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Designing and Implementing a PDP Inquiry Activity for an Introductory Astronomy Research Methods Course

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Abstract

We designed, facilitated, and re-designed an inquiry activity in an introductory undergraduate astronomy research methods course at the University of Texas at Austin over two different semesters. The teaching venue for this inquiry activity took place in the course "*AST 376R: A Practical Introduction to Research Methods*", the inquiry activity was inserted into an existing course structure, taking place over multiple class periods. We discuss how we were able to leverage the Professional Development Program (PDP) inquiry themes and introduce students to specific STEM practices, using this experience as a primer or mini version of a larger research activity and research experience that they would determine and lead themselves later on in the semester. In this paper we describe the benefits for students in this course and the lessons learned by the instructors.

Keywords: activity design, argumentation & explanation, astronomy, course design, inquiry

1. Introduction

The Astronomy Department at the University of Texas at Austin (UT Austin) has been a Regional Chapter of the Institute for Scientist and Engineer Educators (ISEE) since 2016. The PDP was an ISEE program that ran from 2001-2020 in which graduate students, postdocs, and other professionals in science and engineering fields were trained in effective and inclusive teaching practices, centered on inquiry learning, primarily at the undergraduate level. As part of the PDP, two teaching teams worked together to not only experience first-hand the value of inquiry learning in Science, Technology, Engineering, and Math (STEM), but also received training in how to effectively design and implement an inquiry activity. The ISEE inquiry framework (Metevier et al., 2022) focuses on providing learning experiences in which learners have the opportunity to engage with and learn some foundational STEM content (knowledge), but also a core STEM practice. As we describe below, this focus on developing an inquiry activity that simultaneously imparts both content knowledge and STEM practices was especially important for the activity we designed in our unique teaching venue.

In 2018 and 2019, two teaching teams created and iterated on an inquiry activity to take place in our department's Introduction to Research Methods course for astronomy undergraduate students. The activity had a core content theme tied to identifying protostellar / stellar properties and evolutionary stages by utilizing spectral energy distributions of the stellar objects. The core astronomy content was chosen because of the interest and expertise of the facilitators (teaching team members), but as we describe in Section 2, another major focus of this activity was the core STEM practice, explaining results based on evidence, that was part of this inquiry.

In this course, students will often encounter research techniques, skills, and astronomy-specific research tools for the very first time. With this in mind, we aimed to include practices and skills in the inquiry activity that students could utilize throughout the course. Many of the process skills, or practices, that are valued and needed by astronomy and physics students are desired outcomes in a research methods course such as this one. In addition, research has shown that an effective way to learn these process skills is through inquiry teaching, where students are given opportunities to make their own decisions, and enough time to go back and iterate as needed (e.g. Holmes & Wieman, 2018; Metevier, et al. 2022).

Often more traditional content-based courses, especially at the introductory level, focus almost entirely on content / concepts and much less on development of students' expertise with scientific practices. However, in this introductory course, due to the nature of the course outcomes and course structure, we were able to more easily build in a structured inquiry activity to support student learning and skill development. In this paper we will describe the inquiry activity we developed in 2018 and improved in 2019, the teaching venue, and the background of the learners. We will describe the benefits of creating an inquiry activity for a less content-driven course. We will also discuss how this teaching venue differed from other PDP offerings, and what accommodations we had to put into place for one that had to utilize shorter lecture class periods. We will share our implementation strategies and results as an example for others who wish to integrate inquiry into undergraduate lecture courses. We will also share comparative results in terms of student outcomes in the two iterations. Finally, we will discuss lessons learned and benefits of this type of activity both from the student and instructor perspectives.

2. Activity

2.1 Teaching venue / learners

As part of the PDP process, teaching teams are expected to identify a teaching venue where an inquiry activity will be facilitated. Typically, PDP teams might teach inquiry activities in longer workshop settings, such as an introduction to a Research Experience for Undergraduates (REU) program, or some other extended workshop / training event. Another common PDP teaching venue might take place in longer lab style class periods. Even outside of the PDP, we often see that many K-12 educators will have multiple and longer class periods to facilitate an inquiry activity (National Research Council, 2000).

The teaching venue we chose did not follow one of these more traditional settings and did not offer the typical extended learning time. In the fall of 2018 and fall of 2019, we implemented an inquiry activity in the AST 376R "*Practical Introduction to Research Method*" undergraduate course at UT Austin over three shorter, standard / lecture class periods. The 2018 iteration was created and facilitated by Keely Finkelstein (Design Team Lead) and Zach Vanderbosch, with initial development contributions from Jessica Luna. The 2019 iteration was created and facilitated by Raquel Martinez (Design Team Lead), Aaron Rizzuto, and Fabíola Campos.

Approximately twenty students were enrolled in both offerings of the course, for a total of 40 students. This course primarily serves astronomy and physics majors who are in their first or second year of their undergraduate major. There is no pre-requisite for this course, but it is a required course for all astronomy majors at UT Austin. Many students take this course before moving into other independent research projects with faculty members and research groups on campus. The learners will typically have taken one to two semesters of introductory Physics and Calculus, but typically have not yet had very many advanced Physics or Astronomy courses. The overall course learning objectives for this class are very skill-based, and less dependent on specific astronomy content knowledge. For both versions of our inquiry activity, we took three separate class periods, each lasting 75 minutes, for a total of 3.75 hours of direct contact with the learners. This is significantly less than what others might do in a more traditional workshop style inquiry activity spanning 6-8 hours over a single day. This led us to be creative and very intentional about the time we did have with the learners, and also try to leverage some activity pieces that learners could do on their own outside of the class time. We will describe these in more detail in Section 2.3.

2.2 Practice goals of the activity

We identified a number of important reasons for why this specific teaching venue was chosen, despite some of the more logistical challenges that we will discuss further in Section 3.4. One main benefit and reason for teaching an inquiry activity in this venue was the alignment of the STEM practices, which are an integral part of the PDP-designed inquiry activities, with the learning objectives of this course.

Independently, both the 2018 and 2019 teaching teams identified the same STEM practice that we wanted students to engage in and improve at the most. The activity we designed used the following STEM practice which was centered on explaining results based on evidence:

- Making a claim related to the investigation and data
- Connecting claim and evidence through reasoning, and
- Interpreting whether observations support the claim.

The AST 376R course learning objectives also include some of the following:

- Identify and execute existing routines, in an interpreted programming language, that can be used to solve a discrete scientific problem.
- Practice interpreting astronomical plots and summarizing them to others in a classroom setting.
- Find observations of astrophysical objects in telescope archives and decide what information about the object could be extracted from those data.
- Solve complicated multi-stage astrophysical problems using a mix of pre-built routines and new custom-built code.
- Present a short course-based research project to peers for evaluation.

These course learning objectives are more detailed and aimed at the astronomy-specific program learning outcomes for majors but dovetail nicely with the chosen STEM practices.

A second important consideration for the inquiry activity in this teaching venue was that, not only would students be gaining practice at explaining results based on evidence, students would also be able to apply and practice these skills in the class itself, later on in the semester, and for future research endeavors. Throughout the semester, teams of students self-select different content areas to design a research project around. From our own past teaching and mentoring experiences, we recognize that learners often are able to explain, plot, and visualize data, but one of the larger hurdles can be the ability to make a scientific claim and support it through evidence (which can include data and models). In addition, based on feedback from one of the lead instructors for this course, students often do an excellent job at defining a research question, identifying a set of data, and writing algorithms to analyze data, or using other software tools to analyze data. However, one of the areas that students seem to struggle with is fully explaining results and making a scientific claim and supporting it through evidence and reasoning. This is where our PDP inquiry activity came in and where we aimed to support the development of these skills.

2.3 Detailed description of the activity

Both the 2018 and 2019 iterations of this activity had similar content goals, along with very similar STEM practices to implement (as described in previous section).

For content goals, both teams focused on learners using observations of stars or protostars to model and interpret spectral energy distributions to infer stellar properties and evolutionary stages of the stellar objects. In this section we will describe the overall format of the activity, including an in-house Spectral Energy Distribution (SED) fitting tool that was developed and used by both groups. We describe the main activity components, and how they were introduced and implemented over the three-day period and discuss the commonalities and differences in each iteration of the activity.

2.3.1 Activity description — 2018 initial iteration

For the 2018 iteration we had three classroom days with the students for a total of 3.75 contact hours. During Day 1, we started with a broad introduction to the activity, including background terminology / concepts relevant to the activity, such as spectral energy distributions, and blackbody radiation, as well as protostars. We then implemented a "Raising Questions" section with three stations. At each station students were presented with an image or plot of a different star forming region, and students would generate questions, and make observations related to images and data (SEDs of protostars). See examples of stations in Figures 1 and 2.

Following the raising questions station rotations, students had the opportunity to select a question and/or star forming region they wanted to work on by doing a "gallery walk", reviewing all of the previous stations and full list of generated questions from all groups. New groups were then formed (typically 3-4 people per group) based on the students' individual choices. This allowed students to self-select based on their own interests and curiosity. This was a specific design choice, to support one of our underlying goals of helping to promote STEM identity and ownership for learners.

Once teams were formed, they were given a worksheet in order to write down and formalize their Team Research / Investigation Question. The final part of Day 1 featured an introduction to the SED tool by the facilitators. This also involved a small amount of time for students to investigate, and

Figures 1 & 2: Examples of students participating in the Raising Question stations from 2018.

practice with the SED tool, which they used in a more in-depth way on Day 2.

During Day 2, we began with a scaffolded plotting exercise in Python, which involved the entire class, and gave them more practice with using the SED tool. After this review and practice, the team-based data investigations began with teams using the SED Fitting tool and working towards answering the research questions they developed on Day 1. This took an entire class period but was still limited in that students only had about 90 minutes total for the group investigations in class (over the course of all three days). In between classes 2 and 3, groups were encouraged to work on a final wrap-up of their exploration of the data (if needed) using out of class time.

Day 3 of the inquiry activity began with a small amount of time set aside for teams to conduct a final wrap up of the exploration of their data, and quick team debriefs with each other and facilitators as needed. Then the learners were given an individual Culminating Assessment Task (CAT) worksheet. In these CATs, students were presented with a new source (SED) that might be similar or different from some of the protostars / stars their team explored. Students were tasked with using the observations and investigations of their given protostar sample to identify components in this new object's SED, and to determine any physical structures or properties of this new object. Students were asked to label any parts of the SED they could identify, draw a cartoon version of what their new object might look like in reality, and finally make a claim about the evolutionary stage of this object and then explain it to their teammates

After the individual CAT exercise took place, teams then came back together to make a group poster / presentation based on their group's investigation, research question, and findings. The inquiry activity concluded with teams presenting their team posters and findings to the entire class.

2.3.2 Activity redesign — 2019 iteration

In 2019, protostars and SEDs were also used as the content base for the inquiry activity, with alterations from the design team to allow for alignment with their interests and expertise. The activity spanned 2.5 classroom sessions for a total of 3 hours of contact time with learners, slightly less than the original iteration. The changes / additions made for the 2019 version included:

- A broader group lecture during the beginning of Day 1 to contextualize the activity and provide foundational knowledge regarding telescopes, photometry, stellar observations, and blackbody radiation
- Raising Questions — same initial process, but Questions raised were then presented as a gallery walk, and learners ranked three questions they would be interested in investigating
- Formation of small learner investigation teams was done by the teaching team to take into account learners' interests and group demographics
- Facilitators presented a content prompt to guide poster preparation after the student teams' investigations were completed on Day 2.
- On Day 3, learners finalized their posters and presentations. Presentations were given in rotations where one team member presented for their group while the others heard from the rest of the class about their science questions, investigations, and conclusions.

2.3.3 SED tool developed

As the core concepts of spectral energy distributions, blackbody radiation, and protostars or stellar evolution might be new to many of the students in this course, we aimed to create a simple interactive software tool that would help participants visualize these concepts. Developed in-house using the Python programming language, we also wanted this tool to minimize the need for any prior

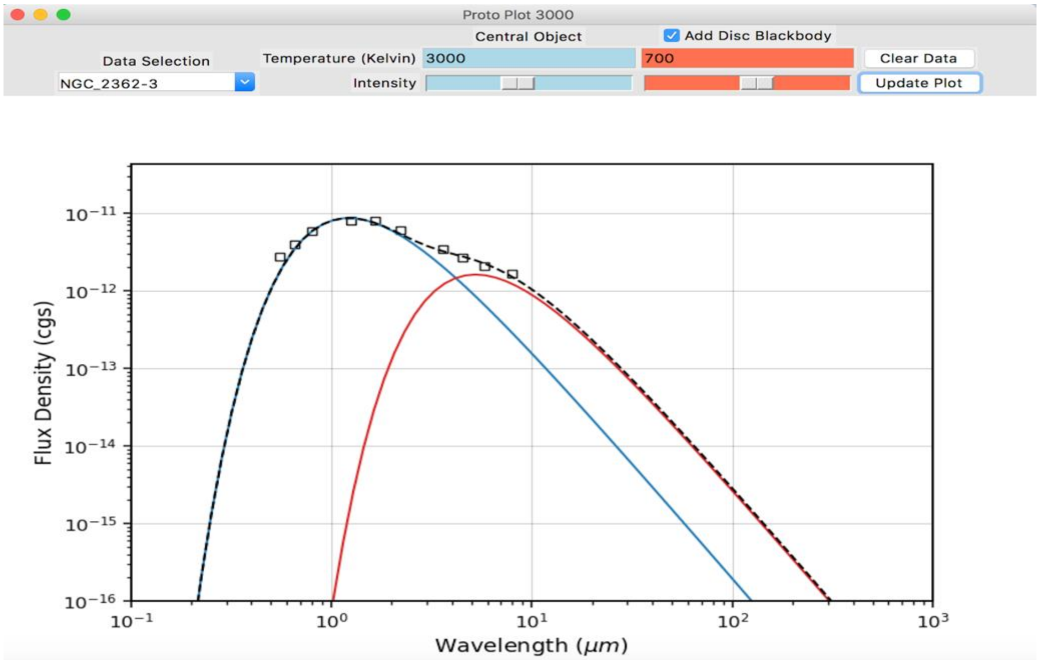

Figure 3: An example of the SED Fitting Tool GUI. A dropdown menu on the left provides a list of real protostars for which data can be plotted (square markers). Students can then overplot one or two blackbody functions (red and blue lines), varying the blackbody temperatures via manual input and the relative blackbody intensities using horizontal sliders to achieve a best fit to the data. The black dashed line shows the sum of the two individual blackbody functions.

programming knowledge amongst the participants while allowing them to interact with real astronomical data and models. The resulting product was a simple graphical user interface (GUI), the SED Fitter tool (see Figure 3).

This tool allows students to display the measured SEDs for a variety of protostars from three different star forming regions and then attempt to fit a simple SED model consisting of one or two blackbody components. These components are meant to represent the central object and/or the surrounding dust and gas. Students had the ability to manipulate the temperatures for each component and their relative strengths, which relates to their relative masses. Students could also choose whether to plot one or two SEDs in order to best fit the data.

This tool was well suited for the *AST 376R* course, which takes place in the UT astronomy department's undergraduate computer lab, where each student has access to their own computer. We were able to deploy and test the SED Fitter tool on each lab computer beforehand, and all students were able to simultaneously use the tool.

3. Discussion

For both iterations, we found many benefits and successful learner-centered outcomes that were achieved through this activity. The location in which we taught the activity during both semesters was in a newly renovated computer lab situated within UT Austin's Department of Astronomy. This space was outfitted with state-of-the-art multimedia equipment, individual computer stations, and ample table space, making for an ideal playground to not only be creative, but also ambitious in designing and running the various aspects of the inquiry activities. In this section, we discuss these results and also highlight some of the challenges and lessons learned from conducting an inquiry activity like this one in this specific teaching venue.

3.1 Design choices specific to our inquiry activity

It is helpful to note some of the specifics that we employed in designing our inquiry activity in order to make it work in this teaching venue. To begin with, we attempted to scaffold in the introductory / background material that we wanted all students to know ahead of time in order to be successful in this activity. We wanted the students to be able to quickly jump into the activity given the small number of contact hours we had with them. In both iterations, we decided to support this in two design ways. The first included having a brief primer on some of the content background and jargon so all students would be on the same page regardless of prior experience with this content area. This included sharing with them key words and definitions like blackbody radiation, spectral energy distributions, and what a protostar is. If we had a longer amount of time, we might have chosen to let students explore and learn for themselves what some of these physical quantities or structures are, but we ultimately determined this was an important step to allow students to fully participate in the inquiry activity given some of the constraints.

The second design aspect that we implemented to support the learning was developing the SED fitting tool itself, as described in Section 2.3.2. This was coupled with a curated set of data that we had preselected and designed with enough variety built in, such as different star forming regions which contained varying numbers of total stellar / protostellar objects present, and range of ages of the objects, but would work with the SED Fitting GUI tool. This allowed students to begin analysis and investigation without having to rely on specific programming skills they may not have yet.

The final intentional adaptation was to encourage and allow students to explore some of the research and literature around their selected regions, or types of objects outside of class time. This especially took place for some student groups between Days 2 and 3 of the inquiry activity, where they were close to finishing their investigations. Again, in a pure inquiry activity this choice would not be an optimal one as it can limit students figuring out some things for themselves within the inquiry, but in our format, it allowed students to expand on what they were discovering in the class / inquiry structure. This also mirrors what researchers do, such as reading other people's work / papers to figure out how their own work fits in with existing knowledge. We note that not all student groups chose to do this.

3.2 Maintaining inquiry nature of activity

Even with all of this, we still wanted to ensure that the learners had the opportunity to fully participate in an inquiry activity, including developing some sense of ownership over their chosen project, and developing their STEM identities. The concept of 'STEM identity' refers to whether a person sees themself as a 'STEM person'. Carlone and Johnson (2007) showed that this relates to one's performance of STEM tasks and behaviors, competence in demonstrating STEM knowledge, and recognition by other meaningful people in STEM, such as peers and mentors. We felt that by providing opportunities for ownership in this activity, we were also providing opportunities for students to engage in ways that supported these aspects of their STEM identities. To achieve this, we relied on the important inquiry aspects of our activity, even if somewhat shortened in terms of time. These included the raising questions stations, where learners were still allowed to generate their own questions based solely on their interests and curiosity over the presented data. Then based on those learner-generated questions, students had the opportunity to choose any question to form their research question on, and this led to team selection. Almost a quarter of our time for this activity was dedicated to this piece, because we wanted to make sure this sense of ownership was a strong part of the inquiry process and experience for students.

As discussed in Buck et al. (2008), the extent to which learners might develop their own procedures and methods can vary quite a lot across inquiry activities, despite whether one calls it a structured or guided inquiry, or a full inquiry. And while we did build in more supports / structure for students as they were making their way through the inquiry activity, including providing the GUI SED Fitting tool, there were still multiple ways student teams could productively participate and use this tool during their explorations. This was basically left completely open to them, and this is also where we feel we preserved the inquiry nature of the activity. For example, some teams zeroed in on one specific star forming region that they wanted to explore and to answer questions about the ages, properties, etc., of the objects in that region. Other student teams focused more on the component aspects of what an SED is, and how / why it changes for various objects, therefore using the tool to more broadly look at different objects across regions. Both types of research questions were achievable through this activity and were completely student driven. This opportunity to productively participate in multiple ways is also a key piece of the equity and inclusion theme (Seagroves et al., 2022). Finally, a remaining key piece of our activity that is a crucial part of the inquiry experience is the opportunity for learners to explain and justify their ideas to their peers (Metevier et al., 2022). This was achieved in the Day 3 components of our activity with the poster presentations, done in teams with each individual responsible for presenting some aspect or to different groups in the classroom.

3.3 Results

In Table 1 we share specifics on the two student / learner populations we worked with in the two iterations of this activity, including numbers of participants, current classifications in school, and student majors.

Our main content goal in both iterations was for students to use observations of stellar objects to interpret the shape of the SED of individual objects. They then could use that to identify components of the individual objects, such as presence of gas, dust, and whether or not a source likely had a large disk around it, matching those likely components to specific features in the SEDs.

Table 1: Characteristics of student groups who participated in inquiry activity.

Inquiry Iterations	2018	2019
Number of Students Participating	20	14
Majors in AST / PHY	14	11
Majors in other STEM related fields	6	3
First / Second-year students	9	7
Third / Fourth-year students	11	7

The two teaching teams created slightly different rubrics for assessing students' content understandings from this activity, but with very similar outcomes, consisting of three dimensions. Students' individual CAT worksheets were assessed along each dimension of our content rubric and scored from 0 (understanding not yet demonstrated) to 1 (understanding demonstrated). The following content outcomes were used for each group:

- Dimension 1:
    - Describe basic properties of protostars (2018).
    - Describe how stars are modeled as blackbodies, and the peak and shape of the blackbody profile is related to temperature (2019).
- Dimension 2:
    - Identify features within the SED (2018).
    - Identify that the SED of a star is made up of multiple components from different sources that affect the observed SED.
- Dimension 3:

- ◦ Compare the protostellar evolutionary stages (2018).
- ◦ Identify that different disk configurations have typical SED morphologies (2019).

As shown in Table 2, both student groups were highly successful in using observations, fitting spectral energy distributions to the data, and interpreting results. The most challenging parts of the core concept, especially for students in Iteration 2018, came with the last dimension of our content rubric. For both groups, this was where we were looking for learners to make an extension and connect the parts of their investigation together (Dimensions 1 & 2) in order to make a specific claim. The task related to Dimension 3 in the CAT for the 2019 iteration was somewhat more specific in what it was asking students to do, whereas for the 2018 version the task was more open-ended. This change in both the rubric and CAT from 2018 to 2019 did help us facilitate student learning more effectively and did see improved results.

3.4 Lessons learned by activity instructors

One of the largest lessons learned was the importance of having faculty / course instructors involved or at least present in the inquiry activity as it was being implemented in the course by the PDP-trained teaching team. In both iterations, the teaching teams consulted with the course instructors ahead of time to get input on timing of when to implement the activity within the course schedule, as well as the content and STEM practices that the inquiry activity would feature. This appeared to work well to get faculty / instructor buy-in and make sure the inquiry activity was implemented during a well-aligned time in the course schedule.

Table 2: Student Outcomes. CAT results based on scores from content rubrics. A total of 20 students participated in 2018, and 14 in 2019.

Inquiry Iterations Students scoring 1	2018	2019
Dimension 1:	19	14
Dimension 2:	17	11
Dimension 3:	8	14

During one of the iterations (2018) we were able to have the instructor and lead course TA present during all of the inquiry activity classes, having them on hand to observe, and occasionally lend an extra hand in terms of items like the raising question stations. They also got to see and observe all of the student work, outcomes, and presentations firsthand. For the other iteration (2019), the lead instructor was not present during the inquiry activity and the PDP-trained teaching team led the activity fully, without the added benefit of the instructor getting to observe the student activity. The TA was present for the 2019 iteration, which did give the teaching team a level of authority that would have been hard to manufacture if no one associated with the class were present to assist and/or observe.

We saw more benefits with having the faculty member involved at least to observe. For future versions of a PDP-style inquiry activity inserted into an existing course structure, we would strongly recommend that the course instructor participate and observe in this way. While only having two data points, and anecdotal evidence, which included feedback from both course instructors, we did see an advantage in the first iteration in that this instructor was able to leverage the inquiry activity more specifically later on throughout the course semester. The instructor remarked to the inquiry teaching team that he would often refer to the steps and process that the student teams engaged in during the inquiry activity as they were working on more in-depth research projects throughout the semester. The course instructor for AST 376R changed between 2018 and 2019, and it appeared there was less incorporation of the lessons learned by the students further on in the semester by the instructor in 2019. We feel this was due to the 2019 course instructor not being able to be present during the inquiry activity.

As noted above, through our CATs, one of the areas students struggled the most with was making conclusions based on the evidence they worked with about the evolutionary stage of certain objects or being able to compare to another example. In the 2018 iteration we often found that students were not able to provide any evidence related to their line of thinking in this component of our CATs. Based on this assessment, we conclude that if doing this activity again it would be beneficial to provide more investigation time to ensure learners get to this step in the investigation. The 2019 activity did lengthen the structured amount of time with facilitators, devoting almost a full class period to investigation. This may be a reason for the improved assessments in Dimension 3.

Another option would be to provide more tools, in addition to the SED fitting tool, to allow learners to develop more rigorous investigation questions. This could allow them to explore their questions more in-depth. One specific example that applies to the 2018 iteration would be giving learners more data related to the star forming regions, such as providing more environmental context for the students to explore. This could include exact coordinates of objects, allowing students to map locations, and make comparisons between images and protostar / stellar data. In 2019, the learners also asked more questions than the activity/SED-fitting tool could realistically let them explore, which was refreshing from an engagement standpoint, but still slightly disappointing from a facilitation standpoint in that we needed to guide the learners back toward what we had already planned. Building avenues for investigating more science questions, or science questions more rigorously, would have really enhanced the learners' ownership and lasting understanding of the material away from the activity.

4. Concluding remarks

We believe our attempts to build an inquiry activity into an Astronomy majors Research Methods course was successful and was assisted by two main factors: one — the course itself does not have a large amount of required astronomy content knowledge; instead since it focuses on skill development, we were not bound to cover any specific astronomy content. Because of this, we were able to create and leverage the benefits of an inquiry activity, and frame it with the astronomy content that best worked with our own backgrounds and what was needed to support the development of the activity. The second major factor that we believe assisted in the success of these efforts was including the lead course instructor in the facilitation, or at the very least having that instructor be present and observe all sessions of the inquiry activity. This strengthened how the experience and the lessons the students learned from the activity itself could be used throughout the semester. Another recommendation tied to this factor is that activities like these implemented in similar course formats should strive to have the inquiry activity take place early on in the course term. We found that conducting these inquiry activities over three 75-minute class periods was an adequate amount of time, but any less than this would present greater challenges. If additional class periods could have been used that could have strengthened the overall learning outcomes for some student groups, however this of course has to be balanced with the other needs and time constraints of the course.

Overall, we found many benefits to conducting an inquiry activity in an established undergraduate astronomy majors class. The process was not without its challenges, primarily being structural and time constraints associated with the class meeting times, course schedule, and other required course components. We found that this process can still be successful and beneficial to students and the inquiry facilitators, as long as those constraints are identified early on and collaboration with the lead course instructor is built in.

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