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ASTRONOMY EDUCATION RESEARCH

An Initial Investigation of Students' Understanding of Space Exploration

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Abstract

The topic of space exploration receives little attention in most introductory astronomy courses. However, students come to such courses with both an interest and ideas informed by popular media–ideas that may or may not be consistent with scientific and engineering outlooks. This study explored what students recall about space exploration ideas after engaging with two short, in-class activities on the possibility of travel to Mars and the use of solar sails for exploration. We asked four open-ended questions for extra credit and coded students' responses (N = 106 to 150) for themes. Coding demonstrated that students had reasonable, if limited, understanding of factors influencing both crewed and uncrewed mission types as well as risks to crews after completing these activities.

Keywords: Space exploration, Student understanding, Introductory astronomy

1 Introduction

The US National Aeronautics and Space Administration—NASA—is a preeminent player in space exploration, often working in collaboration with other agencies such as the European Space Agency (ESA), the Japan Aerospace Exploration Agency (JAXA), and others. Its mission includes leading "an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and bring new knowledge and opportunities back to Earth" (Blodgett, 2021). Exploration strategies include crewed missions such as the earlier Space Shuttle and upcoming Artemis programs; uncrewed missions within the solar system such as Juno (orbiting Jupiter) and various Mars landers; and uncrewed missions around Earth, such as the Hubble Space Telescope or the Solar and Heliospheric Observatory (SOHO). NASA's visibility among the public is high, with 65% of Americans saying that NASA should continue to be involved in space exploration at the same time that private and commercial potential is expanding (Pew Research Center, 2018).

It is unclear, however, how well people understand some of the reasoning behind the variety of different missions that NASA produces. Over two decades ago, Comins (2001) found that many university students held alternative conceptions about space exploration. These include, for example, that many astronauts have travelled to the Moon or that planes can fly in space (Comins, nd). These or other ideas may emerge and be retained, in part, as a result of exposure within popular culture, such as cartoons, television shows, or movies.

Indeed, there are myriad examples of Hollywood versions of human space travel. Two exceptionally popular films within the last decade include *Interstellar* (Nolan, 2014) and *The Martian* (Scott, 2015). Both contain many strong elements of scientific truth, making them unlike a number of other films about humans in space. *Interstellar* director Christopher Nolan worked with Nobel prize winning physicist Kip Thorne to create realistic looking black hole scenes (James et al., 2015; Thorne, 2014). In *The Martian*, original book author Andy Weir (NASA, 2018) and director Ridley Scott have been praised for correctly showing how botany may realistically work in Martian soil (Kluger, 2016). However, in both films the primary aspects of humans in space, the time scales, and the distances involved are not addressed in realistic fashion based upon our current technology. It is not surprising that students as well as the general public do not have a clear understanding of why human space exploration is not as common in real life as it is in film, particularly because these two examples are among the better representations of space exploration. We agree with MacLeish and Thomson (2010) who, in a call for increased global efforts for space education, point out that, "The success of future space exploration will depend upon a scientifically literate public that is informed about the medical and technological benefits of space exploration for life on Earth" (p. 1289).

Introductory astronomy courses at the university level (hereafter, "ASTRO 101") are one place where the challenges of space exploration can be discussed, although this topic is generally a very small portion of the typical survey course, if included at all (Partridge and Greenstein, 2003; Slater et al., 2001). Astronomy instructors often spend time teaching about the scale of the solar system and the Milky Way, but it is not clear that much time is typically spent discussing why human space exploration is so rare. It is this gap we seek to bridge with our current project.

The NASA Heliophysics Activation Team (HEAT) group at Temple University and the American Association of Physics Teachers has created two lecture-tutorial style activities (Prather et al., 2013) around space exploration, "Migration to Mars" and "Solar Sails" (Willoughby et al., 2022) and tested them in ASTRO 101 courses. We then engaged in a small research study to find out what students retained from these lessons. The research question for our study was: ***What do students describe as the benefits and challenges of both human and non-human travel through space, after completing activities on solar sails and human migration to Mars?***

This exploratory study, and the activities used within it, begins to respond to MacLeish and Thomson (2010) by addressing some of the important considerations in space exploration. This can contribute to scientific literacy through understanding of a popular technical topic, and to education research broadly by providing insights into helping students construct this literacy.

2 Literature review

There are a multitude of factors that need to be understood and considered while thinking about space exploration in a classroom setting; those required for actual space exploration are far more numerous and beyond the scope of this paper. This is a little researched area within astronomy and space science education, with what has been done generally focused on younger students.

2.1 Space Exploration

Cook et al. (2011) surveyed US undergraduate students and found widespread support for space exploration, regardless of major. Among non-science majors, the authors found that there was a correlation between science literacy and support for space exploration, suggesting that science literacy may be an important piece of education for widespread support of space related policy goals.

In a survey based in the UK, researchers asked adults about their level of support for exploring space using government funding (Entradas and Miller, 2010). The vast majority of respondents were supportive of space exploration, and most said that a primary reason was to "generate new scientific knowledge and advance human culture." When asked specifically about where this exploration should take place to look for traces of life, the preponderance (31%) of respondents stated that we should look on Mars, the Moon, other places in our solar system, and beyond the solar system. The second most popular response was just to look beyond our solar system, chosen by 25% of respondents. Overall, survey respondents expressed support for the idea of human space exploration, while also expressing unrealistic expectations of the difficulties involved.

Afful et al. (2020) investigated Australian undergraduate students' support for increasing relevant education in order to better support expanding opportunities in space science. The authors found that the vast majority of respondents said that "space science should be part of the university's curriculum in the hope of preparing the next generation of space explorers" (p. 353).

These studies, much like public opinion polling (e.g., Pew Research Center, 2018), focused on the value of or participants' support for space exploration. Investigating student understanding about the topic is far less common. In their thesis work, Duane (1989) explored the question of how US second graders (ages 7-8 years) viewed space exploration. The author designed an instrument that depicted dinosaurs engaging in various ways with technology. Dinosaurs were chosen to remove racial and sexual stereotypes when the children engaged with the materials. Duane found that the majority of students articulated the idea that space exploration will benefit society as a whole. In this work, Duane also points out that, "Space is reality for children. They see astronauts on TV, they witness the launch of space ships, and rockets. They visit the National Air and Space Museum by the thousands. Many have experienced Space Camp in Huntsville, Alabama" (p. 9).

The most directly related work to the present study was completed in Brazil, where students aged 12 to 16 studied planetary habitability in general (Lyra et al., 2020). They were then asked to apply that knowledge to the Martian surface, by choosing areas on the surface of the planet for taking high resolution images with the Mars Reconnaissance Orbiter. Using a pretest and a posttest survey, the researchers found that students did indeed have a better understanding of habitability after the intervention.

2.2 Related Topics

In addition to these studies on support for or understanding of space exploration, a few additional works provide insights into associated topics, much like early findings by Comins (2001). Palma et al. (2017) interviewed middle school (ages 11-14), high school (ages 14-18), and university students in the US regarding how astronomers study objects within our solar system. They found that a large number of students surveyed had the impression that humans have travelled throughout the solar system, and that they have even returned samples from those locations. Generally, students did not seem to understand that the scientific methods employed by astronomers differ widely from bench-top methods employed by chemists and biologists. The authors conclude that students tend to "draw from cultural experiences or classroom experiences in other science domains to formulate their responses", and that "students need instruction that is designed to reveal the limits of human spaceflight" (p.71).

While not asking specifically about space exploration, Nelson (1991) interviewed sixth graders (ages 11-12), asking them to explain causes and effects of gravity, orbits, and weightlessness. The majority of Nelson's interviewees indicated that gravity is specific to Earth, that air and the atmosphere influence gravity, and that when weightless, people undergo physical and behavioural changes. Similar ideas—particularly that there are relations between air and gravity—have been identified in numerous other studies (e.g., Cardinot and Fairfield, 2021; Kavanagh and Sneider, 2007; Ruggiero et al., 1985).

Past research on students' understanding of space exploration is, as we see here, limited and focused predominantly on support for the venture rather than scientific benefits, challenges, or processes. Whereas the present study does not completely fill this gap, it contributes toward improving our understanding in this area.

3 Methods

3.1 Theoretical framework

Both the activities described herein and the research study itself are based in a theoretical framework of constructivism (Driver et al., 1994), where we expect that students build their understanding through interactions with content (e.g., through lectures, text, and activities) and one another (e.g., through group work with peers). Constructivist approaches to teaching, which undergird the lecture-tutorial model on which the two activities are based (Prather et al., 2004), involve providing students with opportunities to actively engage with the content and one another (Lombardi et al., 2021). In the present context, students have likely already constructed initial ideas from sources outside of the classroom, such as those shared by friends, family, popular culture, or former classrooms; they then build on those ideas when engaging with our activities.

3.2 Study design

This is an exploratory, descriptive study using qualitative data (in the form of open-ended questions; Section 3.5 provides more detail). The data were examined using a content analysis, from which we report frequencies (as described further in Section 3.6). This approach has been successfully used as a first step in numerous past studies involving new topics (e.g., Bailey et al., 2009, 2012; Prather et al., 2002).

3.3 Participants and setting

Students involved in the study were primarily second year undergraduate students (44%), while 9% were in their final year of university coursework, and the rest were split between first and third year. Forty-six percent of the students identified as female, 52.6% identified as male, and 0.8% identified otherwise. The majority of students identified as white (85.3%), with the remainder split between Hispanic (6.8%) and multiracial (5.8%). Very few of the students (5.5%) were non-traditional age (i.e., 25+).

This study was completed at a midsize doctoral granting institution with very high research activity in the western United States. Introductory astronomy fulfills one of two science requirements at the institution, although it is just one of several course options for meeting this requirement. As such, the course is geared toward non-science majors, with 85% of this term's students specializing in something other than science.

The course is split into three major units: naked eye astronomy, exploring with telescopes, and exploring our own solar system. The activities in this study (Willoughby et al., 2022, ; see Section 3.4) were given during the last unit of the semester. Students earned full credit for completion of the activities. The two sections of the course participating in this study were taught during the COVID-19 pandemic, with all course materials delivered online.

In this course, students form learning teams of four students each at the start of the semester. The teams persist for the duration of the semester, and students are asked to collaborate with each other on activities designed to be completed as a team. Because these activities were done toward the end of the semester, the learning teams were all well established, and every member of the team earned the same score for every activity. All activities were designed to be given after instruction, with the purpose of deepening student understanding of various topics within astronomy. To our knowledge, these are some of the first activities developed to encourage student understanding of both human and robotic space travel (c.f., Prather et al., 2013).

3.4 The activities

The Migration to Mars activity focussed on the parameters of a hypothetical trip to Mars. It was given after the students heard lectures on Earth as a planet, then on the remaining terrestrial planets. The other lectures in the unit include one on the Sun, a lecture about Jupiter and its moons, and a lecture on the remaining Jovian planets with an emphasis on the moons of Saturn. When discussing terrestrial planets, the lecture emphasized the habitability (or lack thereof) of Venus, Mercury, and Mars. One topic that students typically ask about is the film *The Martian*, so the instructor discussed specifics of this film in the non-synchronous online lecture. In the activity, students were asked to consider some of the obstacles associated with traveling to and possibly occupying Mars. They also read pages from SpaceX and NASA websites. At the end of the activity, students drew Instagram social media pictures of their trip to and time on Mars, either using a tablet to draw them directly or by uploading a scan or photo of a hand-drawn picture.

The second activity was about Solar Sails and how this propulsion system compares with chemical and ion rockets. This was paired with lectures on Jupiter and the remaining Jovian planets. Because the theme of this unit was on exploring our solar system, the lecture focused on Jovian moons more than the planets themselves as the moons have solid surfaces while the Jovian planets do not. In the activity, students used simple math with data from both current and aspirational missions (a solar sail mission—Starshot—specifically) to determine that human exploration outside of our solar system to our nearest neighbouring stars, the Alpha Centauri complex, is unrealistic. Next, students read about how chemical rockets and solar sails work and answered questions about both types of propulsion. Communication delays were then considered, again using a similar list of missions used when calculating travel times. Finally, students considered a map of our local galaxy, and discovered that Alpha Centauri has no near neighbours. The latest version of the two activities can be found online at `https://aapt.org/Resources/NASA_HEAT.cfm`.

3.5 Data collection

At the end of the solar system unit, students completed a quiz online. In addition to covering material in this unit, there were two extra credit questions related directly to the concepts contained within the two space exploration activities. Based on the content of the team activities and how that content tied in with the research question, the authors brainstormed a number of possible open-ended questions. The goal with each question was to probe student understanding of one aspect of space travel, particularly as presented in the two activities. Specifically, our goal was to probe the extent to which students understood, post instruction, some of the specific difficulties of actually attempting space travel within our own solar system, let alone further flung options. The questions were revised iteratively until we achieved consensus amongst the authors.

Although the extra credit questions were not required, the vast majority of students responded to one or both of them. The questions posed were:

Migration to Mars:

1. What are some challenges associated with human travel to Jupiter's moon, Enceladus? [Note: This should have been Saturn rather than Jupiter; implications of this error are discussed below.]
2. Currently the Mars Ingenuity helicopter is being tested. Is this helicopter driven remotely by a person on Earth, or is it autonomous? Explain your reasoning.

Solar Sails:

3. Why is a solar sail a better option than a chemical rocket for sending a spacecraft to study a nearby nebula?
4. What are at least two factors involved in deciding what kind of spacecraft to send to a location in space, and why is each important?

Each of these questions directly probes students' recall of benefits or challenges of various means of space exploration, per the focus of our research question (end of Section 1). Although Question 2 is the most specific framing, the communication lag between Earth and Mars (or any other off-planet target) is one of the challenges that must be addressed in any kind of planning.

Questions 1 and 3 were given to section one, and questions 2 and 4 were given to section two. Students answered the questions individually. For each question, 100-150 responses were collected (this number varied due to section size differences and the questions being optional and so reflect how many students chose to respond). The responses, which were collected via the course's online learning management system, were then imported into separate spreadsheets with all identifying information removed. Because of the way the data were retrieved from the learning management system (i.e., anonymously by question), we were unable to look for consistency in responses for those students who answered both questions available to them. When discussing specific data below, we simply use the row number of the spreadsheet, which is effectively a randomly-assigned identification number. There is no assumption of continuity between ID numbers across questions.

When this study was completed, the team activities associated with this study were still in testing phase. As such, the rest of the quiz was not tied directly to the topics taught in these activities. The multiple-choice questions and the other short answer questions, therefore, are not included in this study. More recently, these materials have been folded into the curriculum, and there are now learning goals and quiz questions tied directly to the space travel activities built into the course.

We note that the first question contains an error about which planet Enceladus orbits. Despite this error, we chose to include the data collected from this question for two reasons: first, most students seemed not to notice that this was, in fact, an error. Of the students who did notice the error, all of them mentioned that point, then answered the question in any case. Hence our thinking is that the data is useful regardless of the error present in the question. Second, the fact that Enceladus orbits Saturn is not actually relevant to why it would be incredibly difficult for humans to visit it or any other gas giant's moon, as the issues do not differ conceptually but only in the details.

3.6 Data analysis

We used a conceptual content analysis (Krippendorff, 2019; Saldaña, 2021) on each question. All the responses were examined first by the third author, who then created several categories and initial codes to help organize the collected data. The third author then analysed all responses again and added new codes when looking more deeply into the details of each response. A minimum of one code was then assigned to each answer, although multiple codes were allowed and were common for longer responses. The spreadsheet data, responses and coded responses, were then reviewed by the third author at least two more times to confirm proposed coding, create new codes in cases they were needed, and make some final adjustments and clarifications. Original codes, potential new codes that emerged, and any student responses for which coding was unclear were discussed by the full team at multiple points throughout the process. The first two authors also conducted "spot checking" of the codes assigned to student responses, particularly in earlier phases.

In the remaining portion of this section, we describe the process and sample codes resulting for each of the four questions. We provide examples of these codes, particularly highlighting areas of subtle or important distinctions. While these examples are technically "results," we include them here for ease of reading and fuller understanding of the coding process. The full lists of categories, along with different example student responses for each question, are provided in the Appendix (Tables 1-4). Both within the main text and in these tables, student responses are provided verbatim and unedited for grammar, spelling, or content. Details of each question and the responses are discussed below.

For Question 1 (travel to Enceladus), the categories created were based on the issues or challenges involved with the spacecraft getting to Enceladus or in other words 'Travelling' there (code T), issues involved with humans 'Surviving' there (code S), and 'Other' (code O). During the team activity on Migration to Mars, students were asked to read a NASA article about hazards to humans during this type of travel (Whiting et al., 2019). This article outlines five hazards: radiation, isolation and confinement, distance from Earth, lack of gravity, and hostile/closed environments. Codes S-HR, S-HI, S-HG, S-HC were used for those who mentioned such hazards as 'radiation,' 'isolation,' 'lack of gravity,' and 'confinement' or closed environment in their responses, respectively. Some students talked about the impact of such hazards on 'physical or/and mental' health of the astronauts. Code S-PM was used for such responses.

An example of cases of overlap for this question is how students used the term 'gravity' in their responses that suggested different foci. In the first case, they mentioned 'lack of gravity' or implied how a low-gravity environment affects the human body and causes muscle atrophy. For these responses, we used code S-HG. In the second case, students talked about the 'strong gravity' of the planet and how it acts as an obstacle on the way of getting the spacecraft to its moon. For these responses, code T-RG was used. Code O-FNR was used for students who failed to provide any reasons to support their answers or if the reasons they provided were irrelevant or unrelated to the question.

Q1.#66: the Distance of the trip, amounts of food and water needed, as well as muscle atrophy due to gravity. [S-HG]

Q1.#2: Since Jupiter's gravity is so strong it would be hard to get a good vector towards the moon. [T-RG]

For Question 2 (Mars Ingenuity helicopter), responses were divided into three main categories: Autonomous (code A), Remotely driven (code R), and Both autonomous and remotely driven (code B). Many students included in their responses the role that people on Earth play in making Ingenuity function. Some students stated that people program the helicopter in advance, but once it is on Mars, Ingenuity is capable of responding to the environment and running by itself. Some others stated that human intervention would only occur in case of emergencies and in order to make changes to the software. To make a distinction between these two groups, two separate codes were created. A-AP was used for the first group, who mentioned 'advanced programming' in their responses, whereas B-PI was used for the second group who mentioned 'people's intervention' during emergencies. An example of each case is given in what follows.

Q2.#22: It is autonomous, but programmed to react to Mars and its surface. [A-AP]

Q2.#123: The team plans flights. It is autonomous but there are people on earth helping it with its travels. [B-PI]

If students used the term 'autonomous', but their reasoning was 'unclear or contradictory', code A-UC was used. For example:

Q2.#95: It is autonomous. It would be very hard to have someone up on Mars to fly it, so people on Earth are making it fly itself. [A-UC]

Code FNR was used for all the cases where students stated 'facts' and did not include any reasons to support their answers, or had irrelevant reasons. This code was applied for all the three categories as A-FNR, R-FNR, and B-FNR.

Q2.#42: NASA's Ingenuity, flies autonomously, tracking the ground during flight. Constantly trying to stay on the correct trajectory. [A-FNR]

Q2.#17: its driven by a person on earth by controlls and a camera. [R-FNR]

Q2.#7: It has both functionalities, it has been tested and shown that the autonomous flight works so far, theoretically ventures with remote controls should be successful. [B-FNR]

In Question 3 (solar sails versus chemical rockets), we categorized all the reasons students provided to support their answers under Reasons (code R), and those who did not provide a valid or relevant reason were put under Other (code O). Ten subcategories were created to cover ten different reasons students used to answer this question. Similar to the previous questions, code FNR was used for all the cases where students talked about 'facts' or stated 'non-relevant' reasons.

At first, all the responses that mentioned 'energy' in some way were sorted under one single code, R-ER, 'reason being energy related'. On subsequent analysis, two new codes were created, R-SE and R-EF, to help distinguish between the ones who specifically talked about 'sustainable energy' and those who mentioned 'energy efficiency' in their responses. Any answer such as *solar sails never run out of energy, solar sails are solar/star powered, energy is sustainable, renewable*, was given an R-SE code, whereas anything that mentioned 'efficiency' in some way, for example *solar sails are more efficient or chemical rockets are less efficient*, was given an R-EF. In the second example (#119), the code R-AS was also used to show how a solar sail can travel much faster than a chemical rocket.

Q3.#67: A solar sail utilizes light particles called photons. Similar to an ion thruster that use ionized atoms that are forced out of a rocket, each atom or particle that makes contact with sail can give a small push, and in space where there is no friction, these pushes create momentum. [R-SE]

Q3.#119: A solar sail is a better option than a chemical rocket for sending a spacecraft to study a nearby nebula because it is much more fuel efficient as we recently learned. [R-EF] And can also reach speeds considerably faster than a chemical rocket. [R-AS]

Some students mentioned in their responses both the fuel efficiency and use of an unlimited source of energy as reasons why solar sails are better options than chemical rockets to study a nearby nebula, for which we used both R-EF and R-SE codes.

Q3.#101: A solar sail uses energy from solar photons compared to a chemical rocket which uses a much less effective fuel source. [R-EF] The solar sail is the better option since it uses solar photons which are essentially infinite compared to a chemical rocket. [R-SE]

In Question 4 (2 factors in spacecraft decisions), many students' responses were unclear as to whether they were describing 'factors' or 'reasons.' Because of this, we ultimately used the same coding scheme for both factors and reasons. The codes were divided into five categories in terms of what relates to Destination (code D), Travel (code T), Spacecraft (code S), Mission (code M), and Other factors (code O). We also created subcategories for each. Category 'Other' had only one subcategory, coded as O-FNR, standing for 'facts/non-relevant' as in the case of the previous questions.

In the example below, the student has specifically mentioned the factors and separated them from her/his reasons.

Q4.#3: one factor is it how far away it it, [D-DT] which effects how much fuel and supplies you need [S-LS] and another factor is the terrain on the planet, [D-LT] the spacecraft needs to have suitable landing or atsomsperic gear available. [S-DE]

Code M-TY was specifically used for those responses that mentioned the type of the mission, including but not limited to the type of the mission being autonomous or driven by a pilot, whereas code S-PT was applied in the cases where students talked specifically about the propulsion type for instance comparing chemical rockets to solar sails. Refer to the example(s) below:

Q4.#98: One factor is the length of the mission. [T-TS] This is important because some forms such as gas or ion thrusters aren't able to go as far as solar sails. [D-DT] Another important factor is what will the mission be trying to achieve. [M-TY] A rocket carrying a rover is a lot different then a rocket carrying a satellite into space. [S-PT]

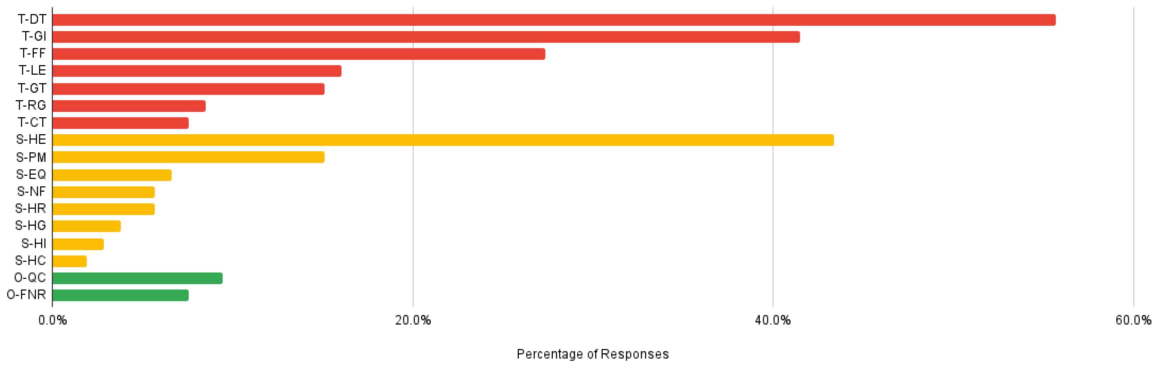

Figure 1. Responses related to Q1: What are some challenges associated with human travel to Enceladus? (N = 106) T:Target, S:Surviving, O:Other. The N and percentages presented here are unique to this question.

In some cases, the same code has been used more than once. We used code T-HR twice for the example below.

> *Q4.#5: Radiation and temperature controls. Moving toward the sun exposes the crew to heavier radiation levels as it gets closer to the sun. [T-HR] Temperature would also be a factor as a craft got closer to planets closer to the sun. [T-HR]*

4 Results

We used N to represent the number of responses collected for each question, and n to represent the number of responses that received the same code. Bar graphs were created to show percentages of different codes for a given N. Students' responses may have up to eight codes each. As such, totals greater than 100% are observed. In this section, we have included each question followed by a description on the number of responses collected, the most and least frequent codes that have been used and the bar chart created for that specific question. As a reminder, the full lists of codes can be found in the Appendix (Tables 1-4) and student quotes are provided verbatim.

4.1 Question 1: Challenges in travel to Enceladus

What are some challenges associated with human travel to Jupiter's moon, Enceladus? [Note: This should have been Saturn rather than Jupiter; student responses to this error are discussed below.]

For this question, N = 106 responses were collected. A minimum of one and a maximum of eight codes were given to each response. Most responses identified 'distance' and 'time' as the main challenges associated with human travel to Enceladus. Therefore, the most frequent code used was T-DT, n = 59 (55.7%). The second and third most frequent codes used were S-HE, n = 46 (43.4%), and T-GI, n = 44 (41.5%). S-HE was applied for those responses that identified a 'harsh environment,' specifically the atmosphere and temperature of the moon as a challenge of surviving there. T-GI was used for students who mentioned that 'geysers and ice' on the surface of Enceladus are challenges associated with traveling to, or more specifically landing on, this moon. Figure 1 shows the frequency of the various codes developed from responses to Question 1.

Ten students corrected the question and stated that Enceladus is Saturn's moon, for which we used code O-QC. Of those ten, several students pointed out that the trip as described would not be possible. Other students simply corrected the error, then proceeded to include information about Saturn's moon, Enceladus.

> *Q1.#7: I think that this is a Saturn moon [O-QC]...But it is a very cold moon, [S-HE] has ice all over its surface, and shoots water out of it. [T-GI] It is not habitable at all! Due to the moon having ice all over, it would be hard to study because to do so you would have to break the ice and since the moon is so cold that would be nearly impossible to achieve.*

The least frequent code used for this question was S-HC, n = 2 (1.9%), which tells us that only two students identified 'confinement or closed environment' as a hazard for people to survive, or a challenge associated with human travel to Enceladus. O-FNR, the code used for those who stated 'facts' or used 'non-relevant' reasons was used only eight times, n = 8 (7.6%).

4.2 Question 2: Ingenuity as autonomous or remote

Currently the Mars Ingenuity helicopter is being tested. Is this helicopter driven remotely by a person on Earth, or is it autonomous? Explain your reasoning.

The total number of responses collected for this question was N = 150. A minimum of one and a maximum of four codes were given to each response. The results show that the number of responses for which we used code A (autonomous) is n = 122 (81.3%), which contrasts with the number of responses for which we used code R (remotely driven), n = 21 (14.0%). The number of responses for which we used code B (both autonomous and remote) is n = 2 (1.3%), and the number of responses for which we used both codes A and B is n = 5 (3.3%). The example below shows how we had such cases where both A and B codes were used for one response.

> *Q2.#10: The helicopter is being driven by both a person on Earth and autonomous. [B-PI] This is because if something were to go wrong, it needs to be overridden by someone on Earth. If nothing is going wrong, it can be driven autonomously because it has its set programming [A-AP].*

In this example, we see both B-PI and A-AP codes, which at first glance seems redundant. This response, and others like it, uses 'both' and 'autonomous. Additionally, our coding process allowed for codes at smaller grain size (e.g., phrases or sentences) as opposed to a single code per response.

Figure 2 shows the frequency of codes emerging from the Question 2 responses. The most frequently used code, A-CT

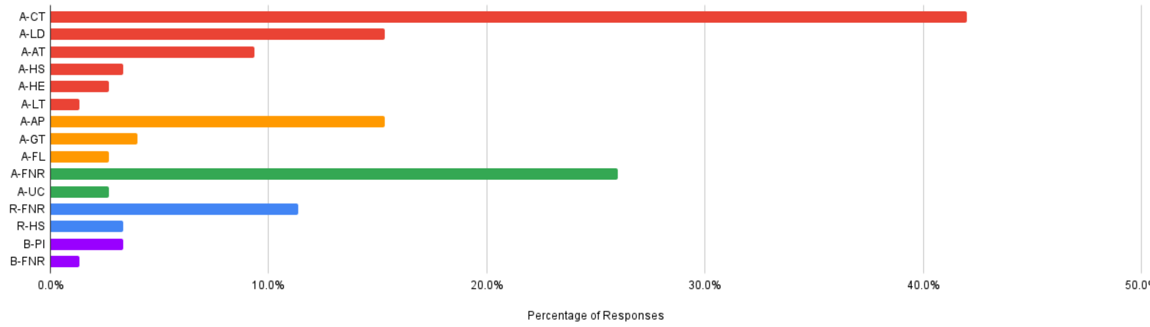

Figure 2. Responses related to Q2: Is Ingenuity driven remotely by a person on Earth, or is it autonomous? (N = 150) A:Autonomous, R:Remotely driven, B:Both. The N and percentages presented here are unique to this question.

(autonomous, communication and timing) was applied to *n* = 63 (42%) of student responses. These students stated that the helicopter must be autonomous, and the communication delay between Earth and Mars, if driven remotely, was their main reason. The second most frequently used code, A-FNR was used for some students, n = 39 (26%) who stated that the helicopter was 'autonomous' but failed to use a valid reason to justify their answers. Similarly, this number is *n* = 17 (11.3%) for those who stated Ingenuity is 'remotely driven' and *n* = 2 (1.3%) for those who stated it is 'both' but failed to justify their answers. Codes R-FNR and B-FNR were used for these cases, respectively.

Codes A-LT and B-FNR, *n* = 2 (1.3%) were the least common codes used. A-LT was applied for those who stated that Ingenuity is 'autonomous' because it would be a 'long and difficult task' if someone was going to remotely control it from Earth.

> *Q2.#24: The Mars Ingenuity helicopter is an autonomous vehicle. The vehicle's mission is experimental and was used to get a reading over long distances covering the surface of Mars. [A-FNR] It is probably easier to have the helicopter fly itself for that long period of time rather than keep a person on a remote control in order for it to fly. less manpower is required. [A-LT]*

A-HE, A-FL, and A-UC codes, respectively meaning 'human error,' precision in 'flying and landing,' and 'unclear reasons' were all the second least common codes used, each *n* = 4, (2.7%).

4.3 Question 3: Solar sails versus chemical rockets

Why is a solar sail a better option than a chemical rocket for sending a spacecraft to study a nearby nebula?

For this question, *N* = 123 responses were collected. A minimum of one and a maximum of six codes were given to the responses. Any response that included at least one valid reason was given an R code. Figure 3 shows the codes and frequency of those codes for this question. The most frequent codes used were R-LF (*n* = 78, 63.4%), R-SE (*n* = 69, 56.1%), and R-AS (*n* = 51, 41.5%), which means that most students identified using 'less fuel', 'sustainable energy', and reaching a higher 'acceleration or speed,' respectively, as the reasons why solar sails are better to study a nearby nebula. The least frequent code used was R-DA (*n* = 2, 1.6%). This code was used for any given reason that was related to 'destination adaptation' such as terrestrial landing.

> *Q3.#19: A solar sail doesn't need fuel carried with it [R-LF] as it uses photons from the son. [R-SE] It can also reach faster speeds than a chemical rocket [R-AS] and because studying a nebula probably wouldn't involve a terrestrial landing [R-DA] a solar sail would be the best option.*

Codes R-LF, R-SE, R-AS, and R-DA were used for the example given above. These codes stand for 'less fuel', 'sustainable energy', acceleration & speed, and 'destination adaptation'. Code O-FNR was used by only n = 3 (2.4%) of students.

4.4 Question 4: Two factors in spacecraft decision making

What are at least two factors involved in deciding what kind of spacecraft to send to a location in space, and why is each important?

The number of responses collected for this question was *N* = 138. One to eight codes were given to each response. Although we originally coded factors and reasons separately, we ultimately found that they were difficult to disentangle and so instead we did not separate these two categories as we came up with the numbers discussed here and in the bar chart below (Figure 4). The most frequent codes used were S-LS: *n* = 77 (55.8%); D-DT: *n* = 68 (49.3%); and T-TS: *n* = 63 (45.7%). The least frequent code used is M-CM: *N* = 13 (9.4%). The results indicate that about 56% of students pointed out that to send a spacecraft to a location in space, 'load and size' of the spacecraft is the most important factor to consider. The second most important determinants are the 'distance from Earth', and desirable 'travel time and speed' of the spacecraft. The results also show that about only 9% of students think that challenges in 'communication' with people on Earth would be a factor in deciding what kind of spacecraft should be sent to a location in space. The example given below is one of the two responses for which we used eight codes.

> *Q4.#74: One factor involved would be the temperature and pressure of the location in space that the spacecraft is going [D-AT] to because temperatures could affect what kind of materials the spacecraft could be made of. [S-MM] For example, the hottest planet, Venus, has temperatures over 800 degrees which can melt different types of metals. The planet also has a thick atmosphere so pressure is very high there which makes it difficult for spacecraft to withstand. Another factor would be how far away the intended location/destination is. [D-DT] This is important because the time it will take for the spacecraft to reach its location [T-TS] can determine the goal of the mission, [M-TY] the budget, [M-CT] and if it is a realistic mission (we can only travel so fast). Additionally, the further away it is, the longer it will take for data to be sent back to Earth [M-CM] which could determine what type of software the spacecraft is equipped with. [S-DE]*

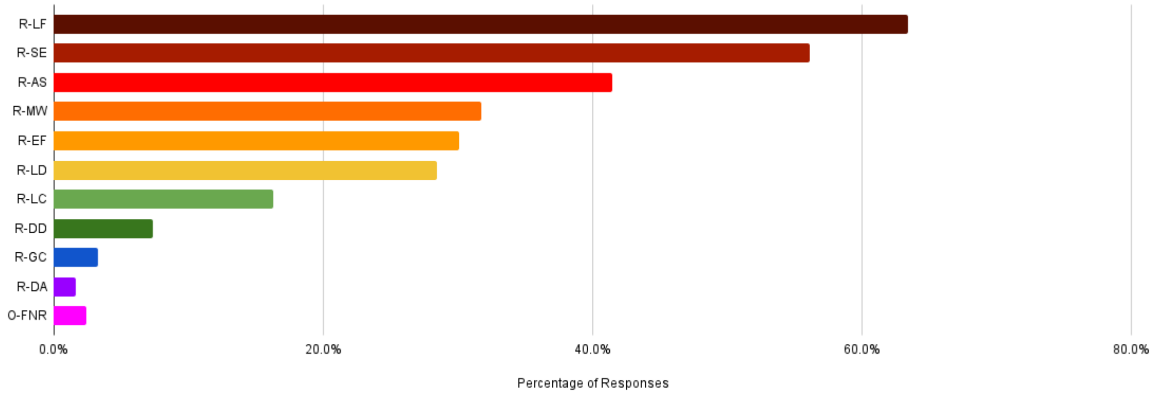

Figure 3. Responses related to Q3: Why is a solar sail a better option than a chemical rocket for sending a spacecraft to study a nearby nebula? (N = 123) R:Reason, O:Other. The N and percentages presented here are unique to this question.

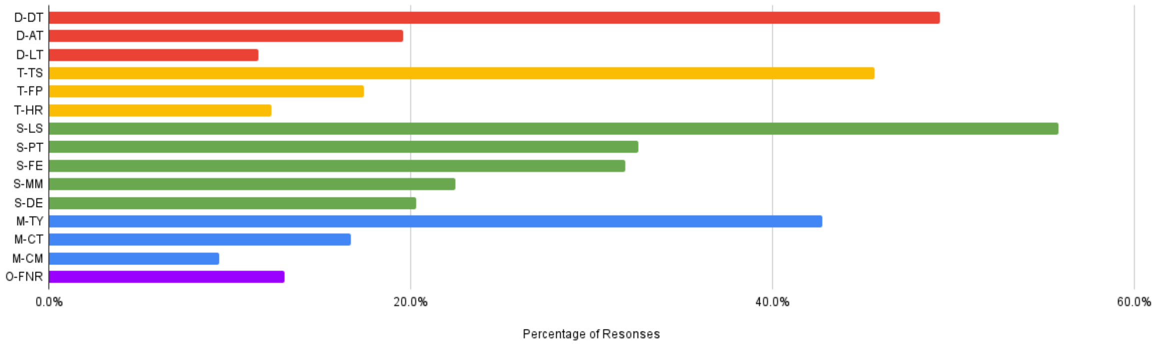

Figure 4. Responses related to Q4: What are two factors involved in deciding what kind of spacecraft to send to a location in space? (N = 138) D:Destination, T:Travel, S:Spacecraft, M:Mission, O:Other. The N and percentages presented here are unique to this question.

4.5 Discussion

As a reminder to the reader, the research question for this exploratory study was: *What do students describe as the benefits and challenges of both human and non-human travel through space, after completing activities on solar sails and human migration to Mars?* With respect to questions that more closely related to the Mission to Mars activity, we find that students are able to describe some challenges realistically. For example, many students (63 responses on Question 2) pointed out that space travel is made more difficult by the fact that communication times increase with distance from Earth. Students also did not express an understanding of the dangers that space travel poses to the human body. Whereas students for the most part pointed out that Enceladus is a frozen and inhospitable moon (46 responses), many students did not express the five hazards (only 15 statements out of 290 responses) that NASA has stated about humans exploring space (Whiting et al., 2019).

Benefits were largely addressed in the Solar Sails activity and associated questions. Most students successfully described meaningful differences between various types of spacecraft propulsion options. Sixty-nine students expressed an understanding that solar sails use light as their fuel, and as a result this type of spacecraft can travel vast distances and also have a relatively small mass—a benefit of this particular type of propulsion. Other benefits included the use of sustainable energy (69 responses of 123), better acceleration (51 responses), and higher energy efficiency (37 responses). Students also successfully explained ideas related to how spacecraft choice depends on the target location (111 responses of 553 total) and mission goals (95 responses).

Considering the responses across questions, we find that students discussed the distances involved despite the different focus of each question. Understanding the vast distances between astronomical objects was a primary focus during this unit in the course. The fact that students chose to bring this up as a real constraint and tie it both to travel time and communication delays is notable, especially given that this point is not frequently the focus of films or other popular media regarding space travel, and in some cases is even misrepresented. They also consistently discussed load size/fuel constraints across varying contexts.

In this study, our questions were very different from the limited past research in this area, and thus it is difficult to draw direct connections to say whether our results corroborate with past studies. For example, Entradas and Miller (2010), Cook (2011), and Afful et al. (2020) all focused on support for space exploration rather than any understanding of its benefits and challenges; we did not ask questions about this in the present study. In the most closely related study, Lyra et al. (2020) found that students better understood the habitability of another planet after their intervention activity.

The present study explored new ideas around students' understanding of space exploration. Qualitative data as used here offer some insights into student thinking; however, choosing how to code student responses is often difficult, and this study is no exception. One example is related to the human hazards of space travel. During the team activity on Migration to Mars, students were asked to read a NASA article about hazards to humans during this type of travel (Whiting et al., 2019). This article outlines five hazards: radiation, isolation and confinement, distance from Earth, lack of gravity, and hostile/closed environments. On the quiz, students were asked to comment on, “What are some challenges associated with human travel to Jupiter’s [sic] moon, Enceladus?”

Several students mentioned radiation and isolation specifically when answering the quiz question. Seven students mentioned radiation, and three students mentioned isolation; one student wrote all five hazards described within the NASA article. Nonetheless, we chose to code all responses related to physical and mental health under one code named as such. Another choice could have been to separate out more specifically the types of hazards that were listed in the article.

Although this cannot be confirmed by the data we have collected, we posit that students provided some answers based on films they have seen about space travel. Several students mentioned mental health issues related to fighting, arguments, living in close proximity to others, and more that are also covered under the more general, ‘closed environment’ hazard. The majority of students who mentioned gravity (n = 8 students total), mentioned the strength of Jupiter’s gravitational field as a potential hazard. This is very different from how the hazard is presented by NASA, which points out the effects of low gravity on the human body. We do note that three students specifically mentioned muscle atrophy as an issue, which is better aligned with what was presented in the reading (Whiting et al., 2019).

In both of these areas, we see that students’ ideas are related to those posed by experts but not always the same. Their ideas provide good starting points for elaboration of the challenges of human space exploration but may need additional instruction to better understand both the nuances of specific facets and the breadth of considerations that NASA and other entities must consider in their decision-making. As written, these activities do seem to improve student understanding about human and non-human space travel. In popular culture, the communication delays are often either glossed over, or greatly reduced. And while there are plenty of films about the psychological aspect of living in space, there are other important risks that must be factored in when determining whether or not to send a human or robotic mission. Finally, having a basic understanding of propulsion systems is also useful for students to comprehend when discussing missions within and beyond our solar system.

For the Migration to Mars activity, students told the instructor that creating Instagram posts was a fun way to express their understanding. Students drew a large array of posts, and many students also created hashtags to go with their drawings. Creativity is incredibly important in science. Problem solving during all phases of mission development and deployment depends on the creativity of the team, and so asking introductory astronomy students to employ their creativity in class aligns well with scientific reasoning. As Duane (1989) said when summarizing work by Arnheim, “Art is an instrument of reasoning and sight is the most efficient organ of human cognition” (p. 135). By drawing Instagram posts of their trip to Mars, students were encouraged to think through specific aspects of the mission.

Much like a space mission itself, the assessment of students’ ideas could benefit from additional refinement and testing. Some students’ responses can be considered useful tools for future planning of the lesson or its assessment. Clearly, fixing Question 1’s reference from Jupiter to Saturn is needed. Additionally, either making a better distinction between “factors” and “reasons” in Question 4 or asking a separate question about the reasons might help make student responses easier to categorize.

4.6 Limitations

There are three primary limitations in this study. The first limitation is that this course has traditionally been taught in person, but this particular semester during which the activities were completed and data collected was fully online due to the COVID-19 pandemic. Second, the student body at this institution is not necessarily representative of the overall US population, let alone students globally. Third, the study explored only post-instructional ideas, and not yet in great depth. We expand on each of these limitations below.

During a non-pandemic semester, students form learning teams of four students each. The teams work together most class periods, completing lecture-tutorial style activities (Prather et al., 2013) on paper and turning them in at the end of class. When the pandemic struck, this class went online, like most classes in the US and elsewhere. For the semester of this study, we were well into online classes, and this was the third time this class had been offered fully online. Whereas the students had mostly gotten used to the fully online format, a number of students struggled with the team work. They were asked to use Microsoft Teams or similar communication software weekly to work with their groups, but this did not always go smoothly. Also, because the class was fully online, students were able to procrastinate until very shortly before the due date. This was not possible in the in-person version of the course. Overall, the team portion was simply more difficult for the students to complete in this format of the course.

Further, the fact that this course was fully online implies that students had free access to the internet during the completion of the team activities and of the quizzes. Although students were told that the quiz was not open book nor open internet, we must assume that some students used these resources in any case. This could mean that some responses were more sophisticated than would be expected had the quiz been given in class with a proctor.

The second major limitation of this study is that it is a sample of convenience. Astronomy classes are very popular across the US, so it is fairly common to have large class sizes in which to do these types of studies. Indeed, that is the case in this sample, with each section containing on average over 150 students. However, the population of students at the institution where the study was completed is more white and more male than the overall US population. Hence our findings may not hold at other institutions. Additionally, this type of course seems to be less common in other countries; as such, it should not be assumed that students around the world would hold similar ideas or take away the same ideas when learning about space exploration.

Finally, this study was intended to be exploratory in nature, and as such did not investigate students’ pre-instructional understanding or how it changed over time, nor did it dig into students’ understanding to a great depth. These were beyond the scope of this particular study but we would encourage future researchers to implement expanded research designs to better understand the nature of these ideas. Such work could take on a more quantitative approach to look at, for example, whether any changes over time are statistically significant or using a cluster analysis to identify groups of students whose thinking is similar to one another. Alternatively, qualitative investigations could allow researchers to better understand the depth of student understanding about the topics. Now that the lessons have been fully incorporated into the curriculum, questions such as the ones here or new ones could be included in the required unit quiz, perhaps providing additional insight into students’ understanding of the benefits and challenges of space exploration.

5 Conclusions

This study investigated what students remembered about certain aspects of space exploration, both crewed and uncrewed, after participating in two lecture-tutorial style activities in an introductory astronomy course. We found that students generally had good, if somewhat incomplete, ideas about the kinds of factors that influence decision-making (e.g., use of solar sails versus chemical rockets) and those that would impact humans (e.g., hazards of longer distance space travel). The two activities used in class, though short in duration and focused on particular examples, can provide a basis for meaningful learning about space exploration. Our study provides a starting point with room for future research to look in more detail about what and how students come to understand factors relating to space exploration.

6 Declarations

6.1 Ethical considerations

This research was approved by the Internal Review Board of Montana State University (SW081721-EX).

6.2 Competing interests

The authors declare that they have no competing interests.

6.3 Funding

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8 Appendix

The following tables provide the detailed code list for each question along with example student responses.

Table 1. Categories and sample student responses for Question 1: *What are some challenges associated with human travel to Jupiter's [sic] moon, Enceladus?*

[a]Sample student responses are provided verbatim, with the most relevant portion of the response for a given code provided in bold.

Categories	Subcategories	Codes	N	Example Student Response[a]
Getting There (code T)	Distance & Time: too far or too long to get there	T-DT	59	A challenge associated with human travel to Jupiter's moon, **is the distance to get there. Since it would take a decent amount of time to get to the moon and back**, fuel could potentially be an issue. Additionally, if something were to go wrong while the humans were traveling, there would be little to no way to send aid on time. Finally, the isolation for the astronauts could prove to be an issue. Human emotions could lead to fighting and breakdowns which would hinder the mission.
	Geysers & Ice: hazards on the surface	T-GI	44	**Enceladus is a moon that has ice geysers on it. This means that it most likely has liquid water beneath the ice surface**. One challenge associated with human travel to this moon is that the extreme weather conditions are something we do not know how to handle at this moment in time. Temperatures can reach down to -330 degrees Fahrenheit which is completely inhabitable for humans to withstand. Another challenge is that it is very far from Earth and would take a long time to get to it.
	Food & Fuel: running out of either	T-FF	29	One issue, is the distance and time it would take to travel there. **The resources, food, and communication are all things that you have to consider**. It is not possible, at this time, to travel that distance because of the cost, the danger, and of course the resources needed.
	Landing & Environment: difficulties in landing	T-LE	17	**The planet does not have a solid surface to land on**. There is also **extreme pressures and temperatures** on Jupiter, which the spacecraft wouldn't be able to handle.
	Good Technology: requires advanced programming	T-GT	16	**We do not yet have the technology to send humans on the long duration of a trip** as it would take multiple years of space travel at the moment, and we could not pack enough essential supplies for life. Also, we do not know if the human body can handle the conditions of space for that long without major negative effects.
	Rings, Gravity, and Debris: objects on the way	T-RG	9	**There is an asteroid belt between Jupiter and Mars, so a spacecraft would need to maneuver around the belt**. Jupiter has very high winds and intense tornadoes, so it would be difficult to live on the surface.
	Cost: too expensive	T-CT	8	**It would be incredibly costly in terms of food, hydration, fuel for the rocket, building the rocket, and tools for building a setup**. It would also be difficult to fly through/near Jupiter to get to Enceladus because of its extremely high temperatures.
Surviving There (code S)	Harsh Environment: temperature and atmosphere	S-HE	46	One major issue would be that **the moon is bitterly cold and would be difficult for crafts and humans to survive its harsh climates**. While liquid water is believed to be under its surface there are not any other known resources and the water itself would be salty which means it would need to purified before human consumption. Lastly there is a giant geyser at the Southern pole that would need to be heavily monitored, as well as the matter it projects out, for entry and exit of the planet.
	Physical & Mental Health	S-PM	16	The gravity is way less than Earth's $9.8 m/s^2$, **so muscle atriophy would pose lots of problems** also, it is 780 million miles away. The only reason I would say is that gravity acting on our body is very unpredictable, and the long-term results are very unexplored.
	Equipment: having what is needed	S-EQ	7	The challenges associated with human travel to Jupiter's moon, Enceladus would be it's distance to get there, and also **the equipment needed to be able to survive while on that moon**.
	Food: not enough food	S-NF	6	The **life support (food, water, air) required to live for the duration of time it takes to reach Jupiter is not feasible** with current technology.

Continued on next page

Table 1 – continued from previous page

Categories	Subcategories	Codes	N	Example Student Response[a]
	Hazard: radiation	S-HR	6	Some of the challenges associated with human travel to Jupiter's moon are the time required to travel to the moon and back, the amount of fuel required to propel the craft there and back, the supplies necessary to sustain a crew for that duration of time, **and potentially Jupiter's radiation belt**.
	Hazard: lack of gravity	S-HG	4	**The gravity is way less than earths** $9.8m/s^2$ **so the muscle atripohy would pose lots of problems** also it is 780 million miles away. The only reason I would say is that gravity acting on our body is very unpredictable and the long term results are very unexplored.
	Hazard: isolation	S-HI	3	The distance makes this quite the risk **since they will be isolated the entire time and can't get help should something happen** also, they will be in close quarters with a small group of people that could end up causing mental issues, and as of now, there is a lot of solar radiation in the way that we are not ready to deal with yet.
	Hazard: confinement	S-HC	2	There are many challenges such as space radiation, isolation, gravity fields, and **closed environments that may affect the human mind**.
Other (code O)	Question Correction	O-QC	10	I believe **Enceladus is a moon around Saturn and not Jupiter**. So the exact answer would be that its impossible since there is no Enceladus around Jupiter. Assuming the question meant Saturns moon Enceladus, it would be challenging to travel on because of its water vapors geysers. They reach out very far into space so if space ship were to make it to enceladus it could be hit by one of the geysers.
	Facts/Non Relevant	O-FNR	8	Enceladus is small and icy. There is an ocean of some sort on enceladus but scientists have found that the active south pole of this moon is in constant motion stretching and cracks are pinched from gravitational forces.

Table 2. Categories and sample student responses for Question 2: *Currently the Mars Ingenuity helicopter is being tested. Is this helicopter driven remotely by a person on Earth, or is it autonomous? Explain your reasoning.*

[a]Sample student responses are provided verbatim, with the most relevant portion of the response for a given code provided in bold.

Categories		Subcategories	Codes	N	Example Student Response[a]
Autonomously Driven (code A)	Constraints	Communication Time: lag and delay in sending and receiving signals	A-CT	63	The helicopter is autonomous because if it were controlled by a human, **it would take too long to communicate with**. Like Curiosity the rover, it can cover more area and explore more since it's autonomous.
		Large Distance: too far to send humans	A-LD	23	The helicopter is autonomous; that is one of the defining features of it! **Mars is too far away for the helicopter to be driven in real-time**, but the flights are pre-planned.
		Mars Atmosphere: atmosphere is too harsh for humans	A-AT	14	This vehicle is autonomous. The helicopter needs to be prepared for anything to happen such as **Mars' crazy sandstorms**. A signal can take up to 20 minutes to get to Mars, and a human may not be able to get the full aspect of the situation and what is around the helicopter. The helicopter will need to be able to protect itself in any emergency situations without a human controlling it.
		Human Survival: not safe for humans	A-HS	5	Autonomous. We would not test it this early with a human. We might as well use technology to do this as a test run and experiment. **It may be safer and more humane**.
		Human Error: programs reduce human errors	A-HE	4	The Mars Ingenuity helicopter is autonomous because **this reduces the amount of human error possible during flights**.

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Table 2 – continued from previous page

Categories		Subcategories	Codes	N	Example Student Response[a]
		Long time for humans	A-LT	2	The Mars Ingenuity helicopter is a robotic helicopter autonomously driven. It has solar cells, batteries, and doesn't carry science instruments. **This mission would be a long and arduous task if someone on Earth was driving it remotely** - which is why it was programmed to navigate itself and carry out the mission. It took about 31 Earth days for Ingenuity to land, which is a long time for someone to be staring at a robotic helicopter and driving it.
	Affordances	Advance Programming: the helicopter is programmed from Earth	A-AP	23	The Mars Ingenuity Helicopter flies autonomously, **but the flights are programmed from Earth**.
		Good Technology & Programming: the helicopter uses advanced technology	A-GT	6	It is autonomous. Mars is too far away for someone on Earth to control the helicopter when it's on Mars, and **the technology is advanced enough that a helicopter can be programmed to functionally perform on its own** in a situation like this.
		Precision in Flying & Landing: autonomous is more precise in flying and landing	A-FL	4	The helicopter will do it itself. **They have to be very careful where they land it on Mars** or the whole system will get messed up and won't work.
	Other	Factoids/Not Relevant	A-FNR	39	The Mars Ingenuity helicopter is able to fly autonomously when charged on solar power. Also, the blades have to spin super fast because of the thin atmosphere on Mars...
		Autonomous, but unclear	A-UC	4	The helicopter is **autonomous but still follows the commands of a NASA** crew on Earth.
Remotely Driven (code R)		Factoids/Not Relevant	R-FNR	17	It is being driven remotely by a person because in order to be recorded we had to know when it would fly.
		Human Survival: not safe for humans	R-HS	5	This helicopter is driven remotely. This is because **we still don't have the technology and knowledge to take people to Mars. This is the safest way to test mars** and test our technology without anyone getting hurt.
Both Autonomous & Remote (code B)		People: humans involved during testing and programming but program runs independently once there	B-PI	5	I haven't researched this, but my guess is that **it's both**. The **autonomous mode would be easier than trying to control it from Earth**, because there would be a delay for radio signals trying to control it (probably only a couple minutes, but enough to be annoying). We would **probably also want to keep remote control possible, just in case we ever want it for some reason**.
		No Reasoning Provided	B-FNR	2	It has **both functionalities**, it has been tested and shown that autonomous flight works so far; theoretically, ventures with remote controls should be successful.

Table 3. Categories and sample student responses for Question 3: *Why is a solar sail a better option than a chemical rocket for sending a spacecraft to study a nearby nebula?*

[a]Sample student responses are provided verbatim, with the most relevant portion of the response for a given code provided in bold.

Categories	Subcategories	Codes	N	Example Student Response[a]
Reasons (code R)	Limited Fuel: does not depend on limited fuel	R-LF	78	Because **they don't rely on a fuel source** besides radiation so they can travel much farther than fuel-reliant spacecrafts.

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Table 3 – continued from previous page

Categories	Subcategories	Codes	N	Example Student Response[a]
	Sustainable Energy: uses energy from the Sun	R-SE	69	A solar sail is better because **it gets the energy/fuel it needs from solar energy (light from the Sun and other stars)**. So there is a virtually unlimited supply of this fuel in space. However, a chemical rocket relies on physical fuel that it can burn, which runs out very quickly. So it would be nearly impossible to "pack" enough physical fuel to get a chemical rocket all the way to a nebula.
	Acceleration & Speed: accelerates more and travels faster	R-AS	51	A solar sail **is much faster** and much more efficient than using a chemical rocket.
	Less WeightMass: is much lighter without the fuel load	R-MW	39	A solar sail **is much lighter weight than having to store chemical fuel on a long spacecraft journey**. It is also very consistant and will fail do to an error in thA solar sail is much lighter weight than having to store chemical fuel on a long spacecraft journey. It is also very consistant and will fail do to an error in the engine or fuel leakage, etc. As long as there is light hitting the solar sail, photons will be pushing the sail and accelerating the spacecraft.
	Energy Efficiency: uses energy more efficiently	R-EF	37	A solar sail is a better option for sending a spacecraft to a nearby nebula because it **is much more efficient and utilizes the protons already in space** instead of utilizing the chemical reactions that will need to be initiated
	Long Distance: can travel longer distances	R-LD	35	The solar sail is a better option **due to its reliability as a source of propulsion and lengths at which it can travel**. The solar sail uses particles from the sun to propel itself forward allowing it to be almost completely reusable as long as there is some sort of star to allow these particles to collide with the solar sail.
	Less Cost: is more cost efficient	R-LC	20	A solar sail is both **more efficient cost wise and material wise**. Due to the all "organic" production and working mechanisms, solar sails are able to gather data in a way that is cheaper when building it and might be less expensive maintaining it since other materials are not needed or used when operating a sail.
	Different Dangers: does not react or explode	R-DD	9	It is more safe due to the **reactions with a chemical rocket and nebula that could occur**.
	Guidance & Communication: is easier to navigate	R-GC	4	It is **easier to control** when it is in space.
	Destination Adaptation: can get closer to the nebula	R-DA	2	Because a solar sail wont have any reaction to the hot source that a nebula has radiating off of it. The chemical can only go so far before the heat makes it less reliable to report information because of the danger it can have of possibly exploding by the magnificent amount of heat. Where as the solar sail would harvest the heat plus the solar power and be **able to possible get closer, not by much but still closer.**
Other (code O)	Facts/Non Relevant	O-FNR	3	The solar sail is a better option because unlike the chemical rocket it does not burn chemicals.

Table 4. Categories and sample student responses for Question 4: *What are at least 2 factors involved in deciding what kind of spacecraft to send to a location in space, and why is each important?*

[a]Sample student responses are provided verbatim, with the most relevant portion of the response for a given code provided in bold.

Categories	Subcategories	Codes	N	Example Student Response[a]
Destination Characteristics (code D)	Distance From Earth: how far is it from Earth	D-DT	68	one factor is it **how far away it is**, which effects how much fuel and supplies you need and another factor is the terrain on the planet, the spacecraft needs to have suitable landing or atsomsperic gear available.
	Atmosphere & Temperature: how its atmosphere and temperature are	D-AT	27	**1. Temperature of the planet:** A very big factor is deciding what type of machinery you will need to build and what temperatures it should be able to handle. Space alone will be quite cold, but a planet such as Venus or Mercury might melt your spacecraft. 2. Distance: If you are planning on sending out a multi-billion dollar piece of machinery into space, you should know how far it needs to travel. Carrying a fuel tank will be costly and weigh heavily. In that case, you can send out a solar sail into space that will charge itself on the Sun's light..
	Landing & Terrain: if and how the spacecraft will land	D-LT	16	Considering location is important. If we are **sending a spacecraft to land on a planet it will need landing gear**, and be able to survive entering an atmosphere. Additionally, considering if the spacecraft will return, or leave its destination after its purpose is served. This requires flight path controls and maneuvers to bring its trajectory back into earth. These are important to consider because there is little to no rules about leaving spacecrafts in space, and if the craft can survive is important because its expensive to send things into space, and we want to glean information from the craft.
Travel (code T)	Travel Time & Speed: how long the mission takes	T-TS	63	Two possible factors include **the time it would take to complete a mission** with said spacecraft as well as the cost of this mission and spacecraft. For example: if the price is substantial for a minor mission then it wouldn't be worth it to send it into space. The spacecraft would have to be minimized in terms of features and supplies. Or if the mission would take an incredible amount of time then the space crafts size would have to larger to support all the food, fuel, and equipment necessary for a long journey.
	Flight Path, Orbit, & Navigation: how is the path/what is on the way	T-FP	24	Flight Trajectory: to see **what the spacecraft may encounter** Distance from Earth: has to sustain different temperatures
	Heat & Radiation Exposure: how much exposed to heat and radiation	T-HR	17	**Radiation and temperature controls.** Moving toward the sun exposes the crew to heavier radiation levels as it gets closer to the sun. Temperature would also be a factor as a craft got closer to planets closer to the sun.
Spacecraft (code S)	Load & Size: its fuel size and supplies	S-LS	77	**Size and weight are probably two of the most important factors**. The larger and heavier the craft, the more complications you might have getting the craft of the ground on Earth and back into a landed location (if you are landing) or to settle it into an orbit somewhere else.
	Propulsion Type	S-PT	45	**One factor is its propulsion**, because that will decide how long it takes to arrive at that destination and what sort of fuel will be needed. Another important factor is where it is going to decide its primary function. Depending on where it is going will decide if it will simply follow and orbit path and take photographs, or if it will need to land on a unknown surface and move over rough terrain, if it will collect samples and analyze data, etc.
	Fuel Type & Efficiency: its fuel efficiency	S-FE	44	**Two factors involved in deciding what kind of spacecraft to send is fuel efficiency and mass**. Fuel efficiency is important because it determines how far a spacecraft can travel. This also leads into the mass of the space ship because liquid fuel accounts for a lot of weight involved. Mass is important to look at because in order to send the mission into space, we must have the capability to lift it out of our atmosphere. The heavier the object is, the harder it is to achieve that task.

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Table 4 – continued from previous page

Categories	Subcategories	Codes	N	Example Student Response[a]
	Materials made of	S-MM	31	**1. Material. Having a space craft that is made out of durable material** that will not combust through Earth's atmosphere, in space, and with the possibility of collisions with other space rocks and junk. 2. Speed. Being able to have a craft that is able to get to the location in the fastest amount of time possible is also a large factor. Scientists need to be able to study quickly, and if there is an astronaut on board, it needs to be able to get there in a human lifespan.
	Technology, design, and equipment	S-DE	28	**the design** and orbit, as not every mission is the same and with our current **technology**, we would need to focus on not landing, but orbiting the planet.
Mission (code M)	Type: autonomous vs. human driven	M-TY	58	1. **factor is mission design**, meaning they design and plan out the path of the spacecraft then this can go into the 2nd factor of orbit determination, meaning they keep tact of the spacecraft while the mission is in flight.
	Cost: the budget	M-CT	23	One factor in deciding what kind of spaceship is **the amount of money that is involved**. Money plays a huge role in what the final decision of what is being bought. Another factor is what they are wanting to make the spaceship out of. This is important because unsafe material that is used for a spacecraft will put many at risk or death, and also if it falls apart they lose a great amount of money.
	Communication: how to send and receive signals/information	M-CM	14	**The ability to communicate with researchers on Earth is important** because the primary purpose of a spacecraft is to provide more information on space. With proper communication from a spacecraft, we will still be able to learn from the mission even if it does not successfully make it back to Earth. It is also important that the spacecraft can hold off and handle heat because the planets in our solar system are very bright.
Other (code O)	Facts/Non Relevant	O-FNR	18	Two factors and methods that are involved in deciding what kind of spacecraft to send to space are the doppler and transit methods. Doppler was invented first, but it faded and requires powerful technology in order to discover new things about space. Transit was discovered during the Kepler mission which measures light from a star.