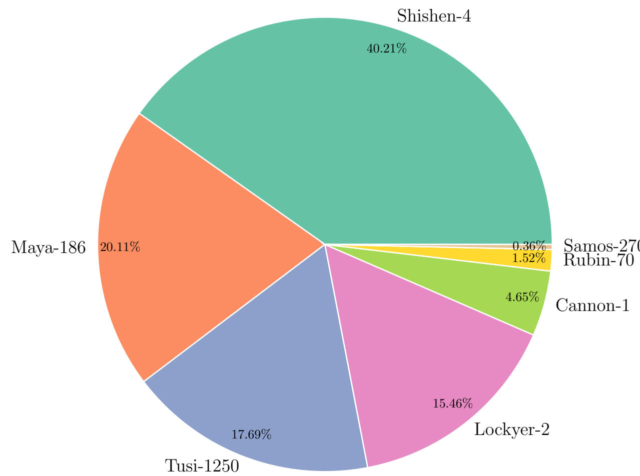

Figure 1. Piechart detailing the middle column of Table 2. This shows the breakdown for the students who completed the Week 6 assignment by their planet choice.

[1] https://www.dedoose.com/

tences that met the major code or added context to help the student/expert meet the requirements of that major code. Within these major codes are subcodes, which were created to differentiate between the reasoning that falls into one of the major codes. The subcodes also differentiate students/experts who may be hitting all the aspects of a rubric item at once from those who only meet portions. This allows for comparison of responses both in quality of the reasoning and the details included within the reasoning. Going back into the code excerpts for each major code, the subcodes were created based on what was seen from the student and experts. Each code excerpt from the major codes was given one or more subcodes. The codes are shown in Table 3. Dedoose has analysis tools that can show the connections between codes, subcodes, and descriptors for the assignments. Qualitative analysis using these codes and tools are shown in Section 4.

Table 3. Table showing the 10 major codes that were used in the qualitative analysis of student and expert assignments. The codes are abbreviated as shown in the brackets for the figures.

Thematic Code
(1) *Atmospheres* (Atmos.)
(2) *Earth Comparison* (Earth Comp.)
(3) *Process of Elimination* (Proc. Elim.)
(4) *Relevant Topics or Reasoning (not in prompt)* (Rel. Stuff)
(5) *Irrelevant Topics or Reasoning (not in prompt)* (Non-Rel. Stuff)
(6) *Evolution of Life/System Age/Geologic Eon* (Evo. Life/Eon)
(7) *Mass/Radius/Density and Type of Exoplanet* (Mass/Radius)
(8) *Spectral Type of Star/Orbital Distance of the Exoplanet and Habitability* (Spec. Type/Orbit)
(9) *Surface Water on the Exoplanet* (Surf. Water)
(10) *Travel Time to the Exoplanet* (Travel)

4. RESULTS

Our comparative analysis of student and expert reasoning in MOOC writing assignments has yielded several significant findings. We begin with an analysis of the relationship between score and word count in 4.1, offer insight into the planets and their characteristics in 4.2, analyze the code frequencies and code presence in the essays in 4.3, move to a qualitative examination of student and expert assignments by code for the planets the experts picked in 4.4.1 and 4.4.1, and finally analyze general themes for student assignments for the planets the experts did not pick in 4.4.3.

4.1. *RQ1: Relationship Between Score and Word Count*

Our initial quantitative analysis of the student assignments revealed that students who wrote longer essays generally received higher grades.

In Figures 2 and 3, we see how the word count in each assignment compares with the grades students received on the assignments. It's interesting to note that most of the students scored a perfect 15/15. Figure 4 uses a contour plot to show the relationship between the number of words written and the grades received across different planets. The areas with the most data points generally have higher scores, indicating that students who write more tend to receive better grades. This could be because of a leniency in peer grading—students might rate their peers' work more generously—or it might reflect that students are getting better at meeting the grading criteria in the rubric after multiple chances to revise their work. However, there are some exceptions to this trend, especially for planets like Shishen-4, Cannon-1, Rubin-70, and notably, the bimodal pattern for Lockyer-2.

Further analysis of the essay content reveals that, regardless of length or score, students and experts often use Earth as a point of comparison. In the shortest essays, between 250 and 300 words, the mentions of Earth and factors like Spectral Type and Orbital Distance are equally frequent. However, the highest-scoring students mention Earth more often, suggesting a deeper and more insightful analysis. As the essays get longer, the focus shifts slightly. For essays between 300 and 350 words, the main topics are Travel Time and Evolution of Life, with Earth still being a common reference. This trend of referencing Earth continues in longer essays, aligning with the approaches used by experts in the field.

Interestingly, as we look at even longer essays, Earth remains a key focus, particularly in high-scoring papers. Only in the 650 to 700 word range does another theme—Process of Elimination—become more prevalent than Earth comparisons. Beyond 700 words, Earth Comparison comes back into focus, evident in both student and expert essays.

Overall, the consistent reference to Earth across different planets, scores, and lengths of essays shows that both students and experts tend to frame their analysis in terms familiar to Earth. This makes sense considering the characteristics of the exoplanets being studied, which are similar to Earth, encouraging comparisons to our own planet as a way to analyze and understand these distant worlds.

4.2. *RQ2: Planet Selection*

While experts selected two planets in their assignments, student choices spanned all but one of the planet choices. Sixty percent of students selected the same two planets as all of the experts, and about 40 percent chose one of the four remaining planet options.

The predominant choice among experts (71.43%) and nearly half of the students (40.21%) was Shishen-4. This

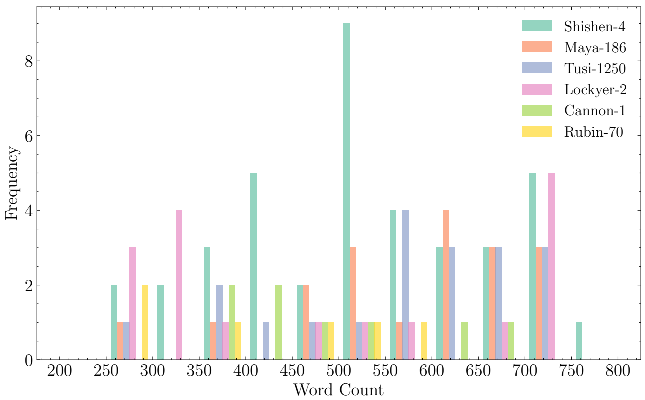

Figure 2. Word Count Distribution Across Exoplanet Choices in Week 6 Assignments. This histogram displays the variation in word count for student submissions, segmented by the exoplanet selected for their mission proposal.

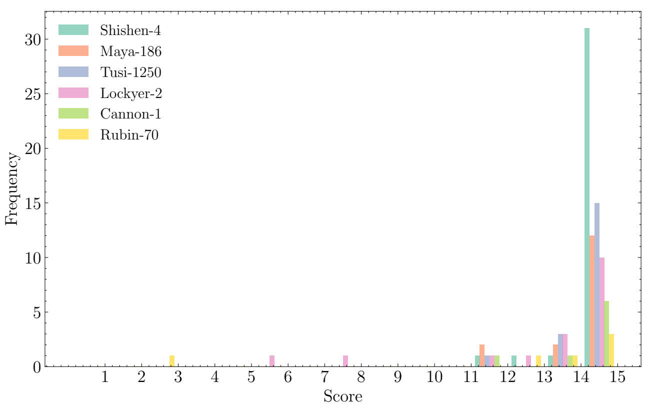

Figure 3. Score Distribution for Week 6 Assignments Based on Peer Review, Segmented by Exoplanet Choice. This histogram showcases the distribution of scores on the assignments from the peer review process, illustrating a trend towards high scores across different exoplanets.

planet stands out as the closest at 11 light years away, boasting an Earth-like orbital period, a placement well within the habitable zone of a solar-type star, characteristics of a Super-Earth, and an evolutionary timeline that aligns with the emergence of unicellular life on our planet.

Maya-186 garnered the second-highest interest from experts (28.57%) and students (20.11%). Despite being the farthest at 38 light years away, its solar-type star, shorter orbital period, and distance—still within the habitable zone—coupled with mass, radius, and density comparable to Earth, make it a contender for biological and advanced intelligence similar to that of our planet.

The third planet, Tusi-1250, was selected by 17.69% of students. Orbiting an M-dwarf, it is situated a mere 23 light years from Earth. While its mass and radius

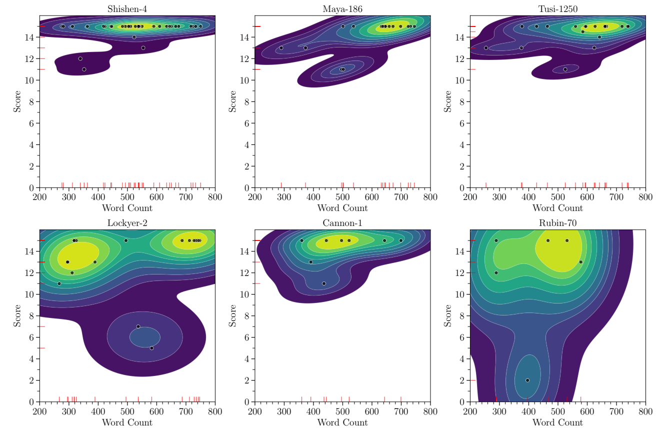

Figure 4. Correlation Between Word Count and Peer Review Scores Across Exoplanet Choices. This contour plot visualizes the nuanced relationship between the length of student assignments and the scores received through the peer review process, segmented by the chosen exoplanet.

slightly undershoot Earth's, its density is similar. The planet's intriguingly short orbital period and considerable age of 8 billion years invite speculation about the existence of super-terrestrial intelligence.

Lockyer-2 is the fourth choice at 15.46%, residing 17 light years away and circling a solar-type star. It is a planet with a low mass, low radius, and lower density, yet with an evolutionary stage conducive to the development of biological intelligence.

Fifth in line is Cannon-1, chosen by 4.65% of the student cohort. It lies 26 light years away, orbiting a solar-type star. Its orbital characteristics—period and distance—expand notably beyond Earth's, yet it shares a similar physicality and posits an age that sparks curiosity about advanced civilizations.

Rubin-70 emerges as the sixth selection, found in a near-Earth 13 light year orbit around a solar-type star. It sits just outside the conventional habitable zone, in what could be considered a cryogenic habitable zone, marked by its potential for icy conditions. With a larger mass and radius but low density, it presents a unique evolutionary stage that predates the rise of multicellular life on Earth.

Finally, Samos-270 was not selected by any students. It represents a stark contrast—a hot, Jupiter-like exoplanet with inhospitable conditions for humans. Situated 19 light years away in a solar-type star's habitable zone, its age of 2.7 billion years correlates with a key epoch in Earth's cellular evolution.

The variance in planet selections suggests that students were drawn to unique planetary characteristics rather than the practicality of human habitation. This divergence in choices illuminates the broader range of interests and curiosities among students compared to the more targeted selections by experts.

4.3. *RQ2: Code Frequency and Presence*

Students who chose the planets the experts selected engaged more with the Atmospheres, Earth Comparison, and Relevant Topics/Reasoning codes. Students who did not select the planets the experts picked had slightly elevated presence of the Evolution of Life/System Age/Geologic Eon and Non-Relevant Topics/Reasoning codes.

We analyzed the average code frequencies per essay as illustrated in Figure 5. This analysis showed that experts, on average, exhibited approximately twice as much engagement with codes related to Atmospheres, Earth Comparison, and Relevant Topics/Reasoning in comparison to student essays. We assume that experts have a more sophisticated understanding, so the lower frequency among students might indicate a less sophisticated understanding.

Additionally, experts demonstrated a moderate preference for delving into aspects pertaining to Spectral Type/Orbital Distance, Evolution of Life/System Age/Geologic Eon, and Surface Water in their essays. The comparative emphasis on these themes implies an expert inclination to accentuate these specific rubric items, potentially due to their significance in the field or their relevance to the assignment prompts.

Conversely, student responses tended to be more uniformly distributed across all codes. Notably, students who opted for planets also chosen by experts reflected marginally higher frequencies in the Atmospheres, Earth Comparison, Mass/Radius/Density, Process of Elimination, Relevant Topics/Reasoning, and Travel Time codes. This trend suggests an alignment with expert-level discourse and effort to satisfy rubric criteria.

Students who ventured beyond expert-preferred planets revealed a slightly elevated occurrence of Evolution of Life/System Age/Geologic Eon and Non-Relevant Topics/Reasoning. Such a pattern could hint at a divergence from higher-level reasoning, as these essays move into discussions aside from the assignment's core objectives shown by the rubric.

Interestingly, the frequencies of Spectral Type/Orbital Distance and Surface Water remained consistent across student essays, independent of whether their chosen planet matched expert selections. This uniformity indicates a shared recognition of the importance of these factors when contemplating planetary habitability, regardless of the respondent's level of expertise.

An additional metric that can be utilized in this analysis is the presence of the codes rather than the frequency of codes. Figure 6 allows for a more direct comparison, as we can see what percentage of the students and experts are including or not including a certain code. A larger percentage of the experts tended to use the Atmospheres and Relevant Topics/Reasoning codes when compared to all students, whether they chose the planets the experts did or not. These are both indicators of higher-level reasoning that students are not achieving as frequently within their explanations. We see that both groups of students had the Process of Elimination code appear more frequently than the experts, indicating that over half of the students in each group chose to approach their responses with the idea of eliminating other planets in mind. We see similar high frequencies of the codes for the five rubric items (Evolution of Life/System Age/Geologic Eon, Mass/Radius/Density and Type, Spectral Type/Orbital Distance and Habitability, Surface Water, and Travel Time) as well as the Earth Comparison code, indicating students are addressing those rubric items well and making connections back to Earth from what they learned in the course.

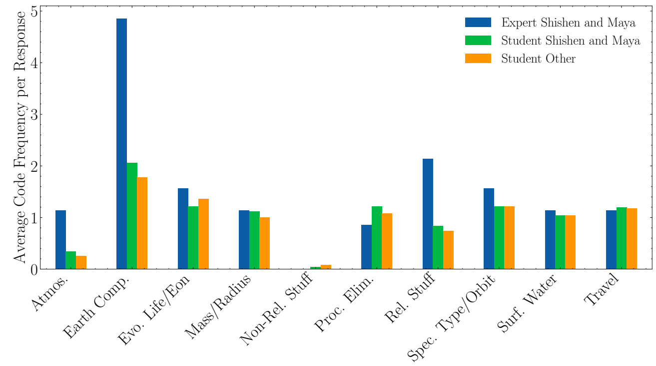

Figure 5. Normalized Code Frequency for Student and Expert Assignments. This histogram represents the normalized frequency of thematic codes across expert and student assignments, segmented by selected planets. Normalization occurred by taking the amount of codes in all assignments and dividing by the number of assignments in the bin. The colors indicate different bins by planet and expertise.

4.4. *RQ2: Content Analysis by Codes*

Students tend to jump to conclusions about a planet based on minimal data in their responses, engage in speculation about futuristic planets or topics they are unfamiliar about, make assumptions that planets are Earth-like despite what the other pieces of data might say, and make statements with more certainty. Experts tend to utilize more complex reasoning and look at a variety of factors rather than focusing on making large conclusions from just a single measurement or a few measurements.

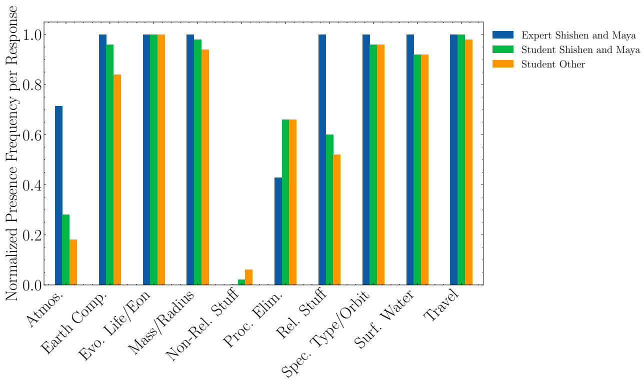

Figure 6. Normalized Code Presence for Student and Expert Assignments. This histogram represents the normalized presence of thematic codes across expert and student assignments, segmented by selected planets. Normalization occurred by taking the presence of codes in all assignments (1 indicates a code is present, 0 indicates the code is not present) and dividing by the number of assignments in the bin. The colors indicate different bins by planet and expertise.

4.4.1. *Shishen-4*

Atmospheres - Experts tend to discuss atmospheric conditions with additional complexity, which is reflected in their mentions of tidal locking, atmospheric composition, and stability. These responses reflect a deeper understanding of the complexity of exoplanetary atmospheres. Students lack some of the contextual depth seen in expert responses. **Student responses also reflect a less nuanced understanding of the scientific uncertainties by being more willing to make definitive statements about the planet's conditions.** Both groups frequently mention Earth-like conditions and the presence of an atmosphere conducive to life. **Students tend to provide more speculative details about the conditions necessary for life, such as magnetic fields and greenhouse gases, which are less frequently mentioned by experts.** Both groups emphasize similarities to Earth as a benchmark for habitability.

Earth Comparison - Students often assert physical similarities (mass, radius, density) to Earth, suggesting these factors may be directly indicative of habitability. Experts mention these similarities too, but often with caveats about the limitations of current knowledge or the need for further investigation. Students are more likely to speculate about life forms and geological epochs based on Earth's history by applying Earth's timeline directly to Shishen-4. Experts discuss biological and geological similarities, but generally underscore the uncertainty around the young age of Shishen-4, which may not support advanced life forms yet. Both groups discuss the importance of the host star's type and Shishen-4's orbital characteristics. However, experts emphasize the "goldilocks zone" and its implications for liquid water, and exhibit caution about overestimating Earth-like conditions. Students jump to conclusions about habitability based on a few Earth-like measurements, whereas experts discuss habitability in the context of many variables, including unknowns that could significantly affect life.

Evolution of Life - Both students and experts often reference the Archaean eon due to Shishen-4's age of 1.9 Gyr, basing their reasoning on Earth's own geological timeline. Students generally expect unicellular life due to the life on Earth during that eon. Experts also speculate on unicellular life but with more emphasis on the lack of complex, multicellular organisms due to the planet's young age. They are more cautious about the extrapolation from Earth's timeline. Students discuss the potential for future habitability and colonization, assuming Shishen-4 will evolve similarly to Earth. Experts focus more on the scientific exploration potential and the need for further studies to understand the planet's environment and biological potential. Experts are more likely to discuss the methodologies for investigating life (e.g., studying stromatolites or other early life forms), whereas students are more focused on the implications of these life forms for future exploration and colonization.

Mass/Radius/Density - Students tend to describe Shishen-4 as a "Super-Earth". They mention the planet's mass, radius, and density in comparison to Earth, suggesting it is similar but slightly larger and denser. Experts also refer to these characteristics but often with a focus on the implications of these characteristics on surface gravity, atmospheric retention, and habitable zone placement. Students often conclude that because Shishen-4 is similar to Earth, it might be habitable. They sometimes utilize these characteristics as a basis to discuss potential for water retention and life support. Experts are more likely to discuss these characteristics in the context of needing further exploration to confirm hypotheses about atmosphere and surface conditions. They are cautious not to overstate the habitability based solely on these parameters. Students make direct comparisons to Earth to draw conclusions about Shishen-4's nature, often assuming that similar physical characteristics straightforwardly imply similar environmental and habitable conditions. While experts make comparisons, they are more likely to highlight the need for empirical data and caution against assuming too much from analogous Earth data, recognizing the limits of current exoplanetary science. Experts tend to delve deeper into what the mass, radius, and density could imply about other planetary characteristics like atmospheric composition or core structure, which are not directly observable, but critical to understanding a planet's habitability.

Process of Elimination - Students tend to focus heavily on practical concerns like travel time (socio-economically and logistically) and basic habitability (presence of water or suitable temperature). They also often speculate about the presence of life based on minimal data, showing a preference for planets without advanced life to avoid potential conflicts. The experts discussions are more nuanced, regarding the spectral characteristics of the star and its impact on the exoplanet's environment. They are more cautious about assumptions regarding life and its development, emphasizing the need for more empirical data before drawing conclusions. They also discuss the star's life cycle and its implications for the planet's future habitability.

Spectral Type - While both students and experts focus on the spectral type and habitable zone, experts may provide more nuanced insights into the stability and longevity of G-type stars, reflecting a deeper understanding of stellar evolution. Several students and experts compare Shishen-4's orbit to Earth's, noting the slight increase from 1 AU (Earth's distance from the Sun) to 1.1 AU. This comparison underscores their expectation that Shishen-4's environment could closely mirror Earth's, particularly in terms of temperature and potential to hold liquid water. The frequent linkage between liquid water and life suggests a strong knowledge of traditional markers of habitability.

Surface Water - Several students and experts draw direct comparisons between Shishen-4's conditions and those of Earth, noting the similar spectral type of the host star, orbital distance, and potential for similar atmospheric conditions. These comparisons bolster arguments about the planet's suitability for life and potential colonization. Experts tend to provide more detailed explanations including precise data. They discuss the specifics of the habitable zone in relation to the star's spectral type and the implications for planetary temperatures and water states. Experts consider long-term evolutionary stability of the star and planet, including factors like stellar life cycle and its impact on the habitable zone over geological timescales. The language used by experts is more technical. For instance, they might discuss the "continuous habitable zone" or specific aspects of the star's luminosity and spectral energy distribution. They often mention the unknowns or uncertainties that could affect habitability assessments or the presence of water. Students demonstrate a strong but more general understanding of habitability. They correctly identify key criteria for habitability, such as the presence of liquid water and an orbit within the habitable zone. Their responses demonstrate understanding of concepts like the habitable zone or the importance of liquid water for life. The language tends to be simpler and more accessible. Students are likely to make direct comparisons to Earth to explain why Shishen-4 might be habitable, which shows a practical application of their knowledge but less technical depth. Students are more optimistic about the potential for life and habitability. They often discuss what could be possible on Shishen-4 rather than what is currently known or can be confidently predicted.

Travel Time - There is a notable pattern regarding the travel time to Shishen-4, which is often cited as 55 years at 20% the speed of light. Both students and experts seem to focus on this aspect as a critical factor in mission planning, considering the implications for crew life, technology requirements, and the feasibility of the mission. Both groups acknowledge that Shishen-4's relative proximity to Earth makes it a more attractive target for exploration due to the shorter travel time compared to other exoplanets. They recognize the significance of a 55-year journey in human terms and the importance of considering the human element of such a mission. Experts emphasize the current limitations of space travel technology, highlighting that even the closest exoplanets like Shishen-4 are challenging to reach with present capabilities. **Experts tend to focus more on the realistic aspects of space travel, such as the limitations of speed, the impacts on the crew's experience of time, and the need for sustainability and self-sufficiency on such missions.** Experts appear more cautious about the prospects of interstellar travel, often noting that substantial advancements in technology are required before undertaking a mission to Shishen-4. Students often speculate about the potential for developing new technologies to support life on the journey and consider the psychological and social implications for the crew. Students seem more willing to delve into hypothetical solutions for the challenges of long-duration spaceflight, such as cryosleep or multi-generational crews. The travel time to Shishen-4 is a central focus due to its implications for mission planning, crew well-being, and technological development. Students demonstrate a proactive approach by suggesting creative solutions, while experts offer a more measured perspective, emphasizing the current limitations and the need for realistic expectations for interstellar travel.

4.4.2. *Maya-186*

Atmospheres - Both experts and students agree on the importance of atmospheric conditions for habitability, citing a common concern about how stellar activity can affect habitability. Experts seem more cautious and highlight the limitations of current knowledge in predicting habitability, whereas students are more willing to speculate based on Earth-like characteristics. There's a discernible difference in the complexity of considerations, with experts discussing the implications of tidal locking and stellar activity in more detail, while students focus on the potential for an Earth-like atmosphere and water. Experts highlight the habitable zone in relation to the tidal lock radius, which could affect heat transport and atmospheric circulation. Concerns are raised about the activity of M stars and the potential for atmospheric stripping. The age of the planet is considered, with a specific reference to atmospheric composition during the Archean era and its potential implications for life support. Experts seem to consider a broader range of factors that could affect habitability, such as the presence of carbon dioxide and methane, and the potential lack of molecular oxygen. They appear to cautiously infer atmospheric composition from the planet's bulk properties. Students seem to exhibit optimism about life-supporting conditions on Maya-186. Students discuss the atmospheric conditions but with a focus on the possibility of Earth-like atmospheres and the potential for water in various forms. Additionally, there's an emphasis on geological activity and the presence of a magnetic field as indicators of a substantial atmosphere, demonstrating an understanding of how Earth-like conditions could be replicated. Some students express concerns about the impact of the host star on the atmosphere, specifically the potential for flares to strip away the atmosphere of planets orbiting close to smaller stars.

Earth Comparison - Both experts and students frequently mention Maya-186's similarity to Earth in terms of mass, radius, density, and its placement within the habitable zone. There is a consensus that these qualities make Maya-186 a promising candidate for habitability and potentially hosting life. Students approach the comparison with Earth in a more speculative manner, sometimes making direct assertions about the potential for life and human habitability. They extend their analysis to include the possible evolutionary paths of life on Maya-186, drawing parallels to Earth's history and biological development. There is a tendency among students to make assumptions about the existence of certain features like a magnetic field, geological activity, or advanced intelligence based on the planet's Earth-like characteristics. Experts emphasize the technical and scientific aspects, delving into specific details such as the planet's bulk properties, atmospheric composition, and geological age, which can inform the likelihood of life and human habitability. They tend to speculate less and base their analysis on the importance of the habitable zone and the potential for similar atmospheric conditions to Earth. Students are more likely to make direct comparisons to Earth's geological eras and evolutionary stages, often suggesting that Maya-186 might currently host life forms at a similar stage of development to those on Earth. Experts generally avoid such direct analogies to Earth's evolutionary history, possibly due to an understanding that life can take many forms and that evolutionary pathways could be drastically different on another planet.

Evolution of Life - Both groups use Earth's history as a model for hypothesizing the evolutionary state of life on Maya-186, assuming that a similar age could mean a similar stage of biological development. There is a shared expectation that Maya-186's age means it could have complex life forms, possibly similar to Earth's current or past life forms. Experts discuss the implications of Maya-186's age and its location within the habitable zone, hypothesizing about the possible presence of life. Experts tend to speak in terms of probabilities and possibilities, often using cautious language to convey the speculative nature of their conclusions. Experts also acknowledge the need for conditions like photosynthesis to have possibly led to an oxygen-rich atmosphere, conducive to life. Students often make direct comparisons to Earth's geologic eons and specific evolutionary milestones, suggesting that Maya-186 might currently host life forms at stages similar to those Earth experienced. Students tend to assert more confidently that certain types of life, including intelligent life, might exist on Maya-186, assuming a direct parallel in evolutionary development to that of Earth. Students tend to fill in these unknowns with vivid scenarios, while experts maintain a more cautious stance, emphasizing the conditions necessary for life rather than specific outcomes. The responses reflect a shared curiosity and optimism about the possibility of life on exoplanets.

Mass/Radius/Density - Both students and experts are drawing comparisons between Maya-186 and Earth based on the mass, radius, and density of the exoplanet, which are considered key factors in assessing the similarity of Maya-186 to Earth and its potential habitability. Experts refer to these physical properties to infer the potential for Earth-like gravity and composition, which could imply a solid surface and the potential for a stable atmosphere conducive to life. Experts make these assessments with a degree of caution, often relating the physical measurements to the potential for liquid water and habitability without overreaching in their conclusions. Experts understand that while mass, radius, and density are important, they are not the sole determinants of habitability. Other factors, such as atmospheric composition, magnetic fields, and stellar activity, also play critical roles. Students frequently assert that the similarity in mass, radius, and density to Earth categorizes Maya-186 as a sub-Earth or super-Earth. **They often extend this comparison to speculate about geological activity, atmospheric composition, and even the existence of a magnetic field, reflecting a greater willingness to make inferences from the data.** Some student responses connect the physical properties to the potential for life, with several mentioning the likelihood of Maya-186 having Earth-like biological evolution. Both students and experts link these physical properties to the potential habitability of Maya-186, suggesting that it might have similar surface conditions to Earth.

Process of Elimination - We see both students and experts using various criteria to narrow down their choices of exoplanets for potential exploration or colonization. Both groups recognize the importance of the star's type and the exoplanet's location within the habitable zone as primary criteria for elimination. The potential for tidal locking and its implications for life is a recurring theme in the elimination process. Experts tend to take a cautious approach by eliminating options based on substantial evidence or strong reasoning related to the viability for life, the age and activity of the host star, and the potential for habitable conditions. Their eliminations are based on critical factors that significantly impact the potential for supporting life, such as the intensity of radiation from the host star, the likelihood of the planet being tidally locked, and the stage of the star's life cycle. Students use a mixture of detailed scientific reasoning and speculative thinking to eliminate options. They often consider a wider range of factors, including some that are less critical or more speculative in nature, such as the exact mass and radius of planets compared to Earth, or the presence of specific geological eras that mirror Earth's history. There is also an element of future planning in the students' reasoning, where they consider the long-term evolution of life and the potential for developing advanced intelligence.

Spectral Type - Both experts and students are focusing on the star's spectral type and the exoplanet's orbital distance, which are critical in determining the habitability of an exoplanet. Both groups appreciate the significance of the star's spectral type and the exoplanet's orbital distance as crucial factors in assessing habitability. There is a common understanding that the star's lifespan and the potential for stable conditions are essential for supporting life. Experts seem to rely more heavily on established scientific principles and current technological understandings, whereas students are more likely to extend their reasoning into speculative territory. Experts consider the longevity and stability of K-type stars as advantageous for the development of life, with a specific focus on the habitable zone's (HZ) location relative to tidal lock radius and heat transport mechanisms. They emphasize the importance of the planet's position within the HZ, considering the type and energy output of the star to ensure conditions suitable for liquid water. Students show a good understanding of the relationship between a star's spectral type and its implications for the exoplanet's environment, recognizing the lower ultraviolet radiation from K-type stars and their wider habitable zones. They often detail the specific orbital distances in astronomical units (AU) and correlate these with the potential for life, drawing parallels between the exoplanet's conditions and Earth's. Some students dive into the star's lifespan and its potential to provide a stable environment for life over billions of years, suggesting long-term habitability as a significant factor in their considerations.

Surface Water - Both students and experts concentrate on whether the exoplanet's conditions are conducive to liquid water, given its importance for habitability. Both groups agree that the exoplanet's placement within the habitable zone is a strong indicator of the presence of liquid water. There's a shared understanding of the importance of a K-type star's habitable zone and how it may be favorable for liquid water. Students often integrate a broader range of factors into their reasoning. Experts, while also detailed, tend to express more caution, likely due to the complexities of confirming the presence of water on distant exoplanets without direct observation. Experts tend to provide a more cautious stance, often using phrases like "likely" or "if present" to describe the presence and state of water. They place significant importance on the planet's equilibrium temperature and position within the habitable zone to support their assertions about liquid water. Students generally seem more confident about the presence of liquid water, often directly asserting its abundance or presence due to the planet's placement within the habitable zone. They also consider additional factors like orbital distance and planetary characteristics (mass, radius, density) in relation to the host star's type to bolster their conclusions about surface water.

Travel Time - Experts and students discuss the time it would take to travel to the exoplanet Maya-186, the feasibility of such a journey given current or speculative future technologies, and the implications of these long travel times for human crews. Both groups are concerned with the time it would take to travel to Maya-186 and the technological advancements required to undertake such a mission. There is a consensus that interstellar travel to Maya-186 would be a monumental undertaking, involving either significant advancements in propulsion technology or methods to support human life over extended periods. Experts are more reserved and highlight the current limitations in technology, referencing ambitious yet theoretical spacecraft like the "Enterprise" capable of traveling at substantial fractions of the speed of light. They seem to understand the importance of such a mission, where the time scales exceed normal human lifespans, and consider advanced concepts like suspended animation. Students show a blend of optimism and pragmatism, acknowledging the impossibility with current technology but speculating on future advancements that could make the journey feasible. They ponder deeply on the human aspect, considering the emotional and social implications of generational ships or the use of hibernation. Some students propose multi-generational approaches or mention the psychological and logistical complexities of long-duration space travel. Students seem willing to delve into speculative and science fiction-like solutions.

4.4.3. *Other Planets Selected By Students*

Tusi-1250 - From the Atmosphere excerpts, it appears that the students are analyzing the habitability of Tusi-1250 based on its similarities to Earth, including geological activity, the presence of an atmosphere capable of retaining heat and water in a liquid state, and protection from solar radiation. Additionally, there is a consideration of how the greenhouse effect might influence the planet's climate and habitability. The references to specific technologies and spectral analysis suggest a sophisticated level of scientific inquiry.

The Earth Comparison excerpts compare Tusi-1250's mass, radius, and density to Earth, suggesting a similar rocky composition and potential for life. They consider its orbit around a cool M-type star, which places it in a habitable zone despite being closer to its star than Earth is to the Sun. The planet's greater age could imply advanced evolutionary development. They also hypothesize that Tusi-1250 may have liquid water and a magnetic field, which are crucial for life. Despite these promising signs, students note that assumptions are based on Earth's characteristics and stress the need for observational data to confirm their theories.

For the Evolution of Life excerpts, students speculate that Tusi-1250, being 8 billion years old, may host super-terrestrial intelligence due to its age, possibly in an Astrozoic eon of development. They suggest this advanced life could have capabilities beyond human understanding, including interstellar travel and communication. There is a sense of caution for any potential contact mission, recognizing the risks of encountering a civilization that may detect humans first. Overall, they see Tusi-1250 as a prime candidate for exploration, with the potential to offer humans unprecedented insights into advanced life forms and technologies.

The Mass/Radius/Density excerpts are consistent across the board regarding Tusi-1250's classification as a "sub-Earth" planet. They all note that it has a slightly smaller mass and radius compared to Earth, with a similar density, which suggests a rocky terrestrial nature. This likeness to Earth's physical properties suggests that Tusi-1250 may have similar gravitational and atmospheric characteristics, making it an intriguing target for the study of exoplanetary systems and the search for life beyond our solar system.

The Process of Elimination excerpts allow students to assess exoplanets for exploration, prioritizing those with feasible travel times, stable parent stars, and signs of advanced life. They prefer planets in later geological stages that may harbor intelligent life and resemble Earth in terms of size, density, and surface water, while discounting those with logistical challenges and those orbiting stars nearing the end of their life cycles. Planets with conditions unsuitable for multicellular life or that pose excessive technical challenges for human survival are considered less desirable for exploration missions.

Within the Spectral Type excerpts, students discuss the habitability potential of Tusi-1250, which orbits an M-type star. They emphasize the star's longevity, estimating its lifespan could be up to trillions of years, making it very stable. This stability increases the likelihood of life's development and evolution. Tusi-1250's orbital distance places it within the star's habitable zone (0.3-0.4 AU), the region where liquid water can exist on a planet's surface — a key criterion for supporting life. The students also note the abundance and stability of M-type stars, which could make planets like Tusi-1250 prime targets for the search for extraterrestrial life.

The students' excerpts in Surface Water strongly suggest that Tusi-1250, a sub-Earth exoplanet orbiting within the habitable zone of an M-type star at a distance of 0.3 AU, is likely to have liquid water on its surface. They highlight the importance of the habitable zone, where temperatures allow for water to remain in liquid form, a crucial condition for life as we know it. The students also consider the star's longevity and stability, factors that contribute to the potential for sustained biological evolution on the planet. There's an acknowledgment of the assumption involved, given that even on Earth, liquid surface water is not always prevalent due to climatic variations such as ice ages. Overall, they express a high probability of liquid water presence due to the exoplanet's favorable orbital position and conditions analogous to Earth.

For the Travel Time excerpts, the students are discussing the practicality of a space mission to Tusi-1250, which is 23 light years away from Earth. They acknowledge that traveling at 20% of the speed of light, the journey would take about 115 years, a span that exceeds a human lifetime. They speculate on future technologies like suspended animation or cryogenic sleep as potential solutions to make such long-duration space travel feasible. The students consider multi-generational crews or unmanned missions using advanced robotics as alternatives. Some also highlight the need for new propulsion technologies to reduce travel time. The immense distances and times involved underscore the challenges of interstellar travel and the importance of technological advancements for future exploration.

Lockyer-2 - In the Atmospheres excerpts, students evaluate the habitability of exoplanets, with Lockyer-2 emerging as a strong candidate due to its Earth-like atmosphere, sufficient oxygen levels for human respiration, and geological age indicative of potential multicellular life. Its proximity to Earth and position within the habitable zone make it a feasible target for exploration without the need for carrying additional oxygen supplies, suggesting easier logistical planning for potential human colonization.

For the Earth Comparison excerpts, the students' discussions center on the characteristics of Lockyer-2, which is described as a sub-Earth or Mars-like planet with significant geological activity and a less dense atmosphere. Its mass is about 10% of Earth's, with half the radius and lower density, but still potentially capable of sustaining geological activity. They speculate that Lockyer-2 is in the Phanerozoic eon, suggesting it could have an oxygen-rich atmosphere suitable for multicellular life, albeit less advanced than humans. The orbit of Lockyer-2 around a G-type star at 1.5 AU places it at the outer edge of the habitable zone, indicating a colder climate with liquid water and ice. The students use Earth's geological timeline as a model to predict the evolutionary stage of life on Lockyer-2, aligning with the later stages of the Phanerozoic eon, which supports diverse and complex life.

In the Evolution of Life excerpts, the students have deduced that Lockyer-2, an exoplanet with about 10% of Earth's mass and half its radius, is approximately 4.3 billion years old and in the Phanerozoic eon. They theorize that it hosts unicellular and multicellular life forms and potentially the beginnings of intelligent life. The planet orbits a G-type star with a long life expectancy, enhancing the prospects for stable, long-term evolution. The Phanerozoic era suggests the presence of complex life forms, although not necessarily as advanced as those found on Earth. There's consensus that the environment on Lockyer-2 could be conducive to life, with its conditions akin to Earth during a similar geological period.

The Mass/Radius/Density excerpts contain students' observations suggesting that Lockyer-2 is a sub-Earth type exoplanet with significant similarities to Mars, having roughly 10% of Earth's mass, about half its radius, and a density of 3.9 g/cm^3. This density, comparable to Mars, implies a rocky composition capable of sustaining an atmosphere. Despite its smaller size, which typically suggests reduced geological activity, its density indicates it may retain some internal heat and geological processes. The exoplanet's mass and size classify it as sub-Earth, likely with a surface and possibly ice bodies, fitting for a body within the habitable zone. However, its reduced mass and size compared to Earth could impact its atmospheric density and the extent of its geological activity.

For Process of Elimination excerpts, the students' discussions focus on eliminating exoplanets that are not ideal for exploration or colonization based on various criteria such as habitability, distance from Earth, evolutionary stage, and potential for human survival. They agree that Samos-270, being a hot Jupiter, and Rubin-70, located in a cryogenic zone, are unsuitable. Cannon-01 is also ruled out due to its star's potential instability. Shishen-4, while close and in a habitable zone, is considered too young for complex life. Tusi-1250 and Maya-186, though in the habitable zone with potential for advanced life, are deemed too distant for current space travel capabilities. Lockyer-2 emerges as a candidate due to its suitable geological age and habitability potential, despite being less evolved than some other exoplanets. The students' selection process emphasizes practical considerations for human exploration and the desire to find a balance between scientific interest and the feasibility of reaching and studying the exoplanet.

The Spectral Type excerpts are centered around Lockyer-2's star's spectral type, which is a G-type like our Sun, with a stable life expectancy conducive to sustaining life. Lockyer-2's orbit is 1.5 AU from its star, which places it within the habitable zone, suggesting potential for liquid water and a climate somewhat colder but comparable to Earth. Despite being on the outer edge of the habitable zone, the planet's position is still considered favorable for life as we understand it. The students discuss the possibility of Lockyer-2 having a Mars-like climate due to its position and characteristics. They also consider the age of the star and its impact on the evolution of life, highlighting that Lockyer-2, being 4.3 billion years old, would likely have ample time left for life to continue developing or for human colonization.

For the Surface Water excerpts, the students discuss Lockyer-2's suitability for surface water, noting its position well within the habitable zone of its G-type star, which is comparable to our Sun. They suggest that although Lockyer-2 is at the outer edge of the habitable zone (1.5 AU), the conditions are still favorable for liquid water to exist. Some speculate that the planet's surface could have both liquid water and ice, particularly at the polar regions, due to its colder climate akin to Mars. The planet's smaller size and distance from its star imply it might not be very hot at the core, supporting the existence of ice as well as liquid water. The students agree that Lockyer-2's conditions — namely, its orbital distance from a stable, long-lived star — are conducive to the presence of surface water essential for life, increasing its potential for supporting biological activity and possibly multicellular organisms.

In the Travel Time excerpts, students note that Lockyer-2 is approximately 17 light-years away from Earth, meaning it would take around 85 years to reach the exoplanet even if traveling at 20% of the speed of light. They delve into the formidable challenges and profound possibilities of this journey, recognizing the necessity of cutting-edge propulsion and life-extension technologies like cryogenic sleep. They underscore the imperative of sustaining the crew's life support systems, attending to both physical and psychological needs over the mission's lengthy duration. The conversation is imbued with a forward-looking vision for humanity's odyssey to new worlds, underpinned by a sense of responsibility as we approach the prospect of discovering and possibly interacting with extraterrestrial life. Moreover, they are attuned to the profound ethical dilemmas posed by interstellar travel, including the consequences of sending humans on potentially irreversible missions to distant worlds.

Cannon-1 - Only one student had an Atmospheres excerpt, which addressed that atmospheric dissipation would not occur due to high UV radiation.

For the Earth Comparison excerpts, the students' analysis is centered around its Earth-like qualities, considering its mass, radius, density, and potential to host life. With a mass 1.3 times and a radius 1.1 times that of Earth, the exoplanet falls into the category of a 'Super Earth.' Its density, comparable to Earth's, suggests a rocky composition, raising the possibility of it having bodies of liquid water and a conducive environment for life as we know it. Some students speculate that, given the planet's age and conditions, life there could have evolved to be more advanced than on Earth, and that the biological and intelligent life forms, if they exist, may have surpassed human capabilities. These discussions also draw parallels between the geologic timelines of Earth and Cannon-1, theorizing that similar stages of life development could have occurred. However, the significant distance from Earth to Cannon-1 presents challenges, as travel at 20% the speed of light would still take a considerably long time from a human lifespan perspective, highlighting the enduring allure and excitement of discovering extraterrestrial life.

In the Evolution of Life excerpts, students engage in a speculative discourse about the potential for advanced life on the exoplanet Cannon-1, hypothesizing based on its significant age of 8.6 billion years. This age suggests it is in the Astrozoic eon, a period when, by drawing parallels to Earth's history, all forms of life including unicellular, multicellular, intelligent, and possibly super-terrestrial intelligence could have evolved. The students posit that, given this lengthy span of time for evolutionary processes, life forms on Cannon-1 might be far more advanced than humans, having had the opportunity to develop complex societies and technologies beyond human capabilities. There's a sense of wonder in their reflections on the diversity and advancement of life that could be found on such an ancient planet, acknowledging that the inhabitants of Cannon-1, if they exist, would be profoundly different from life on Earth, both in intelligence and morphology.

For the Mass/Radius/Density excerpts, students point out that with a mass 1.3 times, and a radius 1.1 times that of Earth, as well as a density of 5.2 g/cm^3, Cannon-1 falls into the category of a 'Super Earth.' Its mass and radius being larger than Earth's, and its density being slightly less than Earth's 5.52 g/cm^3, indicate that it is a rocky planet rather than a gaseous one like a mini-Neptune. These characteristics lead the students to suggest that Cannon-1 could be conducive to life, potentially even advanced life, given its substantial mass and density that are close to Earth's, implying a stable, solid surface environment.

The Process of Elimination excerpts weigh Cannon-1 against other candidates like Maya-186 and Shishen-4. They consider factors such as travel time, with Cannon-1 being 26 light-years away, making it a more viable option than Maya-186, which is 38 light-years away. Despite the less stable F-type star of Cannon-1 compared to the K-type star of Maya-186, the students seem to favor

Cannon-1 due to its age and the potential for advanced life. The decision is also influenced by the level of life evolution on these planets, with Cannon-1 seemingly offering the possibility of intelligent life, as opposed to the less developed life forms on the other candidates, which are still at multicellular and unicellular stages. This suggests that for the students, the presence of potentially intelligent life is a significant factor in prioritizing one exoplanet over others for exploration and travel, even if it means overcoming greater challenges.

For the Spectral Type excerpts, students discuss the spectral type of Cannon-1's star and its implications for habitability. They note the star is of F-type, which is known for being stable for billions of years, thus providing a consistent energy output that could support the evolution of life. The exoplanet's orbital distance is 2.1 astronomical units (AU), comfortably within the habitable zone for an F-type star, which ranges from 1.4 to 2.8 AU. This position within the habitable zone suggests that liquid water could exist on its surface, further indicating the potential for life. The students understand that life's evolution requires significant time, and given the F-type star's long lifetime, there could be advanced life forms on Cannon-1. They highlight the importance of a planet's orbital distance in relation to its star's habitable zone when considering the possibility of life.

In the Surface Water excerpts, students discuss the potential for surface water on the exoplanet Cannon-1, which they associate closely with its ability to support life. They observe that its orbital distance of 2.1 astronomical units (AU) places it firmly within the habitable zone of its parent star, which ranges from 1.4 to 2.8 AU. This zone is where conditions are just right for liquid water to exist—a crucial ingredient for life as we understand it. The students infer from Cannon-1's density and distance from its star that it likely has liquid water in abundant forms, such as oceans, lakes, and rivers, similar to Earth. The presence of liquid water, combined with the planet's appropriate size and temperature range due to its orbital distance, suggests that Cannon-1 could have a climate conducive to sustaining life.

For the Travel Time excerpts, students contemplate the formidable journey to the exoplanet Cannon-01, situated 26 light-years away. They recognize that even at 20% of the speed of light, the travel time of approximately 130 years far exceeds the average human lifespan, posing significant challenges for manned missions. This calls for extraordinary levels of planning, resources for sustaining life such as food and water, and psychological preparation for the crew. The possibility of multi-generational travel and the use of advanced technologies like hypersleep or robotics are discussed as potential solutions to the temporal and logistical issues of such long-duration space travel. There's an understanding that the development of faster propulsion systems and the means to sustain them, potentially reaching speeds of 80% or even 100% of light speed, would be ideal. The conversation reflects a mix of practical considerations and futuristic optimism, balancing the current limitations of space travel with the hope for technological advancements that could one day make the journey to Cannon-01 feasible.

Rubin-70 - Only one student has an Atmospheres excerpt, where they addressed that the atmosphere of Rubin-70 is dominated by more gases (particularly Hydrogen and Helium) because the planet is less dense but more massive than Earth.

For the Earth Comparison excerpts, student analysis focuses on discussions about Rubin-70's mass, radius, density, and potential geologic activity. They classify Rubin-70 as a super-Earth due to its mass being 1.8 times, and its radius 1.7 times that of Earth. The students suggest that with a lower density compared to Earth, Rubin-70 may have a thick atmosphere rich in gases like hydrogen and helium, retained by its stronger gravity. Given its age of 3.6 billion years, they place Rubin-70 in the Proterozoic eon, suggesting that life on Rubin-70, if present, would be unicellular, similar to early Earth. The possibility of a second Cryogenic glaciation event is also mentioned, which could affect the habitability of the planet. Finally, concerns are raised about the long-term effects of a non-Earth-like gravity on the human body, indicating that potential future exploration or habitation would need to address human health and adaptation to a different gravitational environment.

In the Evolution of Life excerpts, student analysis suggests that exoplanet Rubin-70, with an age of 3.6 billion years, is in the Proterozoic eon. They infer that, based on Earth's timeline, life on Rubin-70 would likely be unicellular, with the potential for eukaryotic cells that may utilize photosynthesis or chemosynthesis. There is speculation that the harsh environmental conditions of the planet's past could have led to a diversification of unicellular life, which may evolve into multicellular organisms in the future. Considering Rubin-70's youth relative to the lifespan of its star, the possibility for life to evolve further is noted. The presence of such life forms would likely result in an oxygen-dominated atmosphere, which could have implications for the habitability of the planet and the safety of potential explorers. Students are contemplating the evolutionary stage of life on Rubin-70 and its comparability to Earth's history, as well as the implications for future space exploration missions.

In the Process of Elimination excerpts, students consider various factors like travel time, the exoplanet's eon, atmospheric conditions, and potential hazards. Rubin-70 emerges as a favored candidate due to its proximity compared to others and its position in the Proterozoic eon, which implies that any life would be unicellular and not pose a threat to astronauts. Other exoplanets like Shishen-4 and Maya-186 are dismissed due to their long travel times and the absence of oxygen in their atmospheres. Samos-270 is ruled out because it's a Hot-Jupiter and unsuitable for life as we know it. The decision process takes into account both the practicalities of space travel and the unknowns of extraterrestrial environments, highlighting the careful consideration required to ensure the safety and success of interstellar missions.

For the Spectral Type excerpts, students discuss the characteristics of Rubin-70 in relation to its star, which is identified as a K-type main sequence star. They note that Rubin-70 orbits at a distance of 1.15 astronomical units (AU), which places it just outside the traditional habitable zone defined as 0.5 – 1.1 AU for a K-type star. This suggests that while Rubin-70 is in a zone where temperatures could allow for liquid water (hence potentially habitable conditions), it may also be within what they refer to as a "cryogenic" habitable zone, implying colder conditions that could still potentially support life. The longevity of K-type stars, which have lifetimes longer than our Sun's, is considered sufficient for life to evolve. The proximity of Rubin-70 to Earth, at only 13 light-years away, and its placement in this extended habitable zone, makes it an interesting subject for further study and potential exploration.

Within the Surface Water excerpts, there seems to be a bit of discrepancy among the students regarding the state of water on Rubin-70, given its orbital distance of 1.15 AU from its parent K-type star. They acknowledge that while Rubin-70 is within the cryogenic habitable zone, which typically suggests the presence of ice rather than liquid water, its status as a super-Earth means it could potentially harbor internal heat sources. Such geothermal activity might allow for pockets of liquid water beneath the surface or in protected areas despite the planet being outside the traditional habitable zone. The consensus seems to be that, although the surface water would primarily be frozen due to the planet's distance from its star, the potential for liquid water cannot be entirely ruled out due to Rubin-70's size and geological activity.

For the Travel Time excerpts, students calculated the travel time to exoplanet Rubin-70 as approximately 65 years at 20% of the speed of light, given its distance of 13 light-years from Earth. This travel time is considered in the context of human life expectancy and the challenges of long-duration spaceflight. They discuss the potential need for multiple generations of astronauts to complete the mission, highlighting the necessity for advanced technologies like cryogenic sleep to preserve the crew. Issues such as protection against cosmic radiation, the effects of microgravity on the human body, and the psychological impact of such a long journey are also considered. The feasibility of establishing human colonies and sending messages back to Earth are also deliberated, with the idea that colonization could potentially begin within 140 years from the mission's start, factoring in both travel and communication times. These discussions underscore the immense planning, technological development, and commitment required to undertake an interstellar mission to Rubin-70.

5. CONCLUSIONS AND FUTURE WORK

We determine that there is a positive correlation between score and word count on student essays, as longer essays score higher. Students selected the same planets as the experts 60 percent of the time, and different planets than the experts 40 percent of the time. Students that selected the same planets as the experts tended to have the Atmospheres, Earth Comparison, and Relevant Topics/Reasoning themes present in their responses more often, whereas students who did not select the planets the experts picked had slightly elevated presence of the Evolution of Life/System Age/Geologic Eon and Non-Relevant Topics/Reasoning themes. Finally, we see that students tend to make their statements with more certainty, engage in speculation, jump to conclusions, and make assumptions in their responses more frequently than experts do.

This study's findings not only enhance our understanding of student and expert reasoning patterns in MOOC assignments but also highlight the need for further investigation into the role of interactive elements in online learning environments. Specifically, our results suggest that incorporating more dynamic and engaging content could significantly improve student retention and success rates. Future research should explore this potential by designing and testing the impact of various interactive features on learner engagement and achievement. Among the study's limitations, the reliance on peer grades to ascertain the quality of student essays is particularly noteworthy. This methodology presumes that peer evaluations accurately reflect the essays' merits, an assumption that introduces several potential sources of bias. Peer reviewers vary in their expertise, understanding of grading criteria, and subjective biases, which could lead to inconsistencies in essay assessment. Such variability can affect the reliability of using peer grades as a direct proxy for essay quality, thereby impacting the study's findings on reasoning patterns between students and experts.

Addressing this limitation in future research involves exploring more objective and multifaceted approaches to evaluate essay quality. Incorporating expert reviews from instructors or employing automated essay scoring technologies could offer more consistent and unbiased assessments. Additionally, triangulating data from peer reviews with self-assessments and instructor feedback might provide a richer, more nuanced understanding of essay quality. Implementing these strategies would not only mitigate the limitations associated with peer grading but also enhance the validity and reliability of conclusions drawn from MOOC-based assessments.

There is a need to explore the effectiveness of different instructional strategies in enhancing students' scientific reasoning and language use in MOOCs. Experimental studies that compare the impact of various pedagogical approaches, such as problem-based learning or the use of interactive simulations, could provide valuable insights into how best to support student learning in online environments.

Given the specialized nature of reasoning in STEM fields, future work should not only extend our comparative analysis to disciplines beyond astronomy but also consider the influence of disciplinary-specific content and pedagogy on student and expert reasoning patterns. Such studies could utilize a similar methodological framework to ours, applying a mixed-method analysis to MOOC assignments across various STEM fields. This approach would illuminate whether the differences in reasoning we identified are unique to astronomy or reflect broader trends in online STEM education.

Finally, the development and validation of automated tools for assessing scientific reasoning and vocabulary in student essays could significantly advance the field of educational technology, enabling more scalable and personalized approaches to learning assessment in MOOCs.

In conclusion, this study contributes to our understanding of the challenges and opportunities associated with teaching and learning in MOOCs, particularly with respect to developing advanced reasoning and language skills. By highlighting specific areas where students may struggle to match expert-level reasoning, we underscore the importance of targeted instructional interventions. As MOOCs continue to evolve as a platform for democratizing access to education, ongoing research and innovation in instructional design and assessment will be crucial for maximizing their educational impact.

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APPENDIX

A. ASSIGNMENT PROMPT, TABLE, AND RUBRIC

A.1. *Assignment Prompt*

In 35 years, survey missions like Kepler and TESS have found nearly 4000 exoplanets. 100-200 years into the future we will have detected hundreds of thousands more and, of those, surely hundreds of exoplanets will be interesting candidates for human exploration. At that point, humans may be in a position to realistically consider an interstellar mission. How will we decide which exoplanet to explore first?

For this assignment, you will write a mission proposal to explore one of the seven exoplanets you have just analyzed in the previous sections. You will be leading a crew of your peers on the mission and you need to explain to them where you are headed, and why. Choose one exoplanet as your top candidate and write a 250-750 word proposal justifying why it is the best candidate for human exploration.

Describe the specific characteristics of the exoplanet that make your top choice stand out, and explain how it compares to the other exoplanets that didn't make the cut. Use the data you have entered into Table 2 to support your arguments.

In your proposal, be sure to discuss how the following characteristics influenced your evaluation of habitability:

- Describe the spectral type and stability of the parent star
- Discuss the orbital distance of the exoplanet
- Identify the exoplanet type, in terms of mass, radius and density
- Describe the likely state of water on the surface, and how the exoplanet type and orbital distance informed this conclusion
- Speculate on the possible evolutionary state of biology on this exoplanet.
- Finally, discuss the reality of traveling to this exoplanet. (Interstellar missions will be costly and long, likely requiring decades of planning. Be sure to discuss the travel time, and what considerations you might have to make for your crew based on that travel time. How do you explain to the human crew that your choice is better than another option?)

A.2. *Table of Exoplanet Characteristics*

Candidate	Spectral Type	Distance to Star (ly)	Orbital Period (yr)	Orbital Distance (AU)
Maya-186	K	38	0.72	0.8
Shishen-4	G	11	1.2	1.1
Tusi-1250	M	23	0.02	0.3
Lockyer-2	G	17	1.8	1.5
Cannon-1	F	26	3	2.1
Rubin-70	K	13	1.2	1.15
Samos-270	G	19	0.02	0.08
Candidate	**Exoplanet Mass ($m_\oplus$)**	**Exoplanet Radius ($r_\oplus$)**	**Exoplanet Density (g/cm^3)**	**Age (Gyr)**
Maya-186	0.97	0.98	5.7	4.5
Shishen-4	1.15	1.08	5.03	1.9
Tusi-1250	0.84	0.94	5.6	8
Lockyer-2	0.107	0.53	3.9	4.3
Cannon-1	1.3	1.1	5.2	8.6
Rubin-70	1.8	1.7	1.9	3.6
Samos-270	127.3	8.1	1.3	2.7

Table 4. Table of the given data for the seven possible exoplanets for the mission described in the prompt.

A.3. *Assignment Rubric*

Does the writer clearly identify and describe what makes their top choice a habitable system?

6 points:

• There is a detailed discussion relating spectral type and orbital distance to habitability

• The writer elaborates on how mass, radius and density informed their characterization of the exoplanet type; there is a clear line of logic for why these physical characteristics imply the exoplanet type.

• The writer clearly states what the water is like at the surface, and explains why

2 points: Does the writer use specific numbers and values from Table 1, Table 2 and the reference materials to support their explanations?

The writer's discussion of exobiology and travel time should show that they have carefully considered the relevant timelines and incorporated that into their answer:

4 points:

• The writer takes a clear stance on the state of evolution of life on the planet, and backs up their statements with a discussion that includes system age as it relates to geologic eon

• The writer discusses the time it would take to travel to the exoplanet and makes a clear argument justifying this travel time

2 points: Does the writer use specific numbers and values from Table 1, Table 2 and the reference materials to support their explanations?

1 point: Overall, for the entire mission proposal, does the student write with sufficient clarity and detail to communicate their points effectively?

−−/15 points

B. EXAMPLE ASSIGNMENTS

B.1. *Expert 1*

I have chosen Maya-186 for human exploration. Although it is the most distant planet on the list, it is the most likely planet to be conducive to life from Earth. The planet orbits in the K star habitable zone, which means that it likely has liquid water on the surface, especially due to the comparable mass, radius, and density to Earth. The habitable zone for K stars lies beyond the tidal lock radius, so the planet should have good heat transport and atmospheric circulation. While the planet is about the same age as Earth, the K star will be stable for billions of years longer than the Sun. Assuming the planet followed similar evolution to Earth, there will hopefully be life on the surface that generated oxygen via photosynthesis.

I have eliminated the other systems from consideration for the following reasons: Cannon-1 orbits an old F star, making the planet likely unsuitable at present for life. Tusi-1250 orbits an M star. Although the planet might be orbiting in the habitable zone, M stars are very active, especially in their early age, which can strip the atmospheres of their planets. The planet would also be tidally locked, which makes habitability questionable since one side will face the star and if the planet retained an atmosphere, circulation and heat transport would be difficult. Lockyer-2 is effectively a Mars analog and it would be difficult for the planet to sustain life without a thick atmosphere. Samos-270 is a gas giant orbiting very close to it's parent star, so it would not be suitable for life. The density of Rubin-70 makes it more likely a water world with a thick hydrogen atmosphere, which is not suitable for Earth life. Finally, I seriously considered Shishen-4 as a strong contender because it's mass, radius, and density are comparable to Earth. The distance to the host star could still be in the habitable zone, and if the planet has an Earth-like atmosphere, the greenhouse effect could keep a good fraction of the surface temperate for human life. My main concern with the planet is the age. If the planet is an Earth analog, it would still be in the Archean era, where there is a strong presence of carbon dioxide and methane in the atmosphere, and very little molecular oxygen. I think it is a safer bet to go with Maya-186, which would hopefully have gone through an oxydation event making the planet more suitable for Earth life.

The travel time to any of these systems will likely be decades to centuries. For a generational mission such as this, we need to set the goal to travel to the most likely planet to be suitable for human life and exploration.

B.2. *Expert 2*

The growing exoplanet population showcases unprecedented diversity, offering several interesting candidates for human exploration. But our understanding of exoplanets at the individual level remains largely uncertain through the limits of remote observation. Our decision on optimal target selection is a function of bulk parameter characterization, for which our understanding of Earth itself offers but a single, well-defined datapoint. As such, in determining the best candidate for human exploration, no planet is more globally well-suited than the most textbook Earth-analog of Shishen-4.

From a bulk parameter standpoint, Shishen-4 is near-identical to Earth in both composition and orbital structure. Only slightly larger than Earth in both mass and radius (by 15% and 8%, respectively), Shishen-4 is generally in line with both observational metrics associated with being "Earth-sized." A bulk density of $\sim 5\ \mathrm{g/cm^3}$ is indicative of a rocky composition that may be chemically similar to Earth with a bulk density of $\sim 5.5\ \mathrm{g/cm^3}$. While it is not possible to know the precise interior and surface compositions of exoplanets through distanced remote sensing, these metrics are consistent with both Earth and standard rocky equations of state, heavily favoring an "Earth-like" composition.

What separates Shishen-4 from other compositionally similar targets is its orbital structure: namely, the period and semimajor axis are consistent with an orbit inside the continuous habitable zone of its G-type host star. Other targets may currently orbit within this "goldilocks regime" where Earth-like planets could sustain liquid water on their surface. However, Shishen-4 is the only target with a separation that has – in the absence of migration – always fallen within the habitable zone throughout its host star's luminosity evolution; this "continuous" habitable zone for G-type stars roughly spans 0.9-1.2 AU, consistent with Shishen-4's 1.1 AU semimajor axis. Shishen-4 falling within the continuous habitable zone of its Sun-like host star implies an Earth-like equilibrium temperature, and thus (when coupled with its Earth-like bulk composition) an Earth-like atmospheric structure and composition, capable of sustaining liquid water on the surface. Furthermore, the bulk mass, radius and density are generally inconsistent with a large sub-surface water fraction, implying that any water on the planet should indeed be localized to the surface.

The statement about Shishen-4's atmosphere is, in the absence of remote atmospheric characterization, an assumption derived from our knowledge of Earth and other Earth-like planets. Unfortunately, the system is fairly young on the grand scales of geological and biological evolution (with an age of roughly 1.9 Gyr), and its atmospheric evolution may not have progressed to that of modern-day Earth. Earth is roughly 4.5 Gyr old, with earliest evidence of life dating back to 3.7 Gyr, or roughly ∼0.8 Gyr into the planet's evolution. However, the habitability of Earth as we know it today did not arise until ∼2.5 Gyr ago (i.e., 2 Gyr into Earth's history) following the "great oxidation event," when cyanobacteria productivity led to a sharp rise in the oxygen content of Earth's atmosphere. Making the coarse assumption that Shishen-4's biosphere has evolved on a similar timescale to Earth, an age of 1.9 Gyrs places this planet near the cusp of a potential oxygenic revolution. This could favor habitability, but there is no guarantee that Shishen-4 has a similar atmospheric composition, is at a similar evolutionary point, or has even followed a similar biological evolution. While this atmospheric uncertainty is prominent, the similarities to Earth along every other axis cannot be overvalued as indicators that this target is indeed consistent with our understanding of Earth's composition and (at least geological) evolutionary history. There is an appreciable chance that life has already emerged on Shishen-4, though it may be in earlier stages than what we are used to on Earth today.

Regarding the exploratory process, Shishen-4 is fortuitously the closest target at a distance of ∼11 lightyears. Though the duration of travel to (and from) this planet is non-negligible, its fairly close proximity provides more opportunities for both further mission support and detailed remote characterization than what is possible with farther targets. The crew of any expedition would require sustainable support systems on their journey, both essential (e.g., nutritional and medical aid) and supplemental (e.g., recreational). The comparatively short trip to Shishen-4 reduces the structural and financial overhead required to develop and maintain those systems. The crew could thus launch and reach their target in record time, beginning their search for life on the only idyllically Earth-like planet with an incomparably high change of habitability: Shishen-4.

B.3. *Expert 3*

Of the seven exoplanets presented, planet Shishen-4 is the most promising planet to explore for the possibility of encountering alien life, not considering other factors that might make a planet interesting. Given that we only know one planet with life, which is the Earth, it is reasonable to explore the planet which has characteristics most similar to that of the Earth. While it is not impossible that planets dissimilar from Earth have life, it is safer to explore that which is most similar to Earth first, before exploring other planet types.

Likely a core factor in planetary habitability is the intensity of radiation a planet receives. Planet's that receive the right amount of stellar radiation such that water is mostly liquid rather than solid or gaseous are probably the most favorable for life, as on Earth all life is dependent on liquid water to some extent. Shishen-4 will be the most similar to Earth in terms of stellar radiation received. The star is spectral type G, the same spectral type as the Sun, and will therefore have a similar luminosity to the Sun and spectral distribution of light, with most light in visible wavelengths. The planet is also located at nearly the same distance as Earth is from the Sun, meaning that we can expect liquid water to be possible on its surface. Other candidates could possibly also have liquid water depending on their stellar luminosities, such as Maya-186 and Cannon-1, but they will not have the same spectral energy distribution as the Sun (and more infrared and ultraviolet light respectively), which will have an unknown impact on life there.

Another critical factor is the gravity and composition of the planet, which we can determine from the mass, radius, and derived density. Very low mass planets are probably not good for life as they will struggle to retain an atmosphere. Conversely, very massive planets may have dense atmospheres that may or may not be conducive to life, in addition to potentially crushing surface gravity for any multicellular animal life. In this regard, Shishen-4 is also very similar to Earth with mass and radius just a fraction larger and similar bulk density. From this, we can conclude that the gravity is not too strong and the planet is mostly rock like Earth, as opposed to having a large gaseous atmosphere. Maya-186 is more similar to Earth in this regard, but Shishen-4 is still very similar. In contrast, Samos-270 would be a very dissimilar candidate, and is likely a large gaseous planet.

An additional, lower priority consideration is the age of the star. We may want to avoid traveling to a star near the end of its life, as any life there does not have much time left and it could take a long time for us to get there. Shishen-4 is relatively young and has 5+ billion years left, so it is no concern. Cannon-1, on the other hand, is probably very close to the end of its life at 8.6 Gyr given that it will be slightly more massive and shorter-lived than our Sun, assuming it is a main-sequence star.

Finally, we should consider how long it will take us to get there. Regardless of the speed of travel, which will likely not be more than a small fraction of the speed of light, we will arrive at closer planets faster. Shishen-4 is the closest candidate to us and is therefore the easiest to travel to. If we can manage to travel 50% the speed of light for most of the journey, we can arrive at Shishen-4 in 22 years, long before we all die from old age. Maya-186 would take almost four times longer.

If we travel to Shishen-4 and life is present, we should expect to find it in a microbial form. With Earth as our only sample, we know that cellular life can originate within a billion years after plant formation, but complex multicellular animals and planets can take a few more billions to develop. Shishen-4 is 1.9 Gyr old, so it could certainly have microbial life, but it probably won't talk to us.

With these reasons stated, Shishen-4 is the most likely location for us to find some kind of life. It is possible that we could find more unique or developed organisms on the other planets, but they are more risky given our lack of knowledge beyond what we see on Earth.

B.4. *Expert 4*

The potential habitability of exoplanets is determined by a wide range of factors determined by the exoplanets host star, its orbital distance, and chemical composition. Often, the ideal conditions for habitability are grouped simplistically into a 'Goldilocks Zone', which removes the many intricacies that determine the habitability of a planet. However, the general idea is sound – find a planet that is as like our earth as possible.

Given this, the prime exoplanet candidate for exploration is Shishen-4, as it most closely resembles Earth in its characteristics. In the following, I will detail how the host star characteristics, orbital distance, planet radius, and the distance of the system from Earth make it the ideal candidate for exploration.

Firstly, Shishen-4, from here on referred to as Planet X, orbits a star that resembles our sun: it is a G-type star. Furthermore, its age, 1.9 Gyr, indicates that the star has over $\sim$8 Gyr (billion) left in its main sequence meaning that we will not have to worry about any extreme stellar activity or evolution. Next, it's orbital distance and period, 1.1 AU and 1.2 years respectively, further indicate that the host star is very close in mass to our sun (Kepler's 3rd Law). Importantly, it also suggests that Planet X lives at distance where liquid water is likely to exist, meaning that temperatures on the planet would likely be in the human range (an average temperature of $\sim 10^{\circ}$C) and that it can support human life. Finally, given the distance to its host star, 11 ly, Planet X clearly lies within the Milky Way, meaning that the system is likely carbon rich, another important element for supporting life.

Next, the Planet X resembles Earth closely, which suggests that it is a rocky planet with a surface that humans would be able to live on. Planet X's mass and radius are close to Earth's, at 1.15 and 1.08 that of Earth's. Furthermore, it's density of 5.03 g/cm^3 is functionally the same as Earth's at 5.53 g/cm^3.

Additionally, we must consider the timescales involved. First, the travel time is the least of any of the proposed exoplanets, at 11 light years. Realistically, this journey would take generations to complete, introducing the complexities of having a population that has grown up completely in space without living knowledge of Earth. Reducing any complications associated with this is an important factor to consider, as well as the possibility of a disease wiping out the entire travel group.

Finally, at 1.9 Gyr, the system is the youngest of all that are proposed which means that the planet is also at the earliest point in its biological evolution. This is good because it reduces the likelihood of their existing an advanced civilization using up resources we would have needed. However, a nascent biological system may not yet contain the necessary elements, such as oxygen, in its atmosphere to support human life. Further spectroscopical study of Planet X's atmosphere is necessary.

Shishen-4 is the clear primary target for human exploration. The similarities of the host star to our sun, the planet's mass and density to Earth's, and the orbit to our own, is extremely promising. Furthermore, the travel time is minimized amongst the candidates, and, finally, the star's youth promises long-term stability as well as a likely untouched planet to migrate to.

B.5. *Expert 5*

While life has proven to be resilient beyond previous human understanding, and likely could be found in extraordinary environments, for a mission to seek life outside of Earth it would be best to search for an Earth-like planet. Our star and our planet-moon system seem to possess unique qualities that make it ideal for a life-sustaining environment, as we know it. Thus, I would choose Shishen-4 as our mission's target. Shishen-4 is the closest exoplanet to us given this list, which is a major benefit for a human-powered mission. Shishen is a G star, same as our Sun, which throughout its stellar life cycle resides in a sort of "goldilocks" zone for stellar activity, acting relatively calm with few energetic outbursts. The planet's orbital distance and size/radius/density are all within 15% of Earth's values, making it an earth-like planet including having it exist within the habitable zone, defined as were water will be primarily in liquid form on the surface of the planet. The one non-present-day-Earth-like quality of this planet is its age, it is young at 1.9 Gyr compared to our Earth's $\sim$ 4.6 Gyrs. If this planet is like our Earth, this suggests that we will not find human-life on this planet, not nearly enough time has evolved for that. However, the earliest evidence on life on Earth is at 3-4 Gyrs ago, thus overlapping with the 1.9 Gyr age of Shishen. We can look for signs of early life, such as stromatolites like we find on Earth. One of the biggest questions we have as humans is 'how did life start' and visiting another exoplanet that is primed to create life as we know it would help tremendously in answering this question. We can check this planet's evaporative lakes, ocean vents, and tide pools for life - as these are three of the most popular locations for where we think life started on Earth.

Interstellar missions are not possible as of now, and interstellar missions in the future will be difficult, requiring major advancements in technology and likely multiple generations on a single space craft. Realistically, we cannot reach speeds going even half the speed of light, and even if we could reach that speed or greater, it would have profound impacts on the time experienced by the crew vs time experienced back here on Earth. A crew on this mission must consider the possibility of never coming back to Earth, or being forever space-bound.

B.6. *Expert 6*

As of 2023, we know of only one situation where life can arise: a 1 $M_{\oplus}$, 1 $R_{\oplus}$ planet with an average density of 5.5 g/cm^3, which takes 1 year to orbit a G-type star at a distance of 1 AU. Life may be able to form in other environments, but if we're searching for extraterrestrial life our safest bet is to explore a planet with conditions as similar to Earth's as possible.

Shishen-4 is an Earth-like exoplanet around a Sun-like star. Like Earth, it orbits its G-type host star at a distance of approximately 1 AU, which indicates—along with the fact that its mass and radius, and therefore its density, are nearly identical to Earth's—that it is capable of possessing a stable atmosphere which could keep the planet warm enough to maintain liquid water on its surface. G-type stars are relatively stable (unlike for example M dwarfs), meaning life that forms on this planet has a better chance of persisting long-term.

Shishen-4 is additionally one of the nearest Earth-like exoplanets to the solar system: its host star is only 11 light-years away. The travel time to get to the star would still be long, likely upwards of 10,000 years (assuming a travel speed of 0.001c, or 300 kilometers per second), but this could be cut down by advancements in technology. Critically, the proximity of Shishen-4 to Earth means that regardless of the travel speed, it will take less time to get to Shishen-4 than to any other Earth-like exoplanet.

The one caveat to Shishen-4's resemblance to Earth is its age. While the Earth is approximately 5 billion years old, Shishen-4 is less than 2 billion years old. However, the first life on Earth arose less than a billion years after the Earth's formation. It took much longer for multicellular life to arise (only about 600 million years ago). When we arrive on Shishen-4, we may find that the only life present is single-celled organisms, maybe existing in larger structures resembling stromatolites. Regardless, discovering any form of life on a planet outside the Solar System would undoubtedly revolutionize our understanding of life and the conditions under which it can appear.

B.7. *Expert 7*

Esteemed crew,

I am writing to inform you of an upcoming mission to the planetary system Maya-186, which hosts the Earth-like, potentially habitable planet Maya-186b. Located 38 light years away from Earth, this system hosts an Earth-mass, Earth-size planet (in the habitable zone of its host star). The host star's spectral type is a K dwarf, which is slightly smaller and cooler than the Sun. However, the planet resides at a distance of 0.8 AU from the star, or equivalently, it has a period of 262.98 days. At this period, this planet orbits the star closer to it than the Earth orbits the sun, meaning that Maya-186b receives about as much radiation or stellar flux as the Earth, rendering it a temperate and potentially habitable (and inhabited!) planet. Maya-186b also has a bulk density of 5.7 , which is very similar to the Earth's (5.5) and therefore we expect its surface gravity and composition to be likely similar to the Earth's, making it a formidable and safe place for human exploration. After carefully considering several other exoplanets for this mission, we have come to the conclusion that Maya-186b is the most optimal for our survival. The rest are either too hot, too cold, or their host stars are either too young (and therefore likely too magnetically active) or too old (and likely evolved and engulfed their orbiting planets) and thus not ideal.

From the planet's bulk properties, we suspect that its atmospheric composition might resemble the Earth's, which bodes well for our ability to breathe without oxygen tanks. The stellar host is also about the same age as the Sun, and thus we believe that life, if any, may have had ample time to emerge and evolve, making the prospects for exploration even more exciting. The star is also a middle-aged, stable star, sitting squarely on the main sequence, and it is also very likely that any initial stellar magnetic activity may have largely subsided. Thus, its activity poses little to no threat to our human crew or any life on the surface, maximizing our chances to discover and study life there. Because of the planet's distance to its host star, we know that it is in its habitable zone, and therefore temperate for liquid water to exist on its surface. We cannot confirm the presence of water on its surface, based on the planet's characteristics alone, but if it does have any water, it would be likely in liquid form, given the planet's equilibrium temperature.

Finally, you may be wondering about the practical considerations of this trip. At a distance of 38 light years, this system is quite far. Thus, an international team of engineers is presently tuning and refining the fastest spaceship known to man, the Enterprise, to use for this mission. With these updates, the rocket will be able to travel at 0.8 the speed of light, which implies a roundtrip travel time of 96 years. More details will follow should you decide to join. Given the length of this trip, I would advise you to bring a book (or two) and a few movies to pass the time. Oh, also, make sure to bid the Earth and everyone you know farewell forever. I hope to have your decision by the end of the week, and I hope that you will embark on this truly extraordinary and historic journey.

Per aspera ad astra,

Your captain

C. EXAMPLES OF CODES IN STUDENT ASSIGNMENTS

Code: Atmospheres
Student Example: The problem with smaller stars like these is that planet, in order to be inside the habitable zone, has to be located quite close to the star making it vulnerable to flares that can destroy its atmosphere. (Student 30)

Code: Earth Comparison
Student Example: Seeing as how the biology on our Earth has evolved; for Tusi-1250, the biology should have super-terrestrial intelligence assuming it progresses just like our earth. (Student 89)

Code: Process of Elimination
Student Example: Some might argue that planets such as Tusi, Maya, or Cannon would be better choices, but with travel times over 100 years biology would have to improve greatly. Humans do not tend to survive over 100, much less 115 years in space along with previous years of training. (Student 11)

Code: Relevant Topics or Reasoning
Student Example: The density of Maya-186, similar to Earth, suggests a rocky crust and mantle and a metallic iron-nickel core. The iron-nickel core, even if only partially molten at this time, should provide a protective magnetic field against harmful stellar winds and cosmic radiation. (Student 31)

Code: Irrelevant Topics or Reasoning
Student Example: And the civilization on this exoplanet is capable of interstellar communication, as well. (Always remember these are all assumptions because we do not know some certain data. For instance, we do not know whether a mass extinction happened.) (Student 2)

Code: Evolution of Life / System Age / Geologic Eon
Student Example: The age of Shishen-4 is 1.9 Gyr. If we assume this planet has a similar evolutionary time frame as the Earth, this planet would fall into the Archean Eon and would have some unicellular life-likely of the prokaryotic variety. Prokaryotes, cells without nuclei, were the first types of life to evolve on earth and are thought to have evolved during the early portion of the Archean Eon in deep sea thermal vents. It is estimated the Eukaryotic life didn't evolve until nearly 2 Gyr later in the early middle of the Proterozoic Eon. (Student 62)

Code: Mass / Radius / Density and Type of Exoplanet
Student Example: The mass of the exoplanet Shishen-4 is 1.15 times the mass of the earth and the radius of Shishen-4 is 1.08 times the radius of the earth. And the density of this exoplanet is 5.03 g/cm^3. So, this means that Shishen-4 is slightly larger than earth and its density is close to that of earth's density. Hence, we can say that the exoplanet Shishen-4 is a super-earth. (Student 58)

Code: Spectral Type of Star/Orbital Distance of the Exoplanet and Habitability
Student Example: Spectral Type = G, Orbital Distance = 1.5 AU Since the spectral type for our exoplanets parents star is G, hence, its habitable zone lies between 0.9-1.8 AU. Orbital Distance = 1.5 AU From the data given for Lockyer-2, we can conclude that it lies within the habitable zone of its parent star. (Student 20)

Code: Surface Water on the Exoplanet
Student Example: Maya-186 has an orbital distance of 0.8AU and the habitable zone for a K-type star is in from 0.5AU to 1.1AU. As it is located right in the middle of the habitable zone, it is possible that it would be not too hot for water to vaporiza nor too cold for water to freze. Hence, liquid water would be abundant in this planet. (Student 32)

Code: Travel Time to the Exoplanet
Student Example: Lockyer-2 is 17 light-years away from our planet. It will take 85 years to travel to the exoplanet at 20 percent of the speed of light. I believe it will be easier to preserve humans' health in an isolated place where they're away from diseases and have proper, controlled diets. Blood transfusions and artificial organs might reduce some effects of aging. Also, technologies like cryosleep, low-temperature preservation of a human body, and reducing metabolic rates for humans over extended periods, would get us closer to our dream of interstellar human travel. So I believe astronauts can live and function longer than the average human lifespan in space. (Student 16)

Figure 7. This figure illustrates exemplar extracts from student assignment alongside the corresponding major (thematic) codes identified through content analysis. This coding schema underpins the qualitative analysis, enabling a structured approach to the data and facilitating the comparison of students with that of the experts.