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Culturally responsive astronomy education: using a critical lens to promote equity and social justice

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Abstract To effectively promote equity and social justice in astronomy, we need to acknowledge the role of oppression in the discipline's culture and thus transform the culture into one that is created by and for people of all identities and lived experiences. These actions will improve the teaching and learning of astronomy content. In astronomy-focused learning environments, previous efforts have aimed to address cultural issues by incorporating Indigenous beliefs and practices into astronomy content. Although these efforts are a positive step, they are limited by their lack of critical reflection, thus hindering students from problematizing the systemic and cultural inequities in astronomy, STEM, and society at large. Here, we propose a culturally responsive framework for astronomy education that incorporates asset-building, reflection, and connectedness, and we present a sample curriculum created using this framework. Students learn astronomy content, such as about Solar System dynamics through physical modeling and simulations, as well as participate in discussions that problematize cultural norms and develop potential solutions. Through the use of this framework, students are guided to critically engage with concepts in astronomy, and they are empowered to become change agents for making astronomy a more equitable discipline. Finally, we share some guiding considerations for implementing our proposed framework in other learning environments.

Keywords equity · social justice · culturally responsive · astronomy · education

For decades, the lack of diversity in science, technology, engineering, and mathematics (STEM) has been a topic of concern for both written reports (e.g., National Research Council, 1990) and professional societies (e.g., Gillette, 1972). These reports and programs have highlighted the issue along many axes – racial, gender, ability, sexual orientation, etc. – and at all levels – including students, faculty, and staff in educational settings. However, despite decades of effort, these issues

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continue to persist throughout STEM. Recently, in response to the tragic events of 2020, including the murders of George Floyd, Ahmaud Arbery, and Breonna Taylor, there has been a renewed awareness of systemic biases (especially racism and sexism) in society, leading to an increase in efforts intended to address diversity in STEM. This long-needed attention has spurred the development of movements, such as Particles for Justice's Strike for Black Lives, and programs, such as Unlearning Racism in Geosciences, to try to turn this attention into meaningful action.

While addressing the lack of diversity in STEM will require many solutions along many different avenues, one area where change is needed is within STEM education. The fraction of college STEM degrees received by African American, Latina/o/e/x, Indigenous, and Pacific Islander students falls far below their representation within the general population. For the physical sciences, the American Institute of Physics reports that less than 10% of physics bachelor's degrees are given to Hispanic Americans and less than 4% are given to African Americans (Mulvey and Nicholson, 2020). This trend persists despite the fact that students from these racial and ethnic groups begin college interested in STEM majors at similar rates to White students (Riegle-Crumb, King, and Irizarry, 2019). Additionally, business, humanities, and social science majors experience much lower rates of Black and Latina/o students switching away from these majors as compared to STEM majors (Riegle-Crumb et al., 2019; the terms used to identify the student populations in this sentence are the ones used in their study). Many studies show that students' decisions to leave STEM majors are not a result of academic performance. For example, Richard Kozoll and Margery Osborne (2004) found that students from historically excluded racial and ethnic backgrounds who had high academic achievements still left STEM because they struggled to navigate their experiences and identities within an ideological system and culture that was a barrier to their education. Heidi Carlone and Angela Johnson (2007) interviewed 15 successful women of color in science, and they found that all but two of the black, Latina, and American Indian students (as identified in their study) reported a disrupted science identity, meaning that their experiences in science education were marked by negative recognitions and feelings of invisibility. Elaine Seymour and Anne-Barrie Hunter (2019) pursued the question of why undergraduate students – especially those from historically excluded racial and gender backgrounds – leave STEM fields at higher rates. They found that these students reported lower self-efficacy and sense of belonging in STEM, even when they were performing as well as (or better than) their peers, and many left due to losing confidence in their ability to succeed in STEM. Additionally, Seymour and Hunter (2019) found that poor classroom learning experiences (e.g., poor quality teaching and weed-out effects) dominate the factors contributing to students leaving STEM fields.

The physical sciences, including astronomy, are no exception to these trends. Kathryn Johnston (2019) described the roles of privilege, power, and leadership in academic astronomy, analyzing how individual, unit, and department/organization dynamics reinforced Eurocentric (White- and male-dominated) norms and rejected all other (i.e., non-White and/or non-male) cultures' norms and viewpoints. Additionally, recent decadal surveys for astronomy, which are created by the National Academies of Sciences, Engineering, and Medicine to set the field's priorities for the next decade, have included submissions of white papers about the "state of the profession", including diversity, equity, and inclusion (e.g., Astro2020: APC White

Papers, 2019). More recently, a 2020 report from the American Institute of Physics (AIP) National Task Force to Elevate African American Representation in Undergraduate Physics & Astronomy (TEAM-UP) addressed the fact that the fraction of physics and astronomy undergraduates degrees received by African American students has remained mostly flat for decades, despite numerous programs and efforts intended to increase diversity in these fields. One problem is that these previous programs focused solely on the recruitment of students and did little to address the cultural barriers that hamper their participation. Thus, the report's recommendations included fostering a sense of belonging, improving academic and personal supports for students, and guiding students to develop physics identities (AIP TEAM-UP, 2020).

As another step towards addressing the barriers faced by students from historically excluded backgrounds in STEM, this paper proposes a framework for addressing classroom learning experiences through the implementation of a culturally responsive curriculum. To provide a concrete example of the framework, we present examples from an astronomy curriculum built on a foundation of culturally relevant, responsive, and sustaining education. As Alberto Rodriguez and Deb Morrison (2019) recommended, to ensure we appropriately address diversity, equity, inclusion, and justice, we first need to differentiate and define these terms in ways that stress both *what* they mean and *how* they are exemplified in our work. Drawing from both Rodriguez (2016) and Rodriguez and Morrison (2019), we use the following definitions in this paper.

- **Justice** is a framework for dismantling barriers and sharing power such that everyone can live a full and meaningful life (Rodriguez, 2016, p. 243).
- **Equity** is allocating resources such that everyone has access to the same opportunities and outcomes. Thus, individuals are treated according to their needs, which requires that we cannot treat everyone as exactly the same (Rodriguez, 2016, p. 243). As Rodriguez and Morrison (2019) further clarified, equity and equality are not the same thing.
- **Diversity** is the recognition of "visible and invisible physical and social characteristics" (e.g., racial and ethnic identities, genders, sexual orientations, mental and physical abilities) that "make an individual or group of individuals different from one another" (Rodriguez, 2016, p. 242).
- **Inclusion** creates an environment that is welcoming of peoples of all backgrounds and celebrates diversity as "a source of strength for the community at large" (Rodriguez, 2016, p. 242).

We note that given these definitions, diversity and inclusion are *goals* for us to achieve, and equity and justice provide a *framework* for how we can achieve these goals. To collectively refer to these terms, this paper uses the acronym "JEDI" (justice, equity, diversity, and inclusion).

JEDI in the STEM classroom

Students from historically excluded backgrounds who leave STEM fields often do so because these fields do not foster a sense of belonging. Kozoll and Osborne (2004) found that these students struggled to navigate their culture versus STEM's culture, which is largely dominated by White Eurocentric norms. Thus, the ideological systems and cultures of STEM were a barrier for students regardless of their level of academic achievement. Seymour and Hunter (2019) found similar results, with these students reporting lower levels of belonging in STEM even when out-performing their peers.

One challenge for addressing cultural barriers is that STEM education often assumes that STEM is "“neutral” or “acultural”. While the topics studied may not be inherently biased, STEM is done by people, and thus cultural biases pervade all STEM (e.g., AIP TEAM-UP, 2020). We offer a few examples of how cultural biases affect STEM education, though we recognize that this is not a comprehensive nor exhaustive list.

STEM courses often present a biased picture of who does STEM. In introductory physics and astronomy courses, key topics include Newton's laws of motion, Kepler's laws of planetary orbits, and Maxwell's equations of electricity and magnetism. While all of these scientists and topics are important to STEM, they only reflect the White European males who worked on these topics. However, many important contributions have been made by individuals with different identities, including Chien-Shiung Wu (a nuclear physicist who worked on the Manhattan project to develop processes for uranium enrichment), Katherine Johnson (a mathematician whose work was critical to the success of early American human spaceflight), Lynn Conway (a computer scientist whose innovations led to modern microchip designs), and Vera Rubin (an astronomer whose observations of galaxies confirmed the existence of dark matter). Presenting a biased picture of who does STEM can harm students' development of STEM identities and sense of belonging by denying them role models to whom they can relate (e.g., Lewis et al., 2017).

A related bias is individualism in STEM. In addition to primarily recognizing White European males, we generally speak about them as single-handedly revolutionizing their fields. While individual work is one method of engaging with STEM, much STEM research is done in large collaborations (Wu, Wang, and Evans, 2019). For example, within physics and astronomy, some of the newest discoveries such as the first detection of gravitational waves required the efforts of thousands of scientists, engineers, and others to develop and build the detectors, collect and analyze the data, and obtain the required funding (discovery papers include over 1000 authors, including the first discovery described in Abbott et al., 2016). Similarly, the Event Horizon Telescope's imaging of Pōwehi, the black hole at the center of M87, was accomplished by a team of over 300 scientists (Akiyama et al., 2019). Upcoming projects, such as the Legacy Survey of Space and Time at the Vera Rubin Observatory, will produce petabytes of data, again requiring large collaborations to analyze thoroughly (e.g., Wing, 2019). The primary focus on individual scientists is yet another example of presenting a biased and untrue perspective on STEM.

Finally, STEM has a strong bias towards exclusively valuing “objective” facts. Eileen O'Brien (2004) wrote about Eurocentric educational norms which value objectivity through facts, equations, etc. and dismissed subjective emotions and feelings. This bias is amplified in STEM, where our “products” (e.g., journal articles describing new scientific discoveries) are based on supposedly objective findings. Unfortunately, this bias is also a barrier to discussions of subjective experiences in STEM, including in how we teach, research, and communicate about STEM, and thus inhibits the development of welcoming and inclusive environments. If we want to let students know that they belong in STEM, we are required to value subjective emotions and feelings as important data in our efforts to promote JEDI in STEM education (e.g., Kalamazoo College, 2013). Expecting students to assimilate into the culture of STEM – that is, replacing their own cultures and beliefs with those extolled by STEM – is an inappropriate approach. Instead, STEM needs to change its own culture to be more inclusive (e.g., see Johnston, 2019 for a discussion focused on astronomy; Mattheis, Murphy, and Marin-Spiotta, 2019 for a review focused on geosciences).

Additionally, by not incorporating discussions about JEDI into the STEM classroom, we are failing to prepare our students for their future careers (Chaudhary and Berhe, 2020). For example, as future professionals in STEM, they will have to navigate JEDI topics. As a researcher, they would have to consider issues like citing other researchers in their articles, mentoring students from diverse backgrounds, and incorporating diverse perspectives into their research agendas. As an educator, they would also have to think about whether they are replicating the cycle of teaching a biased perspective of science to their students (e.g., Austin, 2002). Even if our students leave STEM to pursue other careers, these questions and topics will remain relevant because our society as a whole grapples with JEDI (e.g., Starr and Minchella, 2016). Thus, it is important to both incorporate JEDI concepts into the classroom (e.g., by being aware of whose voices are represented in readings) as well as engaging students in explicit conversations and discussions about JEDI.

To transform the cultures of STEM and STEM education, multifaceted solutions will be needed. One approach for JEDI in the classroom is through how we address and incorporate culture into our curricular activities, teaching, pedagogy, and other educational practices (Corneille, Lee, Harris, Jackson, and Covington, 2020). In the following subsections, we first provide background on different educational approaches that attend to students' cultures. Next, we propose a specific curricular framework created from the tenets of culturally relevant, responsive, and sustaining education. We close this section by addressing how these various approaches have been used (or mis-used) in the STEM education literature, including in physics and astronomy. In the following section, we will provide examples from an astronomy curriculum using our proposed framework.

Background: culturally relevant, responsive, and sustaining education

Culturally relevant pedagogy. Gloria Ladson-Billings (1995b) first defined *culturally relevant pedagogy* as one that empowers students academically as well as socially, emotionally, and politically by focusing on building bridges between culture and content to expand knowledge, attitudes, and skills. Students developed cultural competencies, which enabled them to use their cultural knowledge as vehicles for learning. Additionally, students developed a critical consciousness, which empowered them to identify and address social inequities. For example, Ladson-Billings (1995a) detailed an example where students in her largely African American community received older textbooks, but the students in the predominantly White community received new textbooks. The students engaged in "community problem solving" and wrote to their local newspapers to critique the bias in textbook distribution.

Culturally responsive teaching. Building on her work with teachers, Geneva Gay (2018) developed an approach of *culturally responsive teaching.* Teachers following this approach reflected on their own positionality in order to develop an awareness that allowed them to validate students' cultures, leading them to be socially, politically, and emotionally comprehensive as they sought to teach the "whole child". By making connections between culture and the material they teach, they aimed to lift "the veil of presumed absolute authority" and liberated students from oppressive educational practices. Gay (2018) described an example icebreaker activity she did with teachers in her classes. Several teachers were selected at random to publicly declare their ethnic identities and provide "personal evidence", such as examples of values, behaviors, or beliefs that were consistent with their identities. They then reflected on the effects of hearing others' arguments of ethnic identities on their own thinking, as well as how they approach ethnic and cultural diversity in their classrooms. This exercise helped to create the norms for her class, while demonstrating the importance of critical analysis of experiences, and began creating camaraderie among the participating teachers.

Culturally sustaining pedagogy. Complementary to the prior two approaches, Django Paris (2012) proposed a model of *culturally sustaining pedagogy.* Much education can be described as following deficit approaches, which generally viewed students' own beliefs, knowledge, language, etc. as deficiencies that needed to be overcome and replaced by academic content. While both Ladson-Billings (1995b) and Gay (2018) rejected deficit approaches, Paris (2012) argued that they do not go far enough. These prior approaches potentially would have only students maintain their own cultural practices in the process of gaining academic (dominant) ones. Instead, Paris proposed an approach that had students sustain their own cultural competencies while still gaining access to dominant cultural knowledge. For example, educators in the U.S. should support students to continue speaking their native languages while also learning English.

Culturally responsive computing: asset building, reflection, and connectedness (ARC)

Building on the foundational tenets of culturally responsive (Gay, 2018), culturally relevant (Ladson-Billings, 1995b), and culturally sustaining education (Paris, 2012), Kimberly Scott and Mary Aleta White (2013) proposed a framework for applying culturally responsive teaching in a computer science-based curriculum. Their model, culturally responsive computing, incorporated these three tenets:

1. **Asset building**: Recognize and integrate students' beliefs, knowledge, and values into the learning process, which requires building a rapport with students so that they believe their voices will be heard,
2. **Reflection**: Guiding students through a process of identifying, questioning, and assessing knowledge, assumptions, behaviors, identities, etc. and how they came to be, and
3. **Connectedness**: Creating a peer culture and strengthening students' ties to their larger communities, which creates a sense of accountability and commitment to their communities.

This approach (hereafter the “ARC model”) was applied in COMPUGIRLS programs (Scott and White, 2013). As an out-of-school program for girls, COMPUGIRLS began in 2006, encouraging adolescent (ages 13-18) participants from economically strapped contexts to see technology as a means by which they can problematize social inequities and develop solutions. Through a series of digital media courses emphasizing digital storytelling, game building, and/or simulations, the program emphasized that all students are capable of digital innovation, and by learning more about oneself along intersecting social identities, they can expand their contributions to both technology and their communities. Scott and White (2013) found that the participants were motivated by the thrill of learning and mastering technology. They often entered the program with high perceptions of technology’s instrumentality, and so the program created spaces for them to disprove stereotypes about abilities by age, race, and gender and to grow their understandings of how they can participate in digital communities. Furthermore, participants reported a greater sense of empowerment, richer sense of self, and stronger commitment to communities. They were motivated to manipulate technology for self-expression and research that could inform their communities and peers.

Thus, the ARC model guided students to become *techno-social change agents*, people who are capable of problematizing social inequities and developing solutions using the technical knowledge and skills they have learned (Scott and Garcia, 2016). Furthermore, COMPUGIRLS programs included a “closing ceremony” where participants presented a final project to their fellow participants and invited community members. These ceremonies both reinforced connectedness as well as created opportunities for participants to be recognized for their achievements by meaningful others, such as family, friends, etc. (Carlone and Johnson, 2007).

Considering the success of the ARC model in increasing self-efficacy, empowerment, and sense of self, we propose that the three tenets of the ARC model can serve as a framework for improving our approach to STEM education. In the following section, we will present a new astronomy curriculum created using the ARC model. Through use of this model, our goal is to empower students to become techno-social change agents with the skills and knowledge to problematize inequities in astronomy – knowledge and skills that are transferable to their contexts in STEM and society more broadly (Fig. 1). Our new curriculum also draws on the results of previous STEM education literature, which we briefly summarize in the next subsection.

Applications in STEM education literature

In this subsection, we review examples in STEM education research literature about applying culturally relevant, responsive, and sustaining approaches to STEM education settings. First, we discuss the literature on inclusive and learner-centered teaching; next, we discuss specific examples in physics and astronomy. While many of these examples aimed to create inclusive environments that are welcoming of students’ personal knowledge and cultures, they rarely included consistent critical reflection and explicit references to social justice within the material presented to students (e.g., as discussed in Ashcraft, Eger, and Scott, 2017). In contrast, we close this subsection by discussing “social justice (science) education”, which

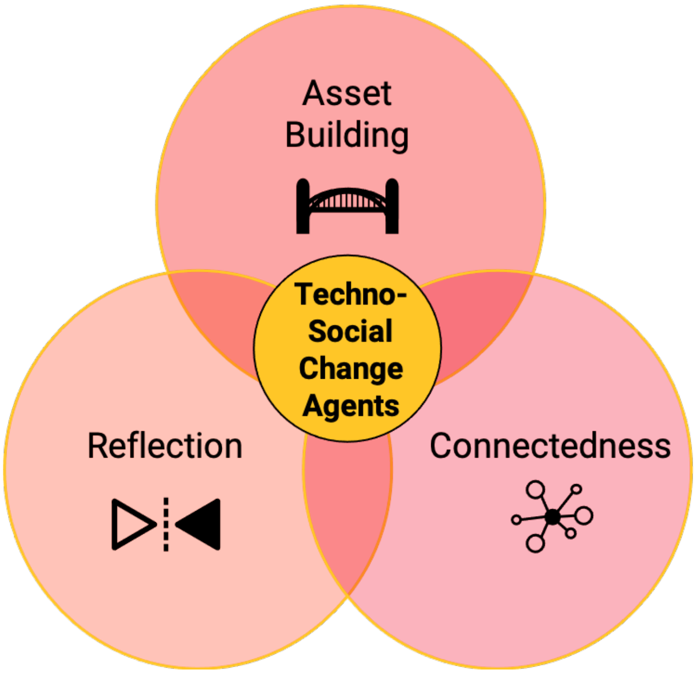

Fig. 1 Schematic representation of the ARC model, leveraging asset building, reflection, and connectedness to empower students to become techno-social change agents. We use this model in developing an astronomy curriculum that empowers students to become change agents for equity and social justice.

draws on the foundations of culturally relevant, responsive, and sustaining education, and explicitly focuses on social justice conversations in the classroom. While beyond the scope of this paper, other studies have investigated topics such as how to effectively conduct professional development for teachers on culturally responsive education (Brown and Crippen, 2016) and how K-12 science standards and practices overlap with culturally responsive and relevant practices (Brown, 2017).

Inclusive and learner-centered teaching. A growing area in STEM education research focuses on "inclusive teaching" and "learner-centered teaching and practices". For example, Bryan Dewsbury and Cynthia Brame (2019) described an evidence-based model for inclusive teaching that encourages teachers to develop self-awareness and empathy for their students, consider the role of classroom climate, and leverage local and national networks to maximize learning and inclusion. Similarly, Christine Hockings (2010) synthesized research to develop policy recommendations for how to structure curriculum, curriculum delivery, assessments, and institutional supports to create inclusive learning environments. Kimberly Tanner (2013) summarized 21 learning strategies to promote student engagement, such as think-pair-share, assigning reporters for group activities, and asking open-ended questions, noting that these strategies can improve classroom equity. Finally, some research offered frameworks for implementing these strategies, such as Universal Design for Learning, which highlights strategies such as providing students with multiple means of engagement, representation, and expression (e.g., CAST, 2018). While these approaches presented crucial best practices that are steps towards addressing JEDI in STEM education, they did not explicitly address the role of critical reflection and discussions among students. In addition to being a key component of the ARC model, these conversations are important for students' continued learning beyond an individual course. Considering that this may be a students' first class to incorporate these concepts, and that their future courses may not share the same priorities, we need to engage students in *why* these approaches matter. By empowering students to problematize biases and inequities in STEM and STEM education, a culturally responsive course has students practice skills to recognize and dismantle potential barriers that they and their communities have encountered and will continue to encounter in future experiences.

Examples in physics and astronomy education literature. Similar concerns about the lack of critical reflection apply to examples from physics and astronomy education research, including in education and public outreach (EPO) programs. Astronomy is sometimes called a "gateway science" with a strong presence in popular culture and TV shows (e.g., Price, 2009), leading to its ubiquity among (informal) EPO programs (for a review, see Pompea and Russo, 2020). Some of these programs explicitly focused on connections with Indigenous communities, a topic of increasing interest within the field due to controversies over telescope locations and the future concerns of space exploration and colonization (e.g., Venkatesan et al., 2019).

Nancy Ali (2010) wrote about one such EPO program. A series of three workshops were held in Hawaii for general public audiences in 2008. These workshops included Indigenous knowledge and content, such as using a Native Hawaiian calendar based on lunar phases to illustrate the differences between the Moon-Earth and Earth-Sun orbits and periods. Despite calling these "culturally relevant" workshops, Ali (2010) did not make reference to the origin of cultural relevance, and there is no indication that these workshops aimed to engender a critical consciousness among participants (cf. Ladson-Billings, 1995b). While the incorporation of Indigenous knowledge – especially when presented by members of the Indigenous community – is a positive step, if we want to address JEDI in astronomy, we also need to ask questions about why these topics are not a "typical" part of the conversation and how we can change that norm.

Furthermore, some of the physics and astronomy education research literature focused on the implementation of inclusive and/or learner-centered teaching in college course environments. Erik Brogt and Erin Galyen (2019) reviewed principles of learner-centered teaching in introductory astronomy courses, including implementation of backwards design, engagement and buy-in from students and teachers, and evaluation strategies. Edward Prather, Alexander Rudolph, Gina Brissenden, and Wayne Schlingman (2009) focused on general-education introductory astronomy courses (i.e., ASTRO 101), and created a set of lecture-tutorials, activities that students complete in small groups to actively engage students on course content. Christine O'Donnell, Edward Prather, and Peter Behroozi (2021) suggested a set of guiding principles for designing a general-education astronomy course that explicitly included the human story of understanding the Universe, respected and valued students' opinions and views, and provided opportunities for self-reflection and self-identification by students. However, while all three of these studies presented varying levels of asset building in the curriculum, none of these examples engaged students in critical reflection about social inequities. To truly address JEDI in our courses, we need to take these models further to more fully reflect an understanding of culturally responsive, relevant, and sustaining education.

Along those lines, Angela Johnson (2019) summarized culturally relevant teaching from Ladson-Billings (1995b) to promote its incorporation as a framework for college physics courses. They argued that it is a needed change – physics content is challenging enough, so we should not add "an extra, pointless layer of challenge" presented by unwelcoming course environments. They included some examples, such as redefining "academic success" (especially since inequities in K-12 education affect students' starting points in college) and addressing implicit bias. However, this short article did not offer a comprehensive depiction of a culturally responsive course environment, nor did it place culturally responsive education within the broader literature context.

A more promising example is offered by Annette Lee (2020) in their dissertation describing implementation of a culturally responsive approach in ASTRO 101 at a university in South Africa. Their curricular activities included many opportunities for student opinions and beliefs, including on topics about the existence of extraterrestrial life and whether we should try to communicate with them, and the course included opportunities for small group discussion and conversations. The course materials also included an explicit acknowledgement of multiple ways of knowing and understanding. Students also engaged with critical thinking, such as on the topic of "dark skies", the challenge of maintaining a dark night sky versus the urban growth of light pollution. The associated homework assignment asked students to think about how individuals around the globe should share the responsibility given different cultural, political, and economic positions. However, it is unclear if the problematization students made was then used as the basis for investigating options for promoting the issue within their own communities beyond the classroom, which is a hallmark of programs implementing the ARC model (Scott and White, 2013). Lee (2020) found that all students demonstrated increased learning gains in a culturally responsive course with higher final grades (3% higher than final grades in a traditional course) and higher scores on an astronomy concept inventory (30% higher than scores from the traditional course). For students whose racial/ethnic backgrounds were underrepresented in typical courses (i.e., African-American, Hispanic-American, Native American, African (not American), and Multicultural students), the results were more significant with a 6% increase in final grades and a 177% increase on scores on an astronomy concept inventory versus students from similar racial/ethnic backgrounds in a typical course. All students also had higher levels of engagement in the culturally responsive course as measured by classroom observations and anonymous student surveys, and they also reported a higher sense of belonging in the culturally responsive course.

Social justice science education In contrast to the prior examples, some STEM education studies used models of "social justice education", which explicitly integrates social justice into the content being covered; these frameworks often have parallel tenets to the ARC model. Unlike inclusive or learner-centered teaching, these studies go beyond only focusing on asset building techniques by also incorporating critical reflection. For example, Liza Finkel (2018) described their work with pre-service middle and high school science teachers. Their goal was to help these teacher candidates re-conceptualize science teaching, especially since much science education is based on decontextualized textbooks and other materials. By employing a "cycle of written reflection, focused observation, and critical reading", teachers learned how to approach social justice through course elements such as science content, their processes of pedagogical strategies, and assessments of student learning (Finkel, 2018, pp. 51-52). As Finkel (2018) noted, while there were promising results for the teacher candidates' motivation and understanding of social justice, it remained to be seen how regularly they followed through on these goals in their future science courses. As another example, Erica Hartwell et al. (2017) presented a variety of strategies for instructors to incorporate JEDI into their classrooms. For example, they suggested that instructors can build their own awareness of cultural issues by writing an autobiography and/or personal mission statement, and instructors can guide students to build a similar awareness by doing these tasks themselves. Furthermore, Hartwell et al. (2017) recommended that instructors can develop students' knowledge of JEDI by providing opportunities for students to put their knowledge and skills into action by problematizing and developing solutions. While their article is not specific to science education, their recommendations are transferable to these learning spaces.

Finally, Daniel Morales-Doyle (2017) reported on a social justice-centered advanced chemistry class from an urban high school. Throughout the course, content from the College Board Advanced Placement (AP) Chemistry standards was applied in real contexts. For example, homework assignments asked students about chemical reactions and processes to describe the effects of lead poisoning, including how lead diffuses into bone and what this means for the therapies used to address lead poisoning. These skills were then applied to other metals, such as uranium. Morales-Doyle (2017) found that these social justice-based prompts supported higher academic achievement in the course. Students also participated in a project to measure chemicals in the soil to determine the lasting impacts of a recently closed coal power plant. They presented their results at a family science night that the students themselves helped to organize. Similar to how the ARC model has been implemented in COMPUGIRLS programs (Scott and White, 2013) as well as in this paper's astronomy curriculum, these presentations empowered students to be seen as community leaders and to be recognized for their STEM work by meaningful others, including family, friends, and other community members (Carlone and Johnson, 2007). Morales-Doyle (2017) referred to the students as "transformative intellectuals", demonstrating complex critical thinking about science and social justice issues with a commitment to their communities. These findings parallel the ARC model's goal of empowering students to become techno-social change agents (Scott and Garcia, 2016).

Creating a culturally responsive astronomy curriculum

Drawing inspiration from the examples in the STEM education literature, we specifically applied our proposed framework – the ARC model – to develop a new astronomy curriculum. This particular curriculum was designed for Hawaiian junior-senior high school girls and gender minorities, with a likely implementation in an out-of-school program (e.g., a week-long camp or a once-per-week program over the course of a couple of months). The astronomy content goals for the program included topics from the Next Generation Science Standards, which have been adopted in Hawaii; content commonly covered in college-level introductory astronomy courses (e.g., Prather et al., 2009); and skills that they would need if they pursue an astronomy degree in college (regardless of whether they choose a 4- or 2-year institution).

Six approximately one-hour lessons were written, with the final lesson centered on a Closing Ceremony. The full curriculum is available at `https://caodonnell.github.io/files/culturally_responsive_astronomy.pdf`. The astronomy content covered includes

- Modeling the Earth's orbit around the Sun to understand seasons,
- Predicting visible constellations based on time and location on Earth, and
- Simulating the orbits of the planets in our Solar System using an interactive Python notebook as an introductory computer coding exercise.

Here, we focus on a few examples from the curriculum to demonstrate what the ARC model looks like in practice. First, we describe how participants co-create norms for the learning environment, which sets the stage for discussions and other curricular elements generated from the ARC model. Next, we provide examples of asset-building, reflection, and connectedness in the curriculum, though we note that these three tenets are not mutually exclusive (e.g., an activity that includes asset building may also include reflection). Thus, the examples are meant to be demonstrative even though in practice, there is not necessarily a perfect delineation between the three tenets. Following these examples, we describe the Closing Ceremony where participants present their final projects. Finally, we share considerations for applying the ARC framework in other learning environments.

Setting norms

Discussions about social inequities, race, etc. can be challenging topics, especially because students may not have had previous opportunities to engage in these discussions in an academic setting. In order to foster a productive environment for these discussions, the first lesson needs to ensure students have a clear understanding of the rationale behind the discussions (e.g., Ashcraft et al., 2017) and that there are norms for discussions and other peer interactions. Traditionally, norms in science classrooms often refer to specific policies, such as homework and attendance policies, but they can also refer to attitudes and behaviors, such as active listening and believing everyone has something to learn (e.g., Tanner, 2013). Thus, the first lesson involves a longer Opening Activity (as compared to the other lessons) to introduce students to the approach used in the curriculum and has them co-create the classroom norms. This step is important to creating a space where students feel comfortable to take ownership over their own learning (Scott and White, 2013). Prompts in the curriculum can guide an instructor to ensure the norms cover topics including

- Norms for conversations: being respectful, active listening, that there may not be a single "correct" answer;
- Norms for expression: multiple valid ways to express one's thoughts and feelings, including writing, drawing, etc.;

- Norms for group activities: different student roles, sharing duties/responsibilities; and
- Norms for community building: how does one ask for help, how does one offer help.

Asset building

To share another example from the curriculum, in the third lesson, students complete an activity about understanding the constellations and how they change based on time and location on Earth. However, many constellation resources and art exclusively include Western (European) constellations. This bias is a topic covered by many examples of culture-based astronomy courses and EPO programs (e.g., Lee, 2020). However, these programs generally do not engage students in critical reflection on this bias, and in our curriculum, we aim to add in that necessary aspect. During the lesson's Opening Activity, students explore constellations using resources such as Stellarium Web (`https://stellarium-web.org/`) to see that visible constellations change depending on time and location (Stellarium Web, 2021). We then ask students about the constellations they are seeing in these resources – are these the constellations they see when they look up at the night sky? We also ask students about how this bias makes them feel, explicitly valuing their emotions and experiences in science. Finally, we ask the students about what they want to do about this situation, which starts to guide students towards problematizing inequities in science and developing solutions. In these discussions, the role of the teacher is to be more of a facilitator who provides the students with resources and opportunities to practice identifying and resolving the problems and barriers they encounter.

For the main Lesson Activity, students use their own constellations to model how and why the visible constellations change. Students are given star fields and are invited to create their own constellations from their knowledge, memory, or imagination, as well as to develop a short story to describe their constellations. They share these constellations with their fellow group members for the Lesson Activity, and then with the whole class at the end of the lesson when all of the groups share their findings. In typical classroom environments, presentations are often used as assessment tools. However, in our curriculum the goal of these sharing exercises is for students to present their work to each other. This approach encourages personal reflection and acknowledgement of their peers' efforts and knowledge, which promotes the building of peer coalitions and connectedness.

Reflection

In the fifth lesson, which is inspired by the *A Hua He Inoa* program from the 'Imiloa Astronomy Center ('Imiloa Astronomy Center, 2020), students explore the language of astronomy. Throughout the curriculum, they will have encountered examples of bias, such as constellation names. In the lesson's Opening Activity, students work in groups to research the origins of these names, as well as items from other categories, such as the names of scientists with popular recognition and spacecraft names. They then report back to the entire class, identifying common themes and problems, who is included and privileged, and who is missing. If there are "missing" elements (e.g., Indigenous cultures are not represented), they are asked to research counterexamples for their reports. Next, students brainstorm solutions to identified biases and discuss the pros and cons of different approaches. The rest of the activity focuses on one particular approach by renaming astronomical objects. Students work in groups to pick a particular astronomical object and propose a new name, which involves researching both the object and their ideas for new names (e.g., the language they want to use and the significance of the name). They also review related protocols from the International Astronomical Union, and students articulate whether or not they plan to follow the protocols. For example, they may learn that the current biases in the object's name are a result of the protocols, and so they may decide that the protocols themselves need to be changed. At the end of the activity, students again reflect on the experience and how they feel about renaming and re-terming astronomical objects as a potential solution to removing language with implied biases.

Connectedness

Throughout the curriculum, students complete many of the activities in groups, which contributes to building peer relationships. For their final projects, students again work in groups, but they also build relationships with a larger community beyond their peers. These relationships promote students as being leaders within their communities who are empowered to share their knowledge and help address social inequities.

Specifically, students are given the opportunity to design both the format and target audience of their final projects. The curriculum asks students what they would feel proud to present, and we list a few examples as potential prompts, including

- A presentation to community members and elders,
- A demonstration to younger audiences, and
- A video series (e.g., YouTube, TikTok, etc.) for their fellow high school students.

By having the students specify an audience, it helps to shape the goals and content for their learning and final presentations. To promote their development of presentation skills, the students need to decide whether their presentations are intended to inform an audience, advocate for a specific change, or serve another purpose.

Closing ceremony

In the final lesson, students present their completed final projects. Based on their decisions of a target community for their projects, students (and teachers and other partners) aim to have members from that target community in the audience. In other similar programs, a keynote speaker with related experience has been featured during these ceremonies (e.g., the COMPUGIRLS programs described in Scott and White, 2013). The goal of this ceremony is for the students to receive recognition of their efforts from meaningful others, which is a step towards their development (1) of identities as persons in STEM (Carlone and Johnson, 2007) and (2) as community leaders and techno-social change agents (Scott and Garcia, 2016).

Applying ARC in other learning environments

While the examples in the previous section demonstrate the ARC model in practice, we recognize that depending on the science content, audience demographics, and location, an interested instructor will need to adapt curricular materials. In this subsection, we offer insights into the process of creating the sample astronomy curriculum as well as guiding considerations for applying the ARC model in other learning environments. First, an important element of culturally responsive education is developing a curriculum that serves the needs of the students and the communities they represent. If you are working with a specific population, consider building relationships with elders or other community leaders to learn about their knowledge systems and needs. For example, an extension to the activity about the language of astronomy (the "reflection" example) would be to have students interview an elder to learn about their ways of understanding the universe. In some cases, it may not be possible to address all of the relevant communities (e.g., a large college-level introductory course), but finding ways to model those relationships (e.g., with a local Indigenous community) can still reinforce norms around the importance of cultural ways of knowing. These relationships are especially important to avoid tokenizing or otherwise exploiting the knowledge of local communities.

Second, the elements of the ARC model serve to create spaces for the students to bring in their own cultural knowledge and assets. Encouraging students to share their own stories can guide them to build connections between the science content and their own experiences. Creating these spaces requires an instructor or curriculum developer to reflect on their own positionality and perspective on science (cf. Gay, 2018). For example, an instructor from a Western or Eurocentric (educational) background may be unaware of parallels between their content with a local Indigenous community's knowledge systems.

Additionally, when instructors and curriculum developers identify opportunities for building connections between science and students' assets, they should consider both science "knowledge" and the practices of science. For example, O'Donnell et al. (2021) described in-class and homework prompts that drew on the parallels between (1) having multiple (contradictory) scientific models to explain a phenomenon and (2) the everyday situation of having a disagreement with another person due to differing perspectives. These strategies are crucial because much science education in the U.S. still teaches science as a series of facts about our Universe (e.g., Fischer, 2011) despite over a century of efforts to teach science as a process of discovery (DeBoer, 2019), which can make finding these connections difficult without specific instruction. If a learning environment does not have constraints about which science concepts are covered, when determining a curriculum's scope, an instructor or curriculum developer should consider choosing content with the strongest opportunities for students to bring in their own knowledge, values, and processes (cf. O'Donnell et al., 2021).

Finally, learning spaces created using the ARC model can enable students to identify their own needs and to problematize inequities within their own experiences. Allowing them to practice the skills of critical reflection on their personal contexts can guide them to take ownership of their own stories. This practice can be reinforced by creating spaces for students to develop peer coalitions and community relationships as part of the learning process. While creating these spaces do require time, these steps empower students to act as techno-social change agents as well as increase students' learning and retention of science content (e.g., Lee, 2020).

Conclusion

Addressing JEDI in STEM will require complex, multifaceted solutions in order to overcome and change the cultural biases, inequities, and barriers that sustain the current state of STEM disciplines. One aspect of this movement will be to transform and improve how we teach STEM to eliminate barriers to participation. Additionally, by transforming STEM education, we can engage students in developing knowledge and practicing skills to address JEDI themselves. To contribute to these efforts, this paper proposed a framework for designing STEM learning experiences by following principles of culturally relevant, responsive, and sustaining education. Specifically, we presented examples from an astronomy curriculum built using the ARC model of asset building, reflection, and connectedness. In this curriculum, we consistently valued and incorporated students' knowledges and assets into the lessons in order to create bridges between their prior knowledge and beliefs with astronomy content. Through this model, students engaged in critical reflection to identify implied biases and assumptions in astronomy. By problematizing these biases and inequities, they started to develop and assess potential solutions to these challenges. Students built peer relationships through regular small group discussions and conversations, and they built connections with their larger communities through their final projects and the Closing Ceremony. By creating these connections, students had opportunities to be seen as community leaders, which guided them to feel a sense of belonging, accountability, and commitment to those communities. Additionally, they received recognition for their contributions to their communities by meaningful others, including peers, friends, and family, which can contribute to their development of a STEM identity.

The next steps are to continue iterating on our model and the curriculum generated with it. We will implement our approach in more contexts, such as with different age groups, in formal classroom settings, on additional astronomy content, and/or incorporating new hands-on activities, all while creating spaces for connections with local communities and their ways of knowing. These studies will allow us to refine our framework and develop more robust best practices for instructors and curriculum developers. Through all this work, we remain committed to our goal of empowering students – the people who will be our future professionals in astronomy and society – to become the techno-social change agents who instigate long-lasting and meaningful changes towards equity and social justice in astronomy, STEM, and society as a whole.

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Conflict of interest

The authors declare that they have no conflict of interest.

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