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ADVANTAGE – SEEING THE UNIVERSE: HOW VIRTUAL REALITY CAN FURTHER AUGMENT A THREE-DIMENSIONAL MODEL OF A STAR-PLANET-SATELLITE SYSTEM FOR EDUCATIONAL GAIN IN UNDERGRADUATE ASTRONOMY EDUCATION

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Source Code Available at: https://github.com/emcnair13/adVantage

“I cannot change the laws of physics!”

- *Montgomery Scott* [1]

[1] Mark Daniels, “The Naked Time,” *Star Trek*, September 29, 1966.

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ABSTRACT:

This thesis introduces the "adVantage – Seeing the Universe" system, a learning environment designed to augment introductory undergraduate astronomy education. The goal of the adVantage project is to show how an immersive virtual reality (VR) environment can be used effectively to model the relative sizes and distances between objects in space. To this end, adVantage leverages the benefits of three-dimensional models by letting users observe astronomical phenomena from multiple locations. The system uses pre-set vantage points to structure students' progress through a "mission" designed to improve their understanding of scale. With this first mission, adVantage demonstrates the potential benefits of representing larger distances as multiples of smaller steps of a constant and observable size to convey relative distance in space, and of judging relative size by making observations at various vantage points a constant distance away from each other. Using an HTC Vive headset and hand-controllers, students exploring in adVantage will be able to observe the relative sizes and orbital movements of the subjects of the system: e.g., the exoplanet WASP-12b, its Sun-like star, WASP-12, and imagined satellites constructed to resemble the Earth and its Moon. In the first mission, users investigate the Earth's average orbital radius around the Sun with the average orbital radius of WASP-12b around WASP-12 as a yardstick.

Key words: Astronomy, Virtual Reality, Virtual Learning Environments, Three-Dimensional Modeling, JavaScript, Unity, SteamVR, HTC Vive

1. INTRODUCTION:

Since the 1990s, Virtual Reality (VR) technologies have been developed to improve student learning in a variety of subjects including "physics, algebra, color science, cultural heritage objects, and the greenhouse effect".[2] The increasing prevalence of VR systems can be attributed, in part, to the availability of technology like smart-boards, mobile-devices, and desktop computers. Desktop computers can now be found in homes, schools, and libraries, allowing more people access to PC based VR experiences than before, when VR technologies were limited to "military, medical, and industrial applications".[3] These simulations allow students to "systematically explore hypothetical situations, interact with a simplified version of a process or system, change the time-scale of events, and practice tasks and solve problems in a realistic environment without stress", none of which can be achieved from textbooks and lectures alone.[4] It is important to note, however, that it is not the VR technologies themselves that cause student learning; rather, they offer a previously unused tool facilitating the construction of mental models.[5]

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[2] Heebok Lee et al., "Students' Understanding of Astronomical Concepts Enhanced by an Immersive Virtual Reality System (IVRS)," in *Recent Research Developments in Learning Technologies (2005)*, ed. A. Méndez-Vilas et al., vol. III (ICTE2005, Badajoz, Spain: FORMATEX, 2005): 1.
[3] Yoav Yair, Rachel Mintz, and Shai Litvak, "3D-Virtual Reality in Science Education: An Implication for Astronomy Teaching," *Journal of Computers in Mathematics and Science Teaching* 20, no. 3 (2001): 296.
[4] Nico Rutten, Wouter R. van Joolingen, and Jan T. van der Veen, "The Learning Effects of Computer Simulations in Science Education," *Computers & Education* 58, no. 1 (January 2012): 136.
[5] Tassos A. Mikropoulos and Antonis Natsis, "Educational Virtual Environments: A Ten-Year Review of Empirical Research (1999–2009)," *Computers & Education* 56, no. 3 (April 2011): 769.

At the core of most Educational Virtual Environments (EVEs) is constructivism, a theoretical/pedagogical approach to learning that places emphasis on learning by doing, or task-oriented learning, that encourages students to carry out small experiments which will replace misconceptions with scientifically supported understandings.[6] Whether implicitly or explicitly stated, constructivism buttresses the majority of published studies on the learning effects of EVEs.[7] As students interact with EVEs, they are encouraged to engage in thought experiments by asking 'What If?' questions about the domain content.[8]

Scientific visualizations powered with VR technologies are of irreplaceable value when, "due to their size, duration, or location, [natural phenomena] are difficult or impossible to observe directly".[9] In the case of astronomy, all three of these characteristics are true. Our solar system spans 4,495,100,000 kilometers from the Sun to Neptune, traveling from the Earth to the neighboring Mars can take anywhere from one-hundred and fifty to three-hundred days,[10] lunar eclipses occur only twice a year, solar eclipses occur every eighteen months,[11] the Moon orbits Earth only once every twenty-eight days, and a complete orbit around the Sun takes the Earth three-hundred and sixty-five days.[12] Compounding with these enormous time and distance scales to complicate the study of astronomy are other factors, like axial tilt, orbital inclination, semi-major and semi-minor orbital distances, orbital speed, and rotational speed, for which the ability to visualize abstract concepts three-dimensionally is essential. Achieving an understanding of many of these phenomena is dependent upon "learners' ability to translate concepts between reference frames, to describe the dynamics of a model over time, … to predict how changes in one factor influence other factors, or to reason quantitatively about physics processes that are best … explored in 3D space".[13] Advanced visualizations do more than help students learn domain content for disciplines already taught, they also broaden the scope of science education to make material that was once too abstract to be included in coursework more accessible.[14]

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[6] Mikropoulos and Natsis, "Educational Virtual Environments: A Ten-Year Review of Empirical Research (1999–2009)", 774-5.
[7] Ibid, 769.
[8] Yoav Yair, Yaron Schur, and Rachel Mintz, "A 'Thinking Journey' to the Planets Using Scientific Visualization Technologies: Implications to Astronomy Education," *Journal of Science Education and Technology* 12, no. 1 (March 1, 2003): 45.
[9] Yoav Yair, Rachel Mintz, and Shai Litvak, "3D-Virtual Reality in Science Education: An Implication for Astronomy Teaching," *Journal of Computers in Mathematics and Science Teaching* 20, no. 3 (2001): 295.
[10] Fraser Cain, "How Long Does It Take to Get to Mars?," Space and Astronomy news, Universe Today, May 9, 2013, https://www.universetoday.com/14841/how-long-does-it-take-to-get-to-mars/.
[11] Flint Wild, "What is an Eclipse?," NASA, July 26, 2017, https://www.nasa.gov/audience/forstudents/k-4/stories/nasa-knows/what-is-an-eclipse-k4.
[12] "Planetary Fact Sheet - Metric" (NASA Space Science Data Coordinated Archive - Lunar and Planetary Science), accessed October 19, 2017, https://nssdc.gsfc.nasa.gov/planetary/factsheet/.
[13] John A. Hansen et al., "The Impact of Three-dimensional Computational Modeling on Student Understanding of Astronomy Concepts: A Qualitative Analysis," *International Journal of Science Education* 26, no. 13 (2004): 1366.
[14] John A. Hansen et al., "The Impact of Three-dimensional Computational Modeling on Student Understanding of Astronomy Concepts: A Qualitative Analysis," *International Journal of Science Education* 26, no. 13 (2004): 1365.

Although many existing EVEs were also designed to supplement or replace more traditional astronomy courses, the adVantage system differentiates itself as a laboratory for student investigation with the exoplanet WASP-12b; its Sun-like star, WASP-12; and imagined satellites constructed to resemble the Earth and the Moon as its subjects. Like many other three-dimensional (3D) learning environments, adVantage leverages the capabilities of 3D models and VR to let users observe astronomical phenomena from multiple perspectives. The shortened name of the system, adVantage, alludes to a phrase common to discussions of 3D programs, both those run on computer monitors and those relying on Virtual Reality (VR) headsets and hand controllers – vantage points. The system uses pre-set vantage points to scaffold students' interactions with the system as they complete "missions" assigned in the system. Thus, the adVantage system departs from both two-dimensional, textbook illustrations and previously constructed EVEs by adding navigable depths to a star-planet-satellite system and by offering students a unique laboratory for experimentation.

Virtual laboratory systems have been used in a variety of scientific disciplines, notably biology and chemistry, as they offer safe, time-saving alternatives to many experimental setups.[15] Although many of these computer-simulated laboratories allow students to complete experiments that could technically be carried out in a physical laboratory space, systems that allow students to visualize and experiment upon otherwise unobservable objects and phenomena, such as the dynamic motions of astronomical bodies, are much more "in line with one of the main advantages of computer simulation" – the ability to take students where they otherwise cannot go, and to grapple with immense scales of distance and time.[16] To students, adVantage offers a physics-style laboratory experience in which they will be directed to relevant vantage points in space to make observations about WASP-12b, WASP-12, and the Earth/Moon proxies. Rather than incorporating the full Solar System, adVantage focuses on a distinct and interesting sub-system of another star – WASP-12 – that serves as a proxy for understanding the scale of our own Solar System. Because the original goal of this study was to show that, for investigations of relative sizes and distances between objects in space, immersive VR models are more effective than those experienced through a computer monitor, the learning activities and vantage points structured into adVantage prioritize observation and analysis of scale on the WASP-12b system.

Twin pillars of educational VR are immersion and interaction, where immersion emphasizes "verisimilitude and multiple simulations of the environment" and interaction emphasizes "the natural interaction in [a] VR environment and interpersonal [interactions] between different users".[17] Although adVantage is a single-player environment, smooth and natural interactions between user and system are crucial in streamlining the learning process; jarring interfaces or bulky, unbelievable menus would make suspending disbelief more challenging. The changing "frame of reference" afforded to users in adVantage by the preset paths for missions is a key

[15] Nico Rutten, Wouter R. van Joolingen, and Jan T. van der Veen, "The Learning Effects of Computer Simulations in Science Education," *Computers & Education* 58, no. 1 (January 2012): 141.
[16] Rutten, van Joolingen, and van der Veen, "The Learning Effects of Computer Simulations in Science Education," 151.
[17] Dejian Liu et al., "The Potentials and Trends of Virtual Reality in Education," in *Virtual, Augmented, and Mixed Realities in Education* (Singapore: Springer, 2017), 109.

advantage of immersive learning environments. The multiple perspectives together yield a more complete understanding of the "complex [phenomena]" of outer space.[18]

Opportunities for learning through VR have exploded in the past decades "as [the] mosaic of technology" that "[support] for the creation of synthetic and [stimulate] a high level of interactions in both real environment and three-dimension context" grows.[19] The upper boundaries of what can be taught through immersive, interactive environments is redefined with every new integration of VR into educational programs. Yet authors like Jeffrey Jacobson caution programmers against overusing immersive media "when some other media will do just as well or better".[20] This is one reason that there is a need for quantitative and qualitative analyses of both short and long term learning gains achieved through immersive/HMD VR and computer-monitor hosted VR systems. Additionally, as we developed the immersive version of adVantage, we considered the constraints enforced by requiring a HMD, hand controllers, and physical space to interact per person per interaction.

2. LITERATURE REVIEW:

Key Features of Educational VR:

Over the past two decades, dozens of studies of the impact of Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) educational environments on student learning, particularly in science education, have been carried out. These studies sought to answer questions like: "How can traditional science education be enhanced by the application of computer simulations? [and] "How are computer simulations best used in order to support learning processes and outcomes?".[21] While the mode of interaction, the content of the tutorials, the degree of interactivity, and the type of 3D modeling technology being deployed varies from system to system, most studies surveyed for this paper appear to agree that 3D computer simulations can be more effective, at least in the short term, than traditional instruction.

In their 2011 paper, "Educational Virtual Environments: A Ten-Year Review of Empirical Research", Tassos A. Mikropoulos and Antonis Natsis surveyed fifty-three articles discussing learning environments tailored toward teaching scientific or mathematical domain content. The authors sought to identify trends in the papers, dating back to the 1990s, that support their interpretation of key features in VR systems: a focus on first-person interaction, on presence in the system, on the constructivist model for knowledge acquisition supporting the system's

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[18] Chris Dede, "Immersive Interfaces for Engagement and Learning," *Science* 323, no. 5910 (February 1, 2009): 66.
[19] Dejian Liu et al., "The Potentials and Trends of Virtual Reality in Education," in *Virtual, Augmented, and Mixed Realities in Education* (Singapore: Springer, 2017), 106.
[20] Jeffrey Jacobson, "Authenticity in Immersive Design for Education," in *Virtual, Augmented, and Mixed Realities in Education* (Singapore: Springer, 2017), 52.
[21] Nico Rutten, Wouter R. van Joolingen, and Jan T. van der Veen, "The Learning Effects of Computer Simulations in Science Education," *Computers & Education* 58, no. 1 (January 2012): 137.

design, and on a conceptual interpretation of VR.[22] Mikropoulos and Natsis defined VR technologies to be a subset of Information and Communication Technologies (ICT), which foster student learning by incorporating "active participation in the learning process for students and teachers, action and feedback through educational scenarios[,] and interactive meaningful learning activities based on a certain theoretical model, as well as processes that support the creation of mental models".[23] It is the view of the authors that the technologies supporting these learning activities are not the cause of learning, but the tools which facilitate learning through activities like those described above.[24] Thus, VR technologies "can be described as a mosaic of technologies that support the creation of synthetic, highly interactive three dimensional (3D) spatial environments that present real or non-real situations".[25]

Mikropoulos and Natsis identified "free navigation and first person point of view"; manipulations of scale in domains with systems too massive to visualize entirely, like astronomy, or too small to observe, like laser physics or microbiology; "carefully constructed learning activities" curated to engage students in the environment; task oriented learning; and the use of multiple perspectives points as characteristic of both conceptual VR and the systems they surveyed.[26] Using the papers they reviewed as support, the authors presented the features of VR described above as essential for supporting student learning. Another important conclusion they drew was that, while a majority of the studies used some quantitative or qualitative measure for analysis of short-term learning gain, there are still no studies on how VR systems impact long-term learning.[27]

"The Virtual Playground: An Educational Virtual Reality Environment for Evaluating Interactivity and Conceptual Learning", a study published in 2006 by authors Maria Roussou, Martin Oliver, and Mel Slater, described a large-scale experiment in which students were broken into three cohorts that used a "Virtual Playground" to complete arithmetical fraction problems. The cohorts represented the three conditions in the study. They included "two experimental virtual reality (VR) conditions and a non-VR condition.[28] The comparisons of how young users, children aged eight to twelve, interacted with and explored immersive virtual environments was intended to demonstrate "the role and effect of interactivity on conceptual learning",[29] and to

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[22] Tassos A. Mikropoulos and Antonis Natsis, "Educational Virtual Environments: A Ten-Year Review of Empirical Research (1999–2009)," *Computers & Education* 56, no. 3 (April 2011): 770.

[23] Mikropoulos and Natsis, "Educational Virtual Environments: A Ten-Year Review of Empirical Research (1999–2009)", 769.

[24] Ibid, 769.

[25] Ibid, 769.

[26] Ibid, 774.

[27] Ibid, 769, 772.

[28] Maria Roussou, Martin Oliver, and Mel Slater, "The Virtual Playground: An Educational Virtual Reality Environment for Evaluating Interactivity and Conceptual Learning," *Virtual Reality* 10, no. 3–4 (December 2006): 227.

[29] Maria Roussou, Martin Oliver, and Mel Slater, "The Virtual Playground: An Educational Virtual Reality Environment for Evaluating Interactivity and Conceptual Learning," *Virtual Reality* 10, no. 3–4 (December 2006): 227.

draw conclusions about what type of user interface was most successful at making positive changes in the children's' conceptual understandings of fractions.[30]

While there appears to be a growing trend of integrating VR systems into educational environments, there is still a gap in understanding of "what exactly constitutes an effective virtual learning environment".[31] A number of papers sought to identify the key features of successful VR systems, and show quantitatively that these features of VR are effective for supporting students' conceptual learning.[32] In the "Virtual Playground" study, the authors identified interactivity, or "the ability to freely move around a virtual environment, to experience it 'first-hand' and from multiple points of view, to modify its elements, [and] to control parameters" as the key feature of a successful VR experience. They asserted that interactivity, free-movement, and control all contribute to a feeling of presence in the system. This sentiment has been echoed in other papers published in the last few decades, but studies that show definitively that interactivity alone can induce successful learning gains in young students are lacking. Emphasizing interactivity and control in empirical studies of VR systems is the niche that Roussou, Oliver, and Slater sought to address with their research.

In the "Virtual Playground" study, students in the interactive VR cohort used a set of stereoscopic glasses, a head-tracker, a joystick, and buttons to interact with a "CAVE-like system";[33] students in the passive VR cohort entered the same virtual environment as the interactive VR students, but were limited to watching "a pre-recorded sequence of actions involving the redesign of the playground … played out by a virtual character, a robot called 'Spike'", and making predictions;[34] and students in the non-VR cohort interacted with a physical LEGO model and completed an "activity [involving] the design of a playground on a grid-like floor plan, similar to seeing the playground from above in the virtual reality environment".[35] Quantitative analysis yielded no significant conclusions, but qualitative analysis indicated that the passive VR system was most effective at making students reflect on their conceptual understanding. The success of the passive VR condition, in which the robot served as a mediator between child and subject matter, or between child and VR environment, indicates that curricular scaffolding is essential for supporting student learning.[36]

VR Systems for Astronomy Education:

One VR system used in several studies that explore how 3D computer simulations is the Virtual Solar System (VSS), a non-immersive environment that allows students to explore 3D space, move between pre-set perspective points, and between shift frames of reference by

[30] Roussou, Oliver, and Slater, "The Virtual Playground: An Educational Virtual Reality Environment for Evaluating Interactivity and Conceptual Learning," 239.
[31] Ibid, 227.
[32] Ibid, 227.
[33] Ibid, 233.
[34] Ibid, 234.
[35] Ibid, 234-5.
[36] Ibid, 239.

selecting various objects in the system.[37] Gazit, Yair, and Chen summarize the chief benefits of a VR environment in their 2005 paper, "Emerging Conceptual Understanding of Complex Astronomical Phenomena by Using a Virtual Solar System", as the ability to "easily and without effort visit places and view objects from different points of view, and … [to] experiment by manipulating variables that cannot be manipulated in the real world".[38]

In Gazit, Yair, and Chen's 2005 study, VSS was used to facilitate student development of "complex cognitive models" through modeling projects. Participants in the study, nine volunteers aged 15 to 16 years, completed projects that were designed to facilitate student understanding of "the Solar system as a complex system", "the day-night phenomena", "the seasons cycle phenomena", and "moon phases".[39] In similar studies using a VSS, conducted in 2000 and 2002, teams of undergraduate students used the VRML editor CosmoWorlds over the course of a semester to build models of the Earth-Moon-Sun system and of the entire Solar System, or the Celestial Sphere.[40] [41]All three of the 2000, 2002, and 2005 VSS-based studies tried to quantify the learning gains of students through scored, pre- and post-interviews.[42]

Although the three studies using a VSS system do provide templates of the interview questions for assessing students' understanding of astronomical phenomena in their appendices, they lack comparative analyses of a VSS modeling course versus a more traditional astronomy course. The 2004 paper by John A. Hansen, Michael Barnett, James G. Makinster, and Thomas Keating, "The Impact of Three-dimensional Computational Modeling on Student Understanding of Astronomy Concepts: A Qualitative Analysis", is as a helpful supplement because it includes quantitative and qualitative analyses comparing "students' understandings of both spatial and declarative [astronomical] knowledge" after two academic interventions. One of the two cohorts of students in Hansen et al.'s study "constructed three-dimensional computational models" , and the other "experienced traditional lecture-based instruction".[43]

The paper's authors stated that three-dimensional thinking is essential for grappling with several scientific concepts and processes, including the dependence of Earth's seasons on axial

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[37] Elhanan Gazit, Yoav Yair, and David Chen, "Emerging Conceptual Understanding of Complex Astronomical Phenomena by Using a Virtual Solar System," *Journal of Science Education and Technology* 14, no. 5/6 (December 2005): 460-1.

[38] Gazit, Yair, and Chen, "Emerging Conceptual Understanding of Complex Astronomical Phenomena by Using a Virtual Solar System," 460.

[39] Ibid, 468.

[40] Sasha A. Barab et al., "Virtual Solar System Project: Learning through a Technology-Rich, Inquiry-Based, Participatory Learning Environment," *Journal of Science Education and Technology* 9, no. 1 (March 2000): 11-2.

[41] Thomas Keating et al., "The Virtual Solar System Project: Developing Conceptual Understanding of Astronomical Concepts through Building Three-Dimensional Computational Models," *Journal of Science Education and Technology* 11, no. 3 (September 2002): 263-4.

[42] Keating et al., "The Virtual Solar System Project: Developing Conceptual Understanding of Astronomical Concepts through Building Three-Dimensional Computational Models," 265.

[43] John A. Hansen et al., "The Impact of Three-dimensional Computational Modeling on Student Understanding of Astronomy Concepts: A Qualitative Analysis," *International Journal of Science Education* 26, no. 13 (2004): 1365.

tilt. They also claimed that many scientific phenomena rely on a learner's ability to "translate among reference frames, to describe the dynamics of a model over time, … to predict how changes in one factor influence other factors, or to reason qualitatively about physics processes that are best … explored in 3D space".[44] With this in mind, they ran two versions of an introductory astronomy course to evaluate the relative effectiveness of the teaching methods. One course was taught using the VSS software, and the other was taught using traditional, two-dimensional reference material lacking the depth and scale conveyed through VSS computer simulations.[45]

In the VSS version of the course, students used Virtual Reality Modeling Language (VRML) to create Solar System models "in a learner-centered, project-based" course that spanned sixteen weeks of a Spring semester.[46] The "traditional introductory astronomy course" was taught during a ten week Summer term, and concluded with the construction of a scale model of the Solar System using balls of different sizes.[47] Using pre- and post-course interviews comprised of spatial and declarative questions, where the spatial questions challenged students "to think through varying distances, perspectives, and relative placement of celestial bodies" and the declarative questions relied on "students' understanding of the properties and general knowledge about facts and figures regarding celestial bodies",[48] the authors concluded that students from the VSS cohort demonstrated a greater understanding on "questions about the seasons, eclipses, and the scale of the solar system" then the students in the other cohort. [49] The researchers concluded that scaffolding an astronomy curriculum so that it makes the best use of the modeling technologies is essential to the successful deployment of VR technologies. They also echoed the conclusion of many other research teams: VR technologies that enable 3D visualizations of complex, abstract systems are helpful to students only when trajectories for achieving learning goals are clearly structured within the systems.[50]

In "3D-Virtual Reality in Science Education: An Implication for Astronomy Teaching", Yoav Yair, Rachel Mintz, and Shai Litvak describe another study using a VSS system called *Touch the Sky, Touch the Universe*. The system is a CD-ROM, 3D/VR learning environment that "was developed through a joint effort of the Center for Education Technology (CET) and Tel-Aviv University's Science and Technology Center (SATEC)".[51] In the system, users are able to manipulate a 3D system without the need for a VR mask or gloves, emphasizing autonomy and

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[44] John A. Hansen et al., "The Impact of Three-dimensional Computational Modeling on Student Understanding of Astronomy Concepts: A Qualitative Analysis," *International Journal of Science Education* 26, no. 13 (2004): 1366.
[45] Hansen et al., "The Impact of Three-dimensional Computational Modeling on Student Understanding of Astronomy Concepts: A Qualitative Analysis," 1367.
[46] Ibid, 1369.
[47] Ibid, 1369.
[48] Ibid, 1369.
[49] Ibid, 1376.
[50] Ibid, 1376.
[51] Yoav Yair, Rachel Mintz, and Shai Litvak, "3D-Virtual Reality in Science Education: An Implication for Astronomy Teaching," *Journal of Computers in Mathematics and Science Teaching* 20, no. 3 (2001): 297.

interaction over presence as the most important features for learning in a 3D system.[52] Unlike the "Virtual Playground" study, which focused on user interfaces and interactivity, Yair, Mintz, and Litvak's study focused on motion in the VSS environment and the perspectives enabled by the *Touch the Sky* software. The contents of the environment included the Sun, planets, Moon, asteroids, comets, Milky Way stars, and constellations with "the relative sizes and distances of the objects … shrunk and scaled" to better fit a computer screen.[53] In the system, the computer mouse served as a "spaceship that permits a journey through space, to zoom in or out as one wishes, easily changing the view point and perspective".[54]

Students learning in *Touch the Sky* observed phenomena like day and night, seasons, eclipses, and lunar phases as they performed a series of investigations using four VSS observation modes.[55] These modes were: "The Free-Mode", which offered users full autonomy of motion in the system and exemplified the characteristics of control and exploration common to VR systems; "Sun-in-Site view", which captured both a chosen object and the Sun on the screen, showing their relative positions in the Solar System; "Planetary view", which maintained the position of a selected planet at the center of the screen so that, as the planet orbited, users could zoom in and out while remaining in orbit with the planet; and "Geocentric view", which locked a selected planet in place so that the rest of the objects in space, including the Sun, appeared to revolve around that planet in a manner reminiscent of both Copernican models and the misconceptions of many children.[56] Through these pre-established perspectives, the *Touch the Sky* system demonstrated how exploration and observation of a system from multiple points of view, at varying depths, and with different anchoring objects could be used to construct a truly 3D mental model.

Immersive VR:

Virtual Reality, Augmented Reality, and any other mode of computer-supported 3D modeling can all be used to effectively teach scientific material when level of abstraction, danger, time, distance, location or cost prohibit learning in the physical world.[57] In all of the studies mentioned above, and in countless others that grapple with the application of VR and 3D modeling technologies, there is a consensus that despite "variations in *representation*; degree of *immersion* (the extent to which users of a virtual environment actually believe they are inside this environment); *instructional support*; *gaming*; level of *engagement*; *teacher guidance*; and

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[52] Yoav Yair, Rachel Mintz, and Shai Litvak, "3D-Virtual Reality in Science Education: An Implication for Astronomy Teaching," *Journal of Computers in Mathematics and Science Teaching* 20, no. 3 (2001): 297.
[53] Yair, Mintz, and Litvak, "3D-Virtual Reality in Science Education: An Implication for Astronomy Teaching," 298.
[54] Ibid, 298.
[55] Ibid, 299.
[56] Ibid, 300-2.
[57] Jung-Chuan Yen, Chih-Hsiao Tsai, and Min Wu, "Augmented Reality in the Higher Education: Students' Science Concept Learning and Academic Achievement in Astronomy," *Procedia - Social and Behavioral Sciences* 103 (November 26, 2013): 166.

collaboration", material too spatially or temporally complex to be represented accurately in two-dimensional (2D) models can be more effectively taught with carefully designed 3D systems.[58]

While VR environments interacted with through a computer monitor[59] do allow students to interact with 3D worlds, they restrict the dimensionality of a user's experience to what can be conveyed through the window of a 2D screen. By contrast, immersive VR, AR, and MR systems mediated through a HMD literally surround users with the digital environment. As defined by Chris Dede, immersion "in a digital experience involves the willing suspension of disbelief, and the design of immersive learning experiences that induce this belief draws on sensory, actional, and symbolic factors".[60] Sensory immersion refers to the sensation that a user has relocated to the digital environment, and can be induced by using "head-mounted displays or immersive [VR] rooms, stereoscopic sound, and – through haptic technologies … – the ability to touch virtual objects".[61] Notably, these interactions between user and system may demand a greater suspension of disbelief when the equipment used does not include haptic technologies. For example, if a user attempts to use a hand controller that cannot simulate a counterforce when it is used to pick up a virtual object, the virtual object will seem weightless to the user. Actional immersion allows users to carry out tasks in the virtual world that would be impossible in the real world.[62] This type of immersion is particularly relevant to systems like adVantage that not only allow users to explore expanses of space in unrealistically short periods of time, but also combine components of different solar systems (our Solar System and the WASP-12 system) into one. Symbolic immersion "[draws] on [a] participant's beliefs, emotions, and values about the real world" to engage them in the virtual world psychologically as well as physically.[63]

In addition to facilitating richer immersive experiences, VR systems experienced through a HMD may also support embodied learning experiences. Embodied learning, as described by Dor Abrahamson and Robb Lindgren in the context of STEM fields, refers to experiences where users "[can] approach a problem in chemistry, biology, physics, material science, or mathematics using their natural bodily instincts and movements".[64] The two authors suggested "that thought and action persist in the absence of the artifacts that shaped them", implying that material learned

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[58] Nico Rutten, Wouter R. van Joolingen, and Jan T. van der Veen, "The Learning Effects of Computer Simulations in Science Education," *Computers & Education* 58, no. 1 (January 2012): 137.
[59] Note: From here forward, VR systems that are explored through computer monitors will be referred to as non-immersive VR environments, as non-immersive environments, or as computer-mediated environments.
[60] Chris Dede, "Immersive Interfaces for Engagement and Learning," *Science* 323, no. 5910 (February 1, 2009): 66.
[61] Dede, "Immersive Interfaces for Engagement and Learning," 66.
[62] Ibid, 66.
[63] Ibid, 66.
[64] Dor Abrahamson and Robb Lindgren, "Embodiment and Embodied Design," in *The Cambridge Handbook of the Learning Sciences*, ed. R. K. Sawyer, 2nd ed. (Cambridge, UK: Cambridge University Press, 2014): 362.

while engaging in some physical activity can be stored into a student's memory by association with the activity.[65]

One project that explored the educational impact of embodied design, broadly defined as the application of embodiment theory to learning environments,[66] was MEteor. The MEteor project linked the movement of a student's body to the movement of other objects as dictated by the laws of kinematics. To understand Newton's and Kepler's laws, students took on the role of an asteroid traveling in space, using "their whole bodies to make predictions about where the asteroid will move as it encounters planets and other objects with gravitational forces".[67] The system provided audio and visual guidance to students immediately so that they can adjust their strategy, and success in the system was defined by modeling the asteroid's motion as accurately as possible.[68] While MEteor used a wall display and foot pad for interaction rather than another, more typical VR setup, the study still qualitatively demonstrated the benefits of embodied learning: students who engaged in the "whole-body metaphor-based interaction"[69] of modeling the asteroid's path with their own bodies "[seemed] to be more attuned to the important dynamic relationships of movement in their post-simulation diagrams".[70] By engaging both a student's mind and their body, immersive VR environments and systems like MEteor explicitly link *learning* with *doing*.

Implications of Literature for adVantage:

From the literature reviewed, several themes emerge with significance for designing the adVantage system. Interactivity, fostered by student-control and freedom of movement in the system; constructivism as the theoretical backbone for learning; immersion and embodied learning experiences, facilitated with the HTC Vive headset and hand controllers in the immersive version of adVantage; and guidance provided by academic scaffolding to students must all be considered while developing adVantage as an educational VR experience. Emphasis must be placed on how a student's understanding changes as they learn from the system, affirming that constructivism – here, the construction of mental models rather than computer models, as in several VSS studies – is the pedagogical/theoretical spine of adVantage. Students often develop their own, erroneous mental models of the Solar System from a young age. Classroom learning, observation, science-fiction pop culture, and other media exposure all blend together to form misunderstandings that can carry over from childhood into a student's undergraduate years without intervention.[71] To motivate learning, the adVantage system will use missions – the academic scaffolding of the system – to focus students' attention on scale. The

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[65] Dor Abrahamson and Robb Lindgren, "Embodiment and Embodied Design," in *The Cambridge Handbook of the Learning Sciences*, ed. R. K. Sawyer, 2nd ed. (Cambridge, UK: Cambridge University Press, 2014): 361.
[66] Abrahamson and Lindgren, "Embodiment and Embodied Design," 362.
[67] Ibid, 367.
[68] Ibid, 367.
[69] Ibid, 367.
[70]Ibid, 368.
[71] Yoav Yair, Yaron Schur, and Rachel Mintz, "A 'Thinking Journey' to the Planets Using Scientific Visualization Technologies: Implications to Astronomy Education," *Journal of Science Education and Technology* 12, no. 1 (March 1, 2003): 43-4.

missions will balance student autonomy with guidance in adVantage. Thus, the adVantage system will be developed with these four, primary features of a successful, academic VR experience – interactivity, immersion/embodiment, constructivism, and scaffolding – in mind.

3. ASTRONOMICAL CONTEXT – WASP 12B:

In its earliest iterations, the proposed adVantage system was much broader in scope than a single star-planet-satellite system. Initially, the project included several solar systems of exoplanets and their central stars. In a later iteration, the system modeled the contents of our own Solar System to establish a sense of familiarity for student users. These versions of the project were ultimately rejected as they were both more complicated than necessary and derivative of VR systems already in existence. From these proposals, though, emerged two defining features crucial to the development of adVantage. The astronomical bodies included in the system being modeled must:

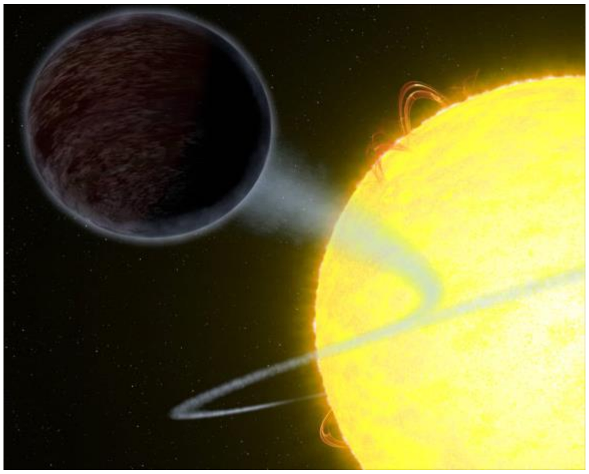
(i) Engage students by introducing some new, astronomical bodies – ideally at least one exoplanet and its star – via adVantage.

(ii) Provide both context and a sense of familiarity to students by incorporating some familiar elements from the Solar System.

With these requirements in mind, Professor Wesley Andrés Watters of Wellesley's Astronomy department; the primary advisor of the project, Professor Scott D. Anderson of Wellesley's Computer Science department; and I determined that a 'hot Jupiter', its central Star, and an imagined satellite were best suited to be the subjects of study in the adVantage system. Hot Jupiters are exoplanets that resemble Jupiter, but have a greater mass and a more unusual orbital pattern. The planets form further away from their central stars, then orbit inwards "for as of yet inexplicable reasons".[72] Since 1995, ninety of these Jovian gas giants have been discovered. Based on the recommendation of Professor Watters, the hot Jupiter, WASP-12b, and the star it orbits, WASP-12, were selected for the adVantage project.

[72] Anne Minard, "Star 'Eating' Superhot Planet's Atmosphere," *National Geographic News*, February 24, 2010, https://news.nationalgeographic.com/news/2010/02/100224-wasp-12b-hot-jupiter-planet-ring/.

Figure 1: "Artist's conception of the exoplanet WASP-12b" [73]



First discovered in 2008 by the United Kingdom's Wide Area Search for Planets (WASP), WASP-12b is particularly well-suited to be the primary subject of an educational program. [74] The exoplanet, which orbits WASP-12 once every 26 hours,[75] has a surface temperature of over 4,700 degrees Fahrenheit due to "a combination of heat from the star and from a gravitational tug-of-war called tidal heating".[76] This extreme temperature may be the cause of the exoplanet's abnormally low albedo which, according to Taylor Bell, the lead author of a recent paper, "The Very Low Albedo of WASP-12b from Spectral Eclipse Observations with Hubble", published in *The Astrophysical Journal Letters*, is at most 0.064. An albedo measurement close to zero indicates that the body in question is nearly "a pristine black body that absorbs all light".[77] WASP-12b's temperature may be the cause of its low albedo, as the star-facing side (which never changes) is too hot for molecules to survive. This relationship dynamic between planet and star "is most likely preventing clouds from forming and reflecting light back into space" so instead the light is "absorbed … and converted into heat energy".[78] Notably, the side of WASP-12b not facing WASP-12 is over 2,000 degrees Fahrenheit cooler than the star-facing side.[79]

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[73] NASA/ESA/G. Bacon, "Artist's conception of the exoplanet WASP-12b," *NASA*, June 7, 2010, https://www.nasa.gov/mission_pages/hubble/science/planet-eater.html.

[74] Anne Minard, "Star 'Eating' Superhot Planet's Atmosphere," *National Geographic News*, February 24, 2010, https://news.nationalgeographic.com/news/2010/02/100224-wasp-12b-hot-jupiter-planet-ring/.

[75] Anne Minard, "Star 'Eating' Superhot Planet's Atmosphere," *National Geographic News*, February 24, 2010, https://news.nationalgeographic.com/news/2010/02/100224-wasp-12b-hot-jupiter-planet-ring/.

[76] Minard, "Star 'Eating' Superhot Planet's Atmosphere."

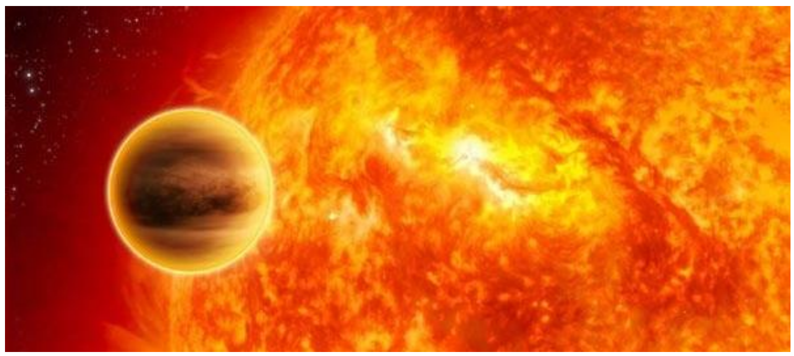
[77] Katyanna Quach, "Hubble Catches a Glimpse WASP-12b, an Almost Pitch-Black Exoplanet," *The Register: Sci/Tech News for the World*, September 14, 2017, https://www.theregister.co.uk/2017/09/14/wasp12b_almost_pitchblack_exoplanet/.

[78] Sage Lazzaro, "Hubble Spots a 'Pitch Black' Hot Jupiter Planet That EATS Light instead of Reflecting It," *Daily Mail*, September 14, 2017, http://www.dailymail.co.uk/sciencetech/article-4885982/Hubble-spots-pitch-black-planet-hot-eats-light.html.

[79] Lazzaro, "Hubble Spots a 'Pitch Black' Hot Jupiter Planet That EATS Light instead of Reflecting It."

Closely related to the extreme temperature of WASP-12b's surface, the exoplanet is also distinguished from other hot Jupiters by its close orbit of WASP-12, its elongated shape, and its outpouring of atmospheric material to WASP-12.[80] [81] The star that WASP-12b orbits is WASP-12, "a yellow dwarf star … in the winter constellation Auriga",[82] approximately 1260 light-years away.[83] [84] The similarity of WASP-12 to our Sun only enhances the relevance of the WASP-12b/WASP-12 pair as subjects for study. WASP-12b orbits its star at an average distance of 3,430,000 kilometers, "approximately 44 times closer … than the Earth is to the Sun".[85] The orbital path is far from standard, orbiting eccentrically rather than circularly due to a changing gravitational pull exerted on the exoplanet by WASP-12. This eccentric path may, in fact, be evidence that WASP-12 has a neighboring, smaller body whose gravitational pull is influencing its orbit.[86]

Figure 2: "Very Hot Jupiter" – WASP-12b and WASP-12 [87]



The extreme temperature of the planet causes significant expansion to the extent that, with only 1.4 times Jupiter's mass, WASP-12b has six-times Jupiter's volume. Gas from the planet's atmosphere that is "pushed out so far from the planet… [may be] getting caught in the star's gravitational pull", forming a ring around WASP-12. Evidence of this ring does not yet exist, but researchers recommend that observers watch for a ring or disk of gas, which a team led by

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[80] Katyanna Quach, "Hubble Catches a Glimpse WASP-12b, an Almost Pitch-Black Exoplanet," *The Register: Sci/Tech News for the World*, September 14, 2017, https://www.theregister.co.uk/2017/09/14/wasp12b_almost_pitchblack_exoplanet/.

[81] "Hubble Finds a Star Eating a Planet," *NASA.gov - Hubble Space Telescope*, June 7, 2010, https://www.nasa.gov/mission_pages/hubble/science/planet-eater.html.

[82] "Hubble Finds a Star Eating a Planet."

[83] Barbara Ryden, "HOW FAR IS A STAR?," The Ohio State University Department of Astronomy, January 13, 2003, http://www.astronomy.ohio-state.edu/~ryden/ast162_2/notes6.html.

[84] "Query : WASP-12," Database, SIMBAD Astronomical Database - CDS (Strasbourg), April 23, 2018, http://simbad.u-strasbg.fr/simbad/sim-id?Ident=WASP-12.

[85] Katyanna Quach, "Hubble Catches a Glimpse WASP-12b, an Almost Pitch-Black Exoplanet," *The Register: Sci/Tech News for the World*, September 14, 2017, https://www.theregister.co.uk/2017/09/14/wasp12b_almost_pitchblack_exoplanet/.

[86] Anne Minard, "Star 'Eating' Superhot Planet's Atmosphere," *National Geographic News*, February 24, 2010, https://news.nationalgeographic.com/news/2010/02/100224-wasp-12b-hot-jupiter-planet-ring/.

[87] ESA/C Carreau, "Very Hot Jupiter," *Universe Today*, October 15, 2008, https://www.universetoday.com/19774/hottest-ever-exoplanet-discovered-wasp-12b/.

astronomer Shu-lin Li of Peking University calculated to be as hot as 7,200 degrees Fahrenheit, emitting detectable infrared radiation.[88] The loss of atmosphere is unique in that the exchange of matter not uncommon between "two stellar objects … in close binary star systems", but was unseen in a planet-star system before WASP-12b.[89] Furthermore, the exchange of atmosphere means that, in an estimated ten million years, WASP-12b will be absorbed entirely by WASP-12.[90]

Although many liberties with both the shape of WASP-12b and its orbit have been taken in the initial construction of the system displayed by the adVantage program – notably, the transformation of the "stretched… football shape" of the planet into a perfect sphere and the adaptation of the incredibly eccentric orbit into a circular path – the relative sizes of WASP-12b and WASP-12 and the planet's orbital radius are maintained.[91] It should also be noted that WASP-12b does not actually appear to be reddish or orange-yellow as it does both in the artistic renditions above and in the adVantage system. The exoplanet should appear blindingly white due to its proximity to WASP-12.

To supplement the WASP-12/WASP-12b system, and to provide some familiar, contextual information for users, two representations of the Earth are included in the adVantage system. One Earth orbits WASP-12 at the distance our Earth orbits the Sun, and the other Earth orbits WASP-12b at the distance that the Moon orbits the Earth. By adding two representations of the Earth in HMD adVantage, users are able to observe both the relative sizes of WASP-12b and the Earth (ratio approximately 21:1), and the relative distance between the two and their stars (ratio approximately 44:1).[92] [93] This configuration of WASP-12/WASP-12b/Earth satisfies both requirements for the adVantage system stated at the beginning of the section by (i) introducing students to new, astronomical bodies – WASP-12b and WASP-12 – and (ii) providing context and familiarity to students using the system via the inclusion of Earth as a satellite of WASP-12b. A proxy for the Moon was also added to the adVantage system, and orbits the Earth representation that orbits WASP-12. Using only these four astronomical objects to model five simulated objects, students are able to observe, experiment, and learn from the customized, astronomy laboratory.

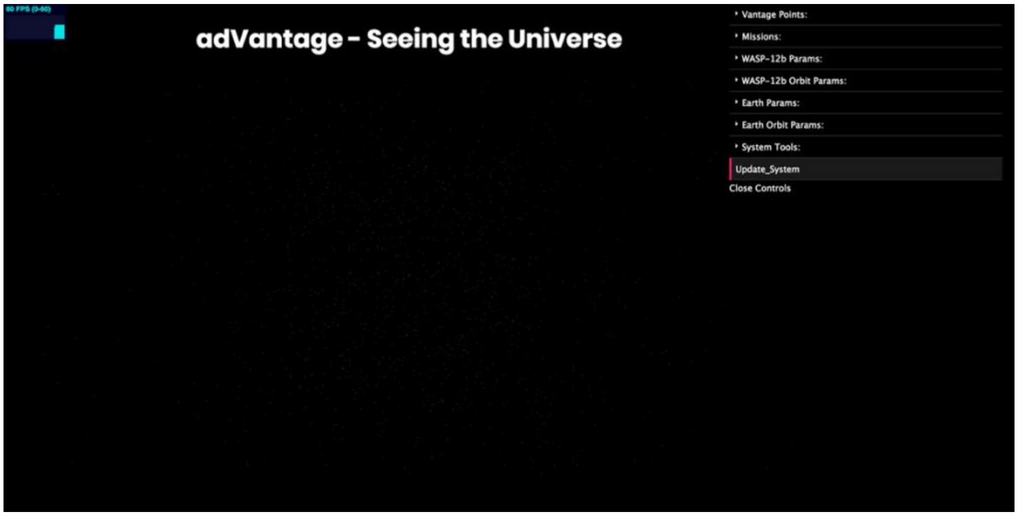
4. THE JAVASCRIPT PROTOTYPE:

The prototyped, web-hosted version of adVantage was built in JavaScript (JS) over the course of a semester, and incorporates all of the essential features that would be carried over into

[88] Anne Minard, "Star 'Eating' Superhot Planet's Atmosphere," *National Geographic News*, February 24, 2010, https://news.nationalgeographic.com/news/2010/02/100224-wasp-12b-hot-jupiter-planet-ring/.
[89] "Hubble Finds a Star Eating a Planet," *NASA.gov - Hubble Space Telescope*, June 7, 2010, https://www.nasa.gov/mission_pages/hubble/science/planet-eater.html.
[90] "Hubble Finds a Star Eating a Planet."
[91] Ibid.
[92] "Planetary Fact Sheet - Metric" (NASA Space Science Data Coordinated Archive - Lunar and Planetary Science), accessed October 19, 2017, https://nssdc.gsfc.nasa.gov/planetary/factsheet/.
[93] "Planet WASP-12B," *The Extrasolar Planets Encyclopaedia*, accessed November 26, 2017, http://exoplanet.eu/catalog/WASP-12_b/.

a final version of the program built with Unity. The non-immersive, JS adVantage system provides context for interactions between student and system by displaying messages that cast the simulation as a first-person adventure story. As an astronaut on the adVantage Task Force, the student is responsible for completing the two missions (that will be introduced in detail in the next section). The messages also describe how users can interact with the system, navigate space, and adjust system parameters using a series of drop down menus on the side of the screen.

Figure 3: The Start-up Scene of the Non-immersive adVantage System



From the initial vantage point in the non-immersive adVantage system, users can see a randomly generated star-field. In the distance there is a small orange object that they will soon discover is the dwarf star, WASP-12 (**see Figure 3**). Students navigate the system by using a mousepad or mouse to scroll in and out of the scene, and by clicking and dragging the screen to adjust the perspective point. In this way, the students are able to explore WASP-12b and WASP-12 from any point in three-dimensional space. When a user first scrolls into the system, the scene includes only WASP-12b orbiting WASP-12, both at their true size and orbiting at the appropriate distance.

Figure 4: WASP-12b Orbiting WASP-12 at the Start-up of the adVantage System

The drop down menus on the far-right side of the screen are made up of seven folders of system variables that students are able to change and one function command, 'Update System'. Clicking the button will apply changes made to the system via the menu, and clicking one of the buttons in the 'Missions' folder or the 'Vantage Points' folder will either launch one of the missions or change the user's vantage point.

5. ACADEMIC SCAFFOLDING IN NON-IMMERSIVE ADVANTAGE:

As stated in the literature review, one essential feature of an effective, academic VR environment is academic scaffolding to help learners stay on track as they interact with the system. In *Touch the Sky, Touch the Universe*, student learning is structured around "inquiries [that have] been added to the … environment, which aim to orient and teach the student[s] various aspects of astronomy".[94] Students using *Touch the Sky* are first person witnesses to "the continual motion of the planets around the only light source in the system (the sun) [which] naturally generates day and night, seasons, eclipses[,] and phases".[95] Using a combination of structured inquiries, pre-programmed vantage points (described in the literature review above), and the scaled solar system representation, *Touch the Sky* guides users through the complexities of astronomy and actively addresses misconceptions held by the users.

In the 2000, 2002, and 2005 VSS studies described by Barab et al.; Gazit, Yair, and Chen; and Barnett et al., model building exercises served as scaffolding for the learning experience. Students participating in the studies built virtual models of our Solar System and of the Earth-Sun-Moon sub-system in CosmoWorlds, then experimented on those models.[96] [97] This approach to astronomy education was evaluated by scoring pre-interview and post-interview responses to a series of questions that targeted different aspects of introductory astronomy. The questions Gazit, Yair, and Chen used in their study are given below:

"The questions were presented to the students in the following order:

Question 1: The Solar System as a complex system:
Draw a diagram of the Solar system and describe it in your own words.

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[94] Yoav Yair, Rachel Mintz, and Shai Litvak, "3D-Virtual Reality in Science Education: An Implication for Astronomy Teaching," *Journal of Computers in Mathematics and Science Teaching* 20, no. 3 (2001): 299.

[95] Yair, Mintz, and Litvak, "3D-Virtual Reality in Science Education: An Implication for Astronomy Teaching," 299.

[96] Sasha A. Barab et al., "Virtual Solar System Project: Learning through a Technology-Rich, Inquiry-Based, Participatory Learning Environment," *Journal of Science Education and Technology* 9, no. 1 (March 2000): 11-2.

[97] Thomas Keating et al., "The Virtual Solar System Project: Developing Conceptual Understanding of Astronomical Concepts through Building Three-Dimensional Computational Models," *Journal of Science Education and Technology* 11, no. 3 (September 2002): 263-4.

Question 2: The Solar System as a complex system:
List the planets which are part of the Solar System according to their relative size (from the smallest to the largest).

Question 3: The Solar System as a complex system:
List the planets which are part of the Solar System according to their relative distance from the Sun (from the closest to the furthest).

Question 4: The day-night phenomena:
Draw a diagram of the Earth's Day-Night phenomena and explain it. Does it occur on the Moon as well? Does it also occur on other planets?

Question 5: The seasons cycle phenomena:
What causes the summer and winter seasons on Earth? Draw a diagram and explain.

Question 6: Moon phases:
Draw the position of the Earth, Moon, and Sun while observing a full Moon, a new Moon, and a Lunar Eclipse from the Earth. Describe the differences and similarities between a Full Moon and a lunar eclipse. What are the factors which affect the changes of the Moon's illumination?"[98]

The overarching themes of these questions – the contents of the Solar System; their relative sizes and distances from the Sun; and the relationships between the physical, rotational, and orbital parameters of objects in the same system (e.g. Earth, Moon, and Sun) – echo the astronomy syllabus for students enrolled in a VSS course. At the conclusion of the class, students would ideally have constructed mental models reflecting how and why astronomical phenomena occur as they do.

Similarly, the non-immersive adVantage system structures student interaction around two missions. These missions are the adVantage equivalent of *Touch the Sky*'s prompts and the VSS model building activities; they are all problem statements that shape a user's progress through the learning environments. The two missions in non-immersive adVantage, which will be described in detail below, involve tasks that focus on guiding student investigation of the relative sizes of radii and orbital radii of planets in the system.

The non-immersive adVantage system engages students in a simulated, restricted reality and asks them both to observe and manipulate the contents of the system: WASP-12, WASP-12b, the two proxy Earths, and the proxy Moon. Understanding the scale of the universe, the relative sizes of planets and stars, and the spatial constraints when modeling astronomically large systems are the primary goals of adVantage. Ideally, learners will manipulate the 3D objects, constructing and updating their mental models of scale in space as they make changes to the system and observe the effects. To help students learn, the non-immersive adVantage system makes the

[98] Elhanan Gazit, Yoav Yair, and David Chen, "Emerging Conceptual Understanding of Complex Astronomical Phenomena by Using a Virtual Solar System," *Journal of Science Education and Technology* 14, no. 5/6 (December 2005): 468.

underlying geometries of the universe visible to students by showing them the axis systems and orbital paths of both WASP-12b and the astronomical “yardstick” for comparison, the Earth.

Mission 1: Finding Earth

The first mission assigned to students interacting with adVantage is “Finding Earth”, a highly interactive challenge that will increase student familiarity with the drop-down menus, reveal how much smaller the Earth is than WASP-12b, and show how much further the Earth is from its Sun than WASP-12b is from WASP-12. When a student launches the first mission from the menu, they will be shown a series of messages introducing the mission:

> ***Message 1:*** *"adVantage... come in adVantage, this is Mission Control. Your first mission in the WASP-12b system will be FINDING EARTH. By the time you have finished reading this transmission and accepted the mission, you will have arrived at your first vantage point - two-hundred million kilometers (200,000,000 km) directly above the star, WASP-12. We've activated two of the tools in the 'System Tools' panel of your control box so that you can see both the orbital path of WASP-12b, and the orbital path of an imagined Earth we've programmed into your space shuttle window as a reference. Right now, both the 'Earth' and WASP-12b are their true sizes, and are orbiting WASP-12 at the true distances from their respective stars."*

> ***Message 2:*** *"Your mission is to find the Earth by manipulating the parameters of the system to bring the Earth closer to WASP-12. Look in the 'Earth Params' panel of your control box - try adjusting the semi-major and semi-minor radial parameters of the Earth's orbit. How does this affect your system? Can you see the Earth? Remember, if you ever lose yourself in space, look in the 'Vantage Points' panel of the control box, and navigate back to the overhead perspective. Good luck, adVantage."*

When the user has read the mission introduction, the parameters of the system are updated and the appropriate methods are called to prepare adVantage for the first mission. As described, this mission makes use of the pre-defined vantage point, Overhead_Viewpoint. Positioned at point (0, 200000000, 0) and looking in the negative y-direction at point (0, 0, 0), users are able to see the orbital paths of both WASP-12b and the Earth.

Figure 5: The Overhead Vantage Point for Mission 1

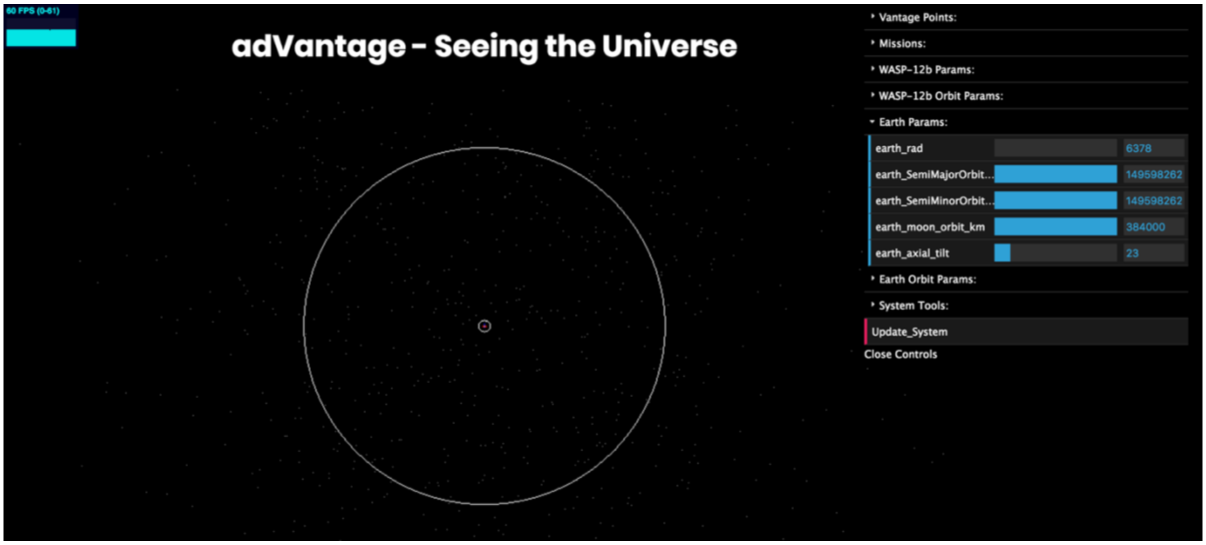


Figure 6: A Zoomed in, Overhead View of WASP-12b Orbiting WASP-12

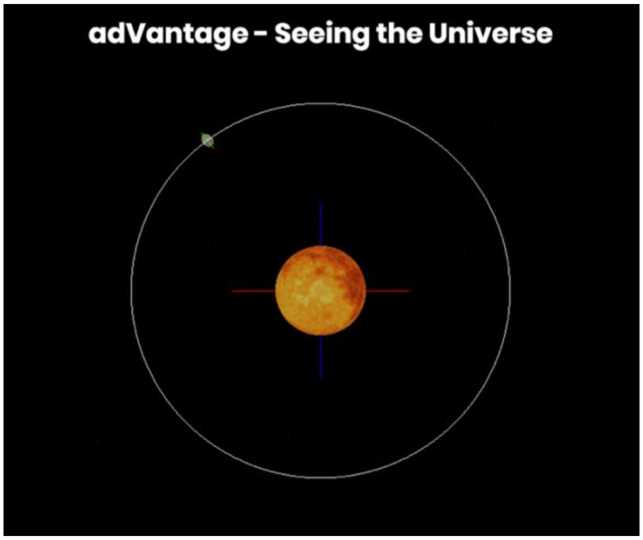
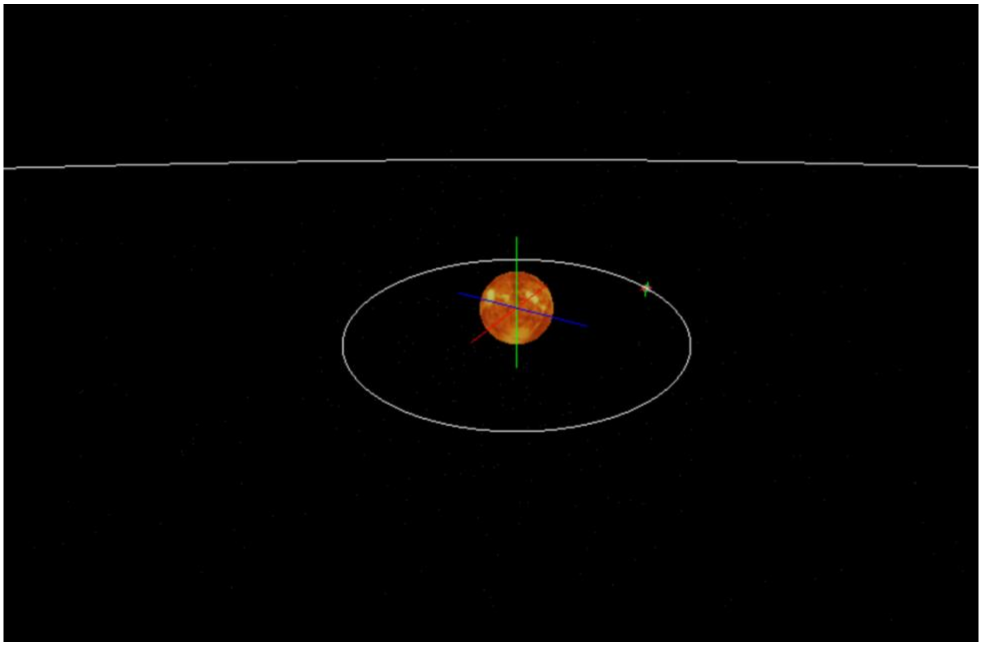
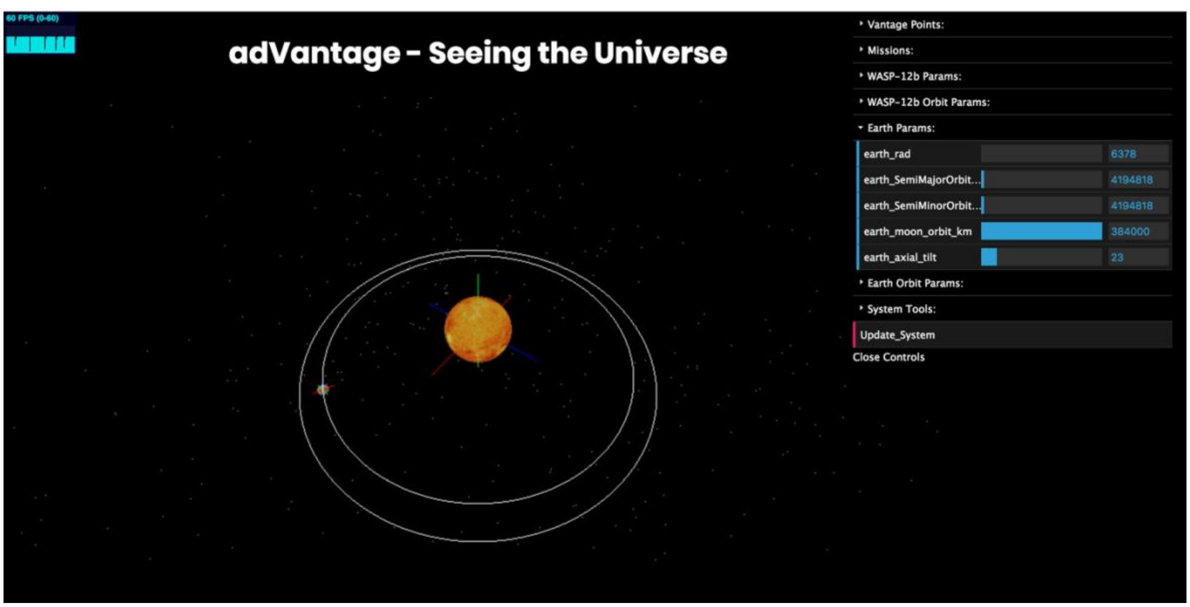


Figure 7: A Zoomed in View of WASP-12b Orbiting WASP-12 with Earth's Orbital Path Visible



Immediately, the difference in the semi-major and semi-minor orbital distances of the two planets is apparent (see **Figure 5** – the outer white ring represents the Earth's orbital path, and the inner ring represents WASP-12b's). Zooming into the system, users will be able to find both WASP-12b and WASP-12 on their screens, but the Earth's current radius and orbital radii (semi-major and semi-minor) make the planet impossible to find (see **Figures 6 and 7**).

Figure 8: WASP-12b and Earth's Orbital Paths Both Visible, With the Earth's Orbital Radii Set to 4,194,818 km



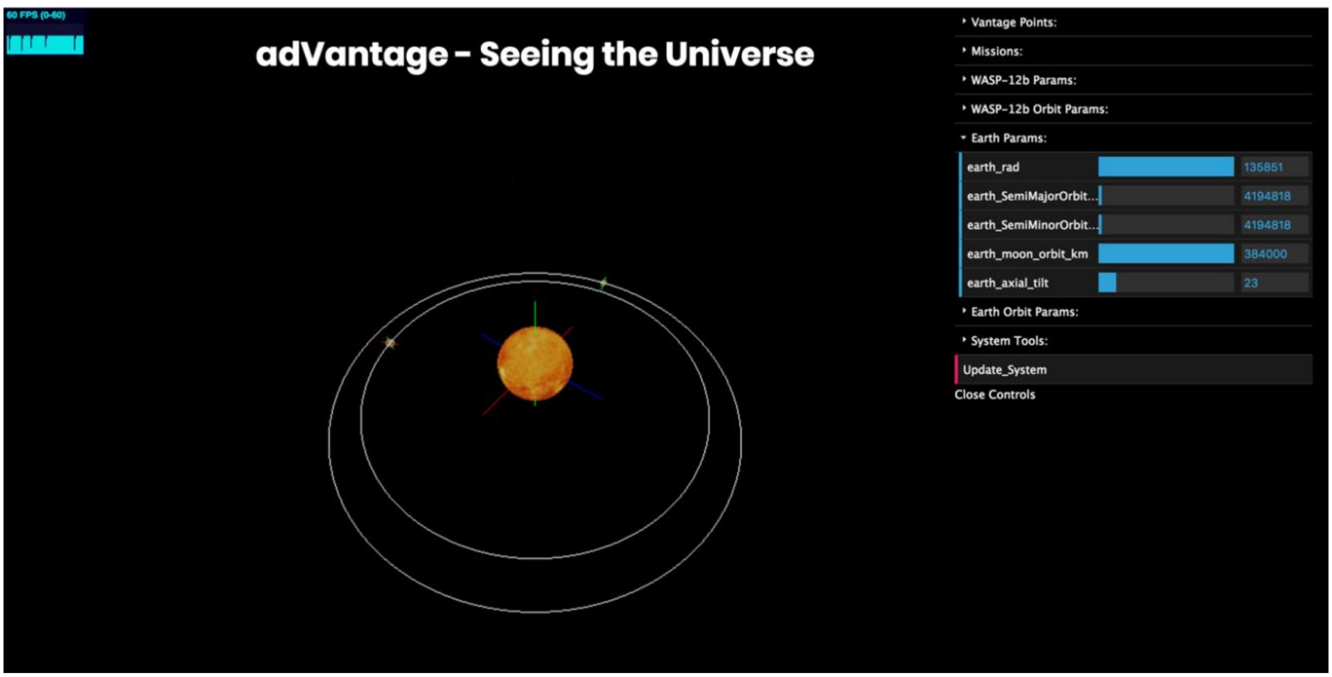
As a user follows the mission instructions and modifies the Earth's semi-major and semi-minor orbital radii in the appropriate drop-down menu, the orbital paths of both planets can again be seen on the screen. However, because of the Earth's size as compared to WASP-12 and WASP-12b, the planet will still be invisible to the user.

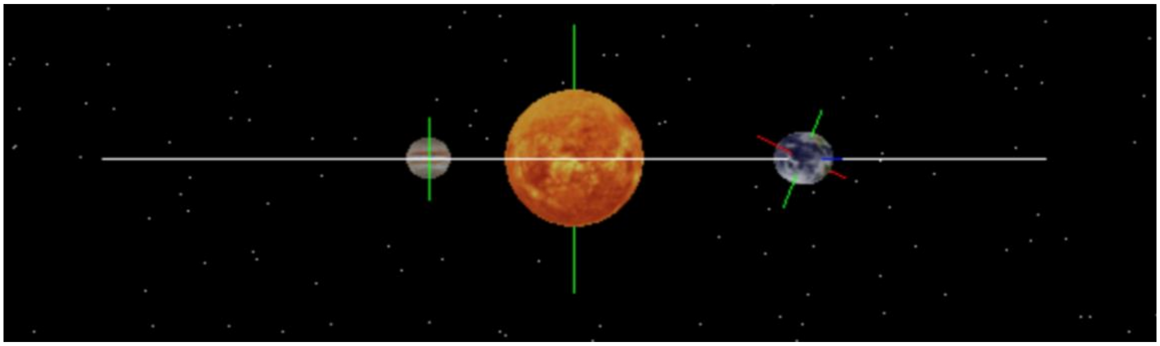
At this point, students will ideally realize that Earth's radius must be increased for the planet to be visible. If this does not occur to a student, though, the student can use the 'Mission 1 Hint' button in the drop-down menus. Pressing the hint button will cause the following message to appear to the user:

> ***Mission 1 Hint:*** *"adVantage... this is Mission Control. We've received more information about your first mission to help you find the Earth. If you've adjusted the orbit of the Earth in your 'Earth Params' panel but still cannot see the planet, try adjusting the Earth's radius. Notice, the current size of the Earth's radius - its actual size - is the minimum value allowed by your control box. Why might this be?"*

Like the opening messages, the hint is phrased to emphasize a student's control over the system. By increasing the Earth's radius from its true size (the minimum value allowed by the system) to the radius of WASP-12b (the maximum value allowed by the system), the student will succeed in finding the Earth.

Figure 9 (a, b): WASP-12b and the Earth Orbiting WASP-12, With the Earth Radius Scaled to Match WASP-12b's Radius





After completing the mission, students should press the ‘Mission 1 Report’ button in the drop-down menu. Although student responses to the report prompt are not currently being used for any system functions, or for further analysis, the report feature is still included in non-immersive adVantage to promote reflective thinking. Interaction with the system can only be fruitful if those interactions help students restructure their mental models of the Solar System, and of the WASP-12b/WASP-12/Earth system. The report prompt for Mission 1 is:

> ***Mission 1 Report Prompt:*** *"Please input your findings about the relative sizes of WASP-12b and of Earth, and about the relative distances between WASP-12b and its star (WASP-12) and between the Earth and the Sun."*

Mission 2: Into the Depths of Space and Space Scales

The second mission in the adVantage system is a two-part challenge: “Into the Depths of Space” and “Space Scales”. The two parts of the mission are designed to further users’ understandings about the scale of WASP-12b as compared to the Earth, and about the extreme proximity of WASP-12b and WASP-12 as compared to the Earth’s proximity to the Sun. The first part of the mission, “Into the Depths of Space”, guides users along of line of four nodes: the Moon, the Earth, WASP-12b, and WASP-12. All four objects are placed on the x-axis at an appropriate distance: first, WASP-12 at the center of the system; second, WASP-12b at its orbital distance from WASP-12; third, the Earth at its orbital distance from the Sun; and fourth, the Moon at its orbital distance from the Earth. In the second part of Mission 2, “Space Scales”, the four objects are placed significantly closer together so that users can more easily compare their sizes.

While Mission 2 is less interactive than Mission 1, requiring only that students press and hold a keyboard key to ‘fly’ through the system, it offers users unique opportunities for observation. The premise of the mission is that the user is a member of the adVantage Task Force, and is responsible for collecting data about the WASP-12b/WASP-12 system as they fly along the lines of nodes. When Part 1 of Mission 2 is launched, students are shown the following messages to introduce their role in the mission:

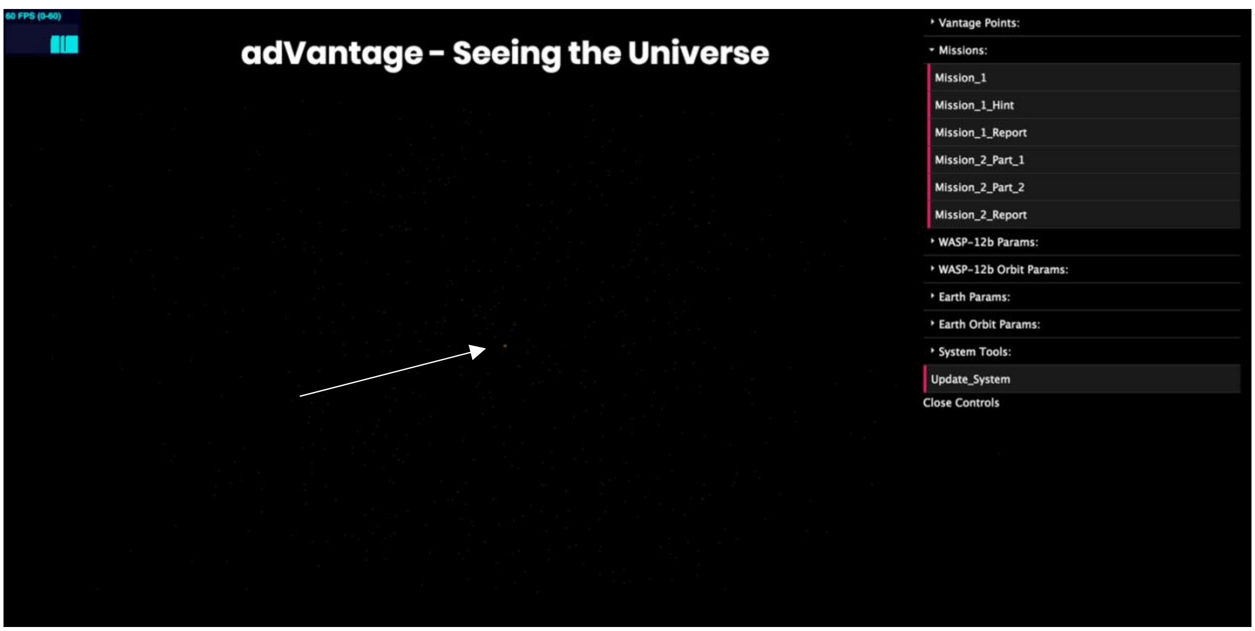
> ***Message 1:*** *"adVantage... come in adVantage, this is Mission Control. The first part of your second mission in the WASP-12b system will be INTO THE DEPTHS OF SPACE. You will need to complete the mission in two parts. First, you will navigate your space shuttle along*

the line of nodes formed between four objects in Space. As before, the system is comprised of WASP-12, WASP-12b, and an imagined Earth programmed into your space shuttle window. For this mission, we have added another imagined object to your view-screen - Earth's Moon. You will begin the first part of your mission at a new Vantage Point, 200,000,000 km away from WASP-12. To fly through space, press and hold the 'i' key the space shuttle keyboard. As you approach each object, your shuttle will slow down, giving you time to observe the planets and star."

Message 2: *"As you complete the INTO THE DEPTHS OF SPACE sub-mission, pay attention to the distance between the Moon, Earth, WASP-12b, and WASP-12. Although your travel through space has been accelerated by new technologies, you should still notice a difference in time spend traveling between planets and star. When you complete the first part of Mission 2, press the 'Mission_2_Part_2' button in the 'Missions' panel of your control box. You will use the data you collected about the relative distances between objects to construct a simulation that will explore on your space shuttle view-screen. Good luck, adVantage."*

When the two messages are closed, the system positions the user at point (200000000, 0, 0), looking in the negative X-direction toward point (0, 0, 0). Initially, although the four objects, by proximity to the camera, are in the order Moon, Earth, WASP-12b, WASP-12, only WASP-12 can be seen (see **Figure 10** – WASP-12 is the small orange dot at which the arrow is pointing).

Figure 10: The Initial Vantage Point for Mission 2, Part 1

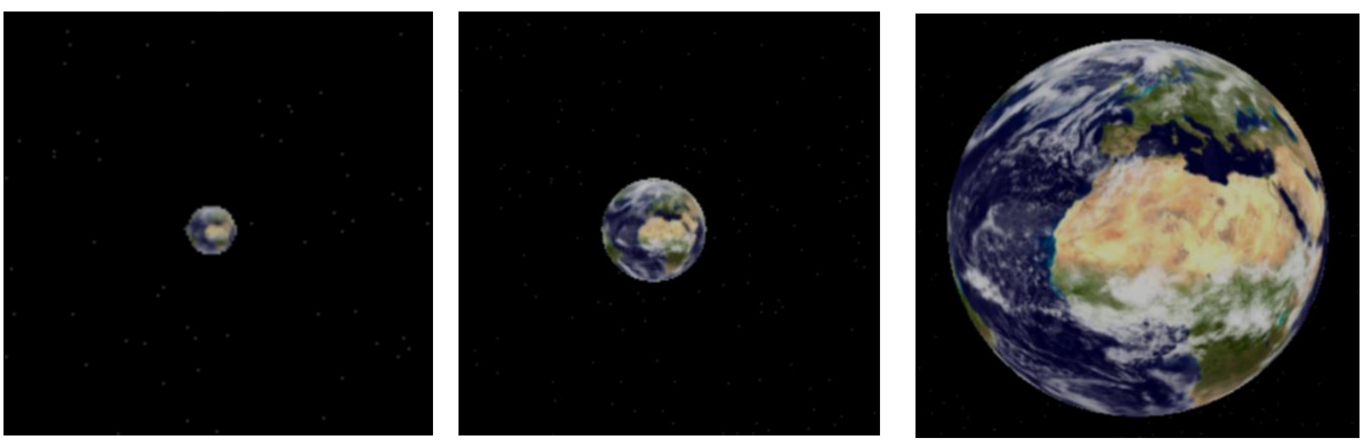


When the ‘i’ key is pressed, the system takes a step along the X-axis closing the distance between the camera and WASP-12. As the camera approaches each upcoming object, the size of these X-steps is decreased fractionally, creating the illusion of slowing down travel as the user approaches each planet, satellite, or star. As described in the introductory messages, the pace of travel between objects is beyond belief, but varying the apparent speed of travel by adjusting the size of X-steps both preserves the sense of relative distance and provides a necessary distortion of time and space.

The following series of images show how the Moon and the Earth appear to users as they approach the objects see (see **Figures 11 and 12**). The final images show that, due to the immense size of WASP-12 and the extreme proximity of WASP-12 and WASP-12b, the star can be seen behind the exoplanet as the student approaches (see **Figure 13**).

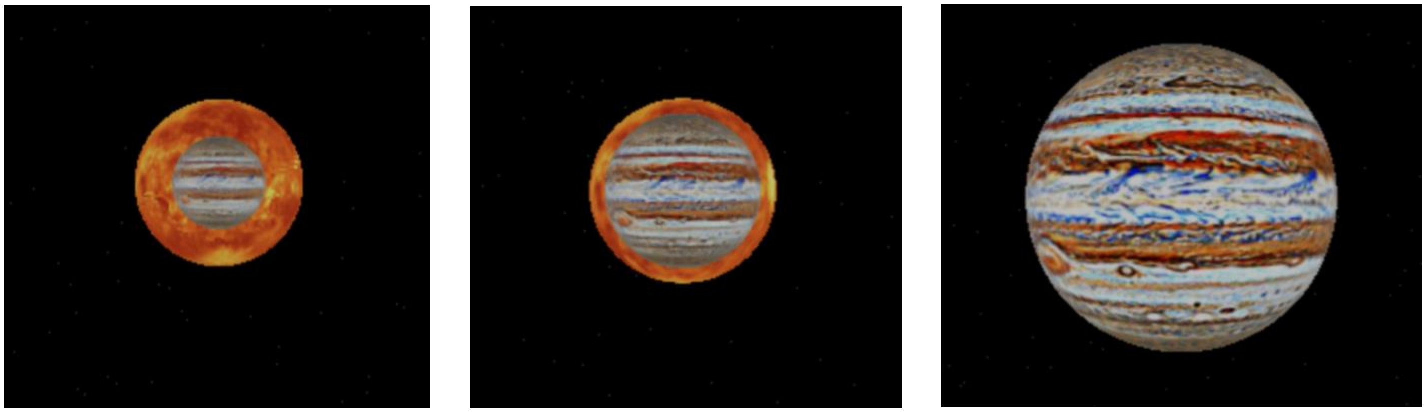
Figure 11 (a, b, c): The Moon on Approach in Mission 2, Part 1 [99]

Figure 12 (a, b, c): The Earth on Approach in Mission 2, Part 1



[99] Note: The texture used to create the JS Moon representation above (as well as the Moon representation in the Unity/Immersive version of adVantage that will be described in detail below) does not represent the entire lunar surface, so these representations of the Moon are not true to life.

Figure 13 (a, b, c): Approaching WASP-12b in Mission 2, Part 1 with WASP-12 Partially Visible



In both parts of Mission 2, as the user approaches a planet or moon, it arcs up and over the planet's surface at one radius distance. This strategy for travel allows users to see from another perspective how each object is positioned compared to the others. It also makes the journey through space less jarring than it would be if a user jumped from one side of a planet to the other or passed through its interior. **Figures 14 and 15** show how WASP-12 appears to be a tiny orange spot from the user's vantage point above the Earth, and appears significantly larger when viewed from the user's vantage point above WASP-12b.

Figure 14: WASP-12 Visible in the Distance as the Camera Arcs Up and Over the Earth in Mission 2, Part 1

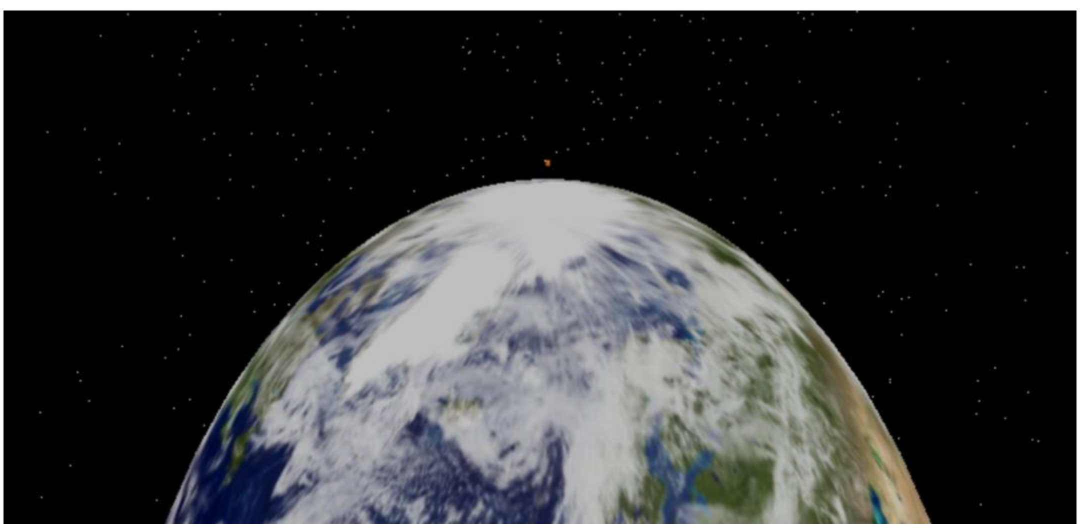
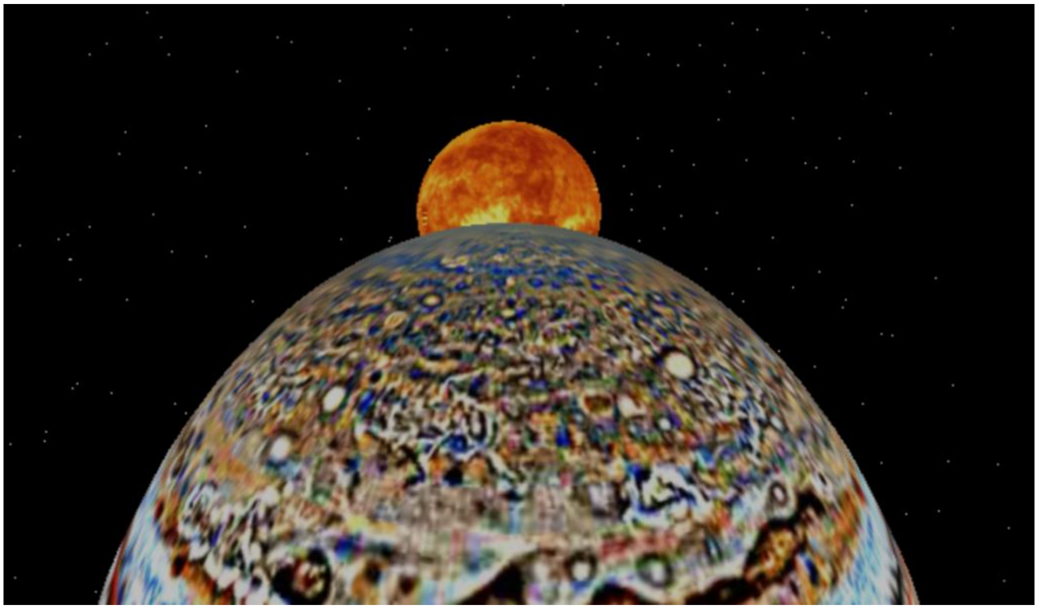


Figure 15: WASP-12 Visible in the Distance as the Camera Arcs Up and Over WASP-12b in Mission 2, Part 1



In Part 2 of Mission 2, the user is positioned at point (20000000, 0, 0), looking in the negative X-direction toward point (0, 0, 0). Because this part of Mission 2 requires that the distances between planets, satellite, and star be significantly reduced, the introductory message suggests to users that the data collected in "Into the Depths of Space" was used to create a simulation that the user will interact with on the view-screen of their space shuttle in "Space Scales". The introductory message for "Space Scales" is:

> ***Message 1:*** *"adVantage, this is Mission Control. Congratulations on completing the first part of your second mission, INTO THE DEPTHS OF SPACE. Now, you will use the data you collected about the relative sizes of planets and star, as well as about the distances between them, to explore a simulation on your space shuttle view-screen. This part of the second mission will be SPACE SCALES. The purpose of this simulation is to let you visualize more easily differences in planet/star size. For this part of the mission, you will begin at a new Vantage Point, 20,000,000 km away from WASP-12. Using information from your flight, we constructed a model with the planets and star displayed at their true size, but with their distances condensed. Again, to fly through the simulated system in SPACE SCALES, press and hold the 'i' key. Good luck."*

When Part 2 of Mission 2 begins, only WASP-12 can be clearly distinguished. Another planet can be seen in front of WASP-12, partially concealing the star (see **Figure 16**), but the user will not be able to tell whether the planet is WASP-12b or the Earth. As the user uses the 'i' key to navigate into the system, the planets, star, and satellite will appear to be layered on top of each other. Depending on the distance, up to three of the objects can be seen stacked from largest to smallest (see **Figure 17**). This effect is possible because the distances between the planets and star were reduced and standardized so that a distance of ten radii of an object separates that object and the next planet further away from WASP-12. **Figure 18** shows another benefit of the condensed distances between planets and star is apparent: up to three objects can be seen together by the user as the camera is shifted in an arc up and over each planet.

Figure 16: The Initial Vantage Point for Mission 2, Part 2

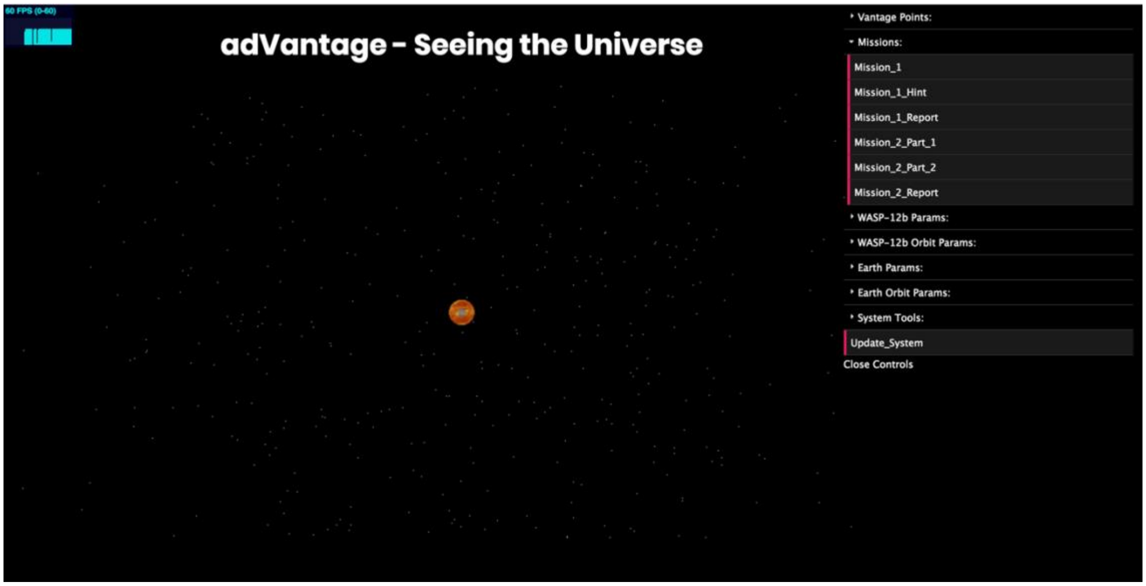


Figure 17 (a, b, c): (a) The Moon, Earth, and WASP-12b; and (b) the Earth, WASP-12b, and WASP-12 seen in Mission 2, Part 2

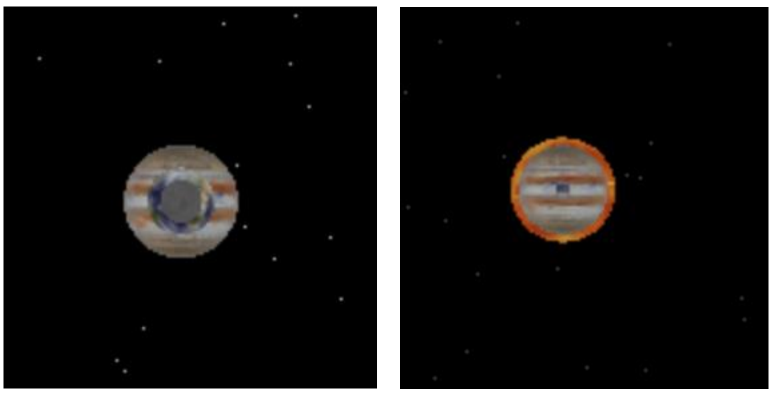
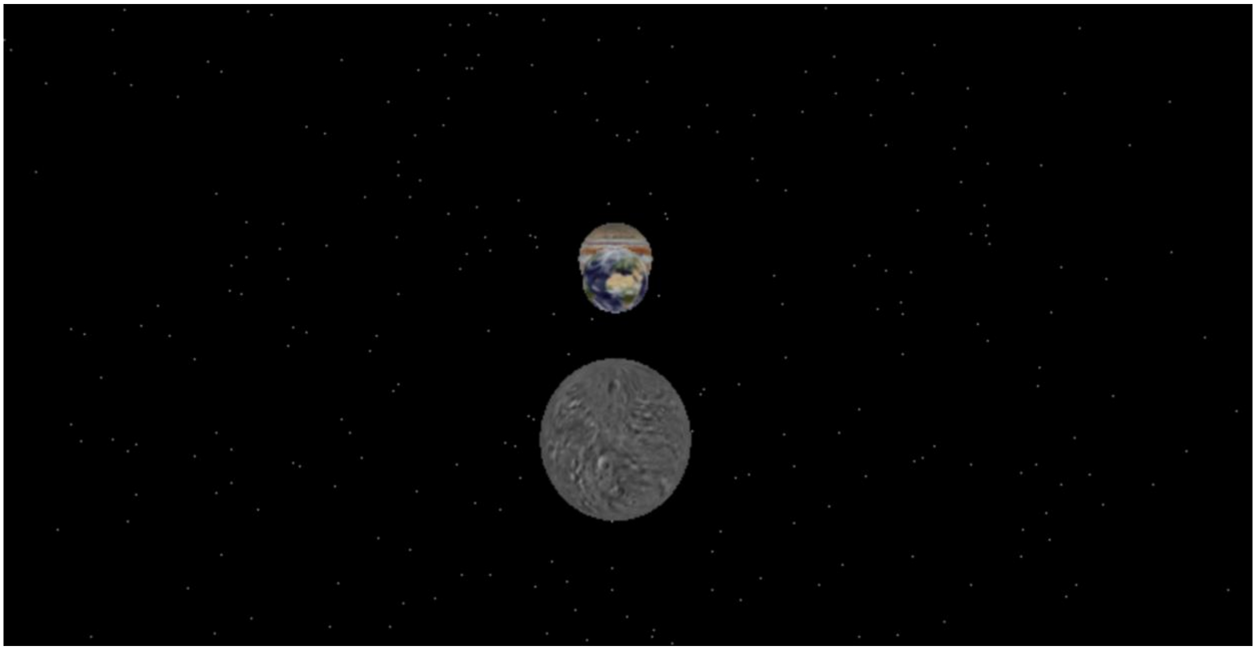


Figure 18: The Moon, the Earth, and WASP-12b Visible as the Camera Arcs Up and Over the Moon in Mission 2, Part 2



As in the first mission, students should press the 'Mission 2 Report' button in the drop-down menu when they completes both parts of Mission 2. The report prompt for Mission 2 is:

> ***Mission 2 Report Prompt****: "Please input your impressions about the relative sizes of WASP-12, WASP-12b, the Earth, and the Moon, and about the relative distances between those planets, satellite, and star from the two sub-missions of Mission 2, INTO THE DEPTHS OF SPACE and SPACE SCALES."*

When a user has completed both missions in adVantage, they will be free to explore the system, adjusting parameters and exploring how those parameters interact using menu.

6. UNITY DEVELOPMENT:

The primary goal work on the adVantage project in the spring semester was to develop an immersive VR supported version of the system using the game engine Unity and the virtual reality system SteamVR. Rather than using keyboard and mouse commands to facilitate user interaction, this version of adVantage[100] will use a HTC Vive headset and the accompanying hand controllers. Because adVantage was prototyped in JavaScript, the user interaction was mediated through pop-up windows (JS alert boxes), drop-down menus (dat.GUI), and mouse/keyboard interaction (OrbitControls and onKeyPress() event listeners), the primary

[100] Note: From here forward, the Unity/SteamVR version of adVantage will be referred to as HMD adVantage, immersive adVantage, and Unity/SteamVR adVantage. The JavaScript prototype of adVantage will continue to be referred to as non-immersive adVantage.

challenges of adapting the system from JS to Unity were learning how to program the HTC Vive hand controllers, translating core system function from JavaScript to C# scripts, and pairing touchpad/trigger inputs on the hand controllers with system behaviors to create an intuitive user interface.

Figure 19 (a, b): (a) Vive VR System, [101] **(b) HTV Vive Hand Controllers with Arrows Indicating Buttons and Points for User Input**

Adapting the adVantage System for Unity:

Early development of Unity/SteamVR adVantage focused on scaling the objects in the system so that the distances between objects were compatible with Unity's upper bounds of coordinate positions, writing a C# script that handles the rotational and orbital movements of all astronomical objects, and experimenting with different forms of user interaction with the system. Because Unity could not accommodate a one kilometer to one Unity unit conversion due to the distances of the Earth and Moon proxies from the origin, scaling the radii and orbital radii was necessary before work on adVantage could be continued. Using the smallest distance parameter in the system – the radius of the Moon – to scale the system, the Moon's radius became one Unity unit and the initial orbital radius of the Earth became 86,070 Unity units. The decision to scale by the smallest distance rather than another, larger distance that would have further reduced the Earth's orbital radius was made so that no parameter in the system would be less than one Unity unit.[102] The scaled values for all radii and orbital radii, as well as the initial coordinates for all objects in the system, are shown in the tables below (see **Figures 20 and 21**):

---

[101] "Vive VR System," *Vive*, https://www.vive.com/media/filer_public/8f/ef/8fef879f-c986-4c89-a0b3-12126e8ba6f7/vive-pdp-hero-desktop-031918-v3.jpg.

[102] Note: We later discovered that the scaling tool for Unity objects referred not to the radius of an object but to its diameter. Now, the Moon has a diameter of two Unity units, and future work could include halving all parameters of the system to reduce its total size.

Figure 20: Conversion Table From Actual to Moon-Scaled Radii and Orbital Radii

Parameter	Value in km.	Scale by Moon rad.	Scaled Value	Scaled Rounded
WASP-12 radius	695700	1738.1	400.2646568	400.26
WASP-12b radius	135851.4	1738.1	78.16086531	78.16
WASP-12b orbit dist.	3430288	1738.1	1973.584949	1973.58
Earth radius	6378.137	1738.1	3.669603015	3.67
Earth as Planet orbit dist.	149598262	1738.1	86069.99712	86070
Moon radius	1738.1	1738.1	1	1
Moon orbit dist.	384000	1738.1	220.9309016	220.93
Earth as Moon orbit dist.	384000	1738.1	220.9309016	220.93

**Figure 21: Scaled Radii, Initial adVantage Coordinates,
and Scale Parameter for Spheres in Unity (twice the radius)**

Object	Start x	Start y	Start z	Radius	Unity Scale Value
Wasp-12	0	0	0	400.26	800.52
Wasp-12b	1973.58	0	0	78.16	156.32
EarthMoon	2194.51	0	0	3.67	7.34
Earth	86070	0	0	3.67	7.34
Moon	86290.93	0	0	1	2

Once all of WASP-12, WASP-12b, the Earth/Moon proxy (that orbits WASP-12b), the Earth proxy, and the Moon proxy were placed in adVantage, adapting the JS code handling all rotational and orbital movements in the system became a priority (see **Figure 22 (a, b, c, d, e)** for the versions of WASP-12, WASP-12b, the Earth/Moon proxy, the Earth, and the Moon that appear in adVantage; **Figure 23** shows the exoplanet, HD 149026b, that WASP-12b was modeled after; **Figure 24 (a, b)** show two initial perspectives of WASP-12, WASP-12b, and the Earth/Moon proxy).

Figure 22 (a, b, c, d, e): As They Appear in adVantage – (a) WASP-12,[103] (b) WASP-12b, (c) the Earth/Moon proxy, (d) the Earth, and (e) the Moon

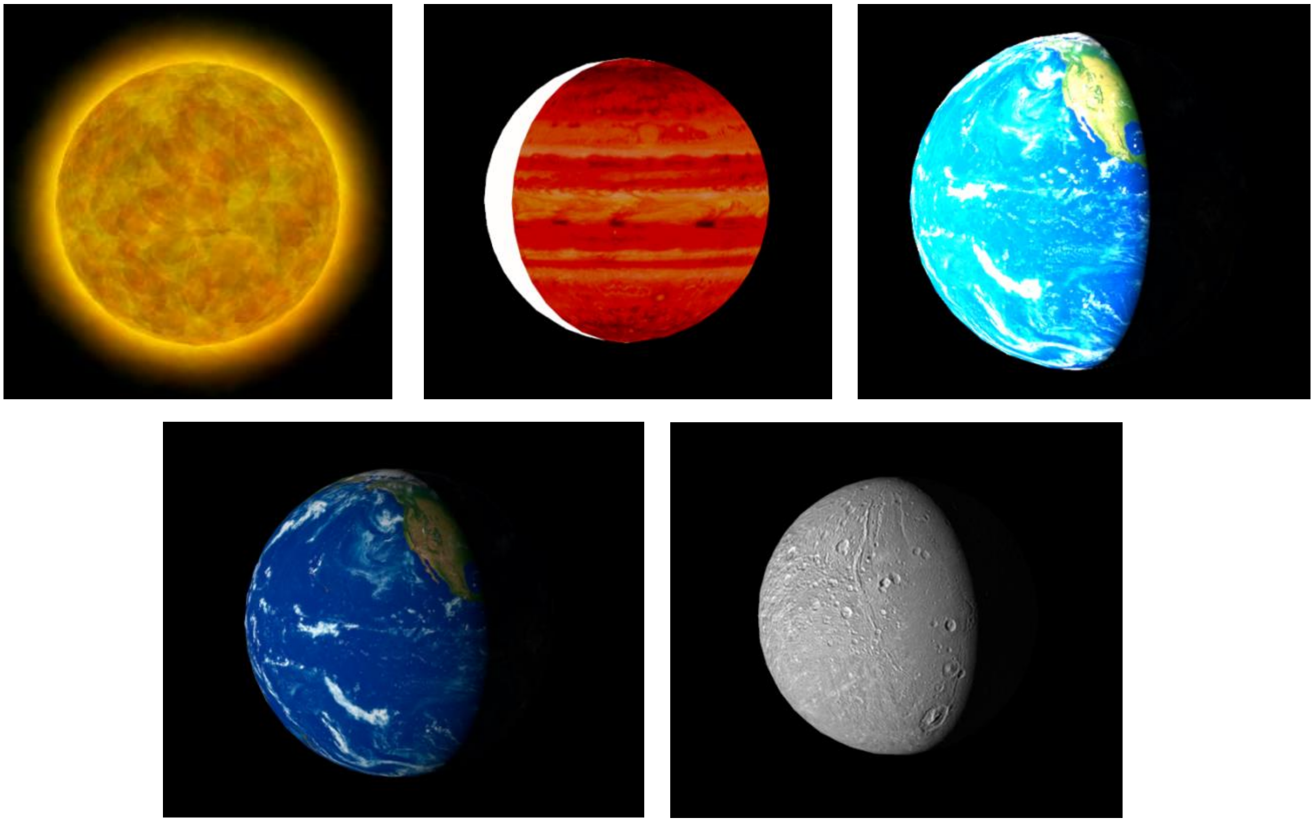
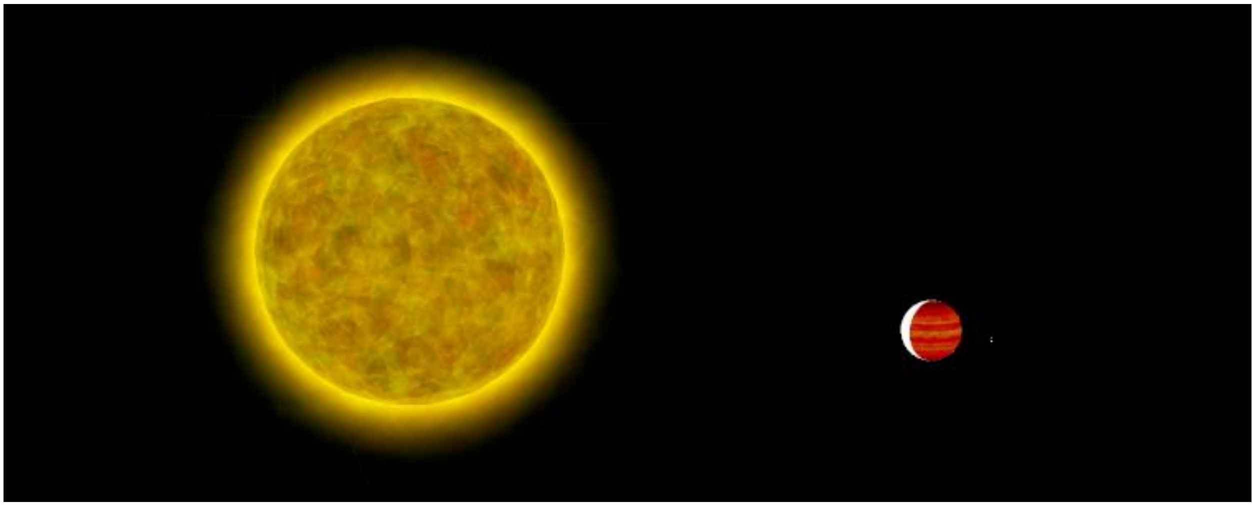


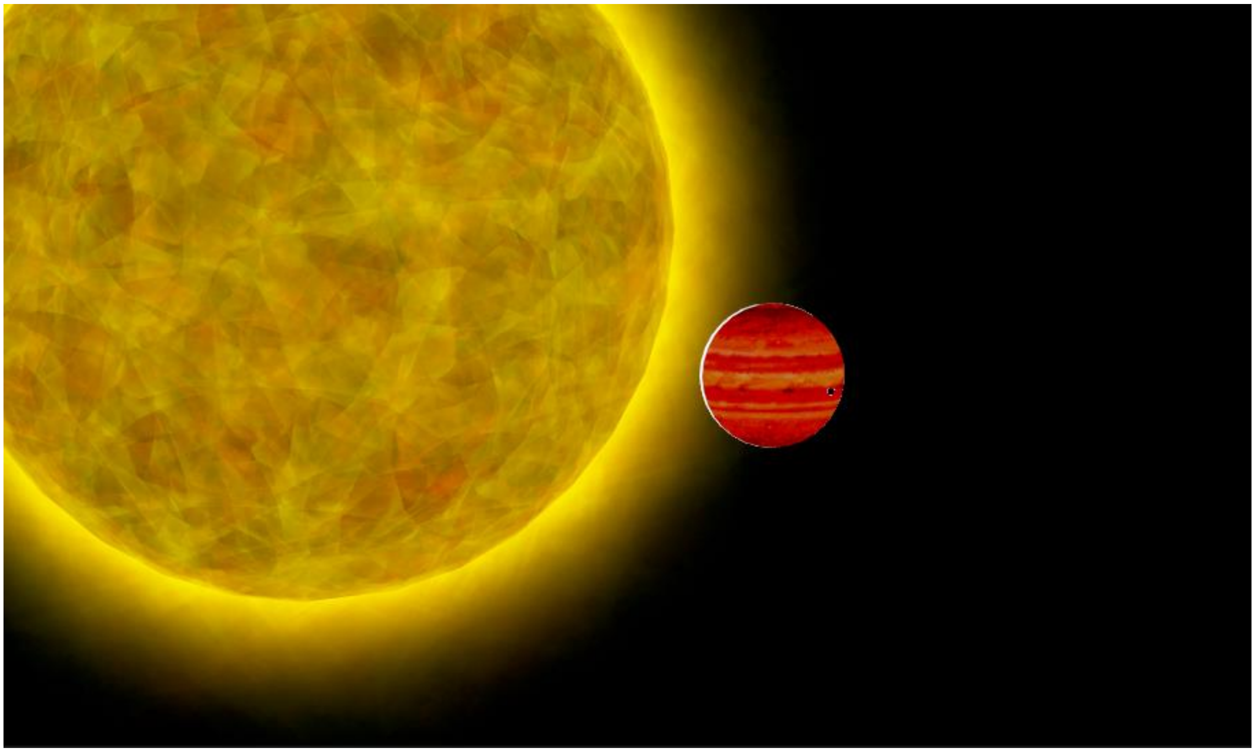
Figure 23: "Artist illustration of the planet orbiting the sun-like star HD 149026" (HD 149026b) [104]

[103] Note: Although the representation of WASP-12 in adVantage makes the star appear less bright than the planet, the opposite is true: WASP-12 is brighter than WASP-12b.

[104] U.C. Santa Cruz, "Artist illustration of the planet orbiting the sun-like star HD 149026," *Universe Today*, October 15, 2008, https://www.universetoday.com/19774/hottest-ever-exoplanet-discovered-wasp-12b/.

Figure 24 (a, b): Initial Perspectives of WASP-12, WASP-12b, and the Earth/Moon Proxy; in (a) the Earth/Moon Proxy is the Small, White Spot To the Right of WASP-12b, and in (b) the Earth/Moon Proxy is the Black Spot Overlapping WASP-12b Near its Right Edge

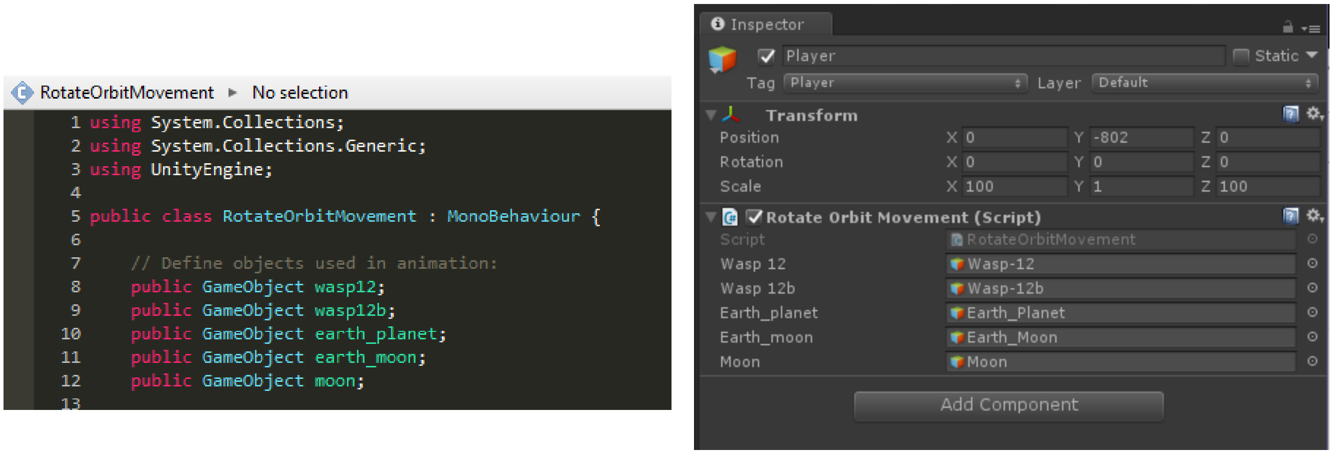




Translation of the scripts from JS to C# was straightforward. The option of declaring public, named variables in the C# script that referred to Unity GameObjects (e.g. the star, planets, and moons) was particularly useful, as the 3D models constructed to represent each object could be paired with named variables in the instance of the rotational/orbital script instance added as a component to the in-game container called 'Player'. In addition to the script dictating system movements, the 'Player' container also holds the system references to the in-game camera, the

HMD, the hand controllers, and other adVantage effects which are most easily positioned relative the player's current location.

Figure 25 (a, b): (a) Public GameObject Variables Declared in Script and (b) Variable and GameObject Parings in Player Script Component that Handles Rotational and Orbital Motion in adVantage



User-System Interaction in Immersive adVantage:

During this initial stage of development, one crucial difference between the non-immersive and immersive versions of adVantage crystalized: allowing students to manipulate system parameters using drop-down menus and an update function in the JS prototype was much more feasible than creating similar menus that worked in an immersive, 3D environment. Because of the un-immersive, 2D nature of the computer monitor, and because of its relatively small size, there is little to no chance that a student user will feel present within the adVantage space-system. Therefore, creating 2D drop-down menus that are positioned in front of all other objects currently shown in the scene was not overly disruptive to a learning experience. The benefits of allowing users to experiment with parameters and manipulate the solar system far outweighed the disruption. In the immersive adVantage system, though, students are more likely to suspend their disbelief and accept that they are present in the immersive, virtual world. Panels with menu options and textual information are included in Unity/SteamVR adVantage, but they are not present in the user's field of view to the same degree that the drop-down menu equivalent would be.

Although more realistic parameter manipulation menus could be integrated into the immersive adVantage system if they were modeled as spaceship control panels that neighbor or surround the user at a constant height relative to the HMD (e.g. if the user was standing or sitting in front of the panels for the extent of their travels, and the spaceship/panels moved with the user through space), adapting the sliders and number entry fields used in JS adVantage (see **Figure 5**, pg. 21, **Figure 8**, pg. 22, in **Section 5**) to a Unity environment still presented a problem. Menu panels with the level of detail necessary to give users clear, visual control over all system parameters encompassed in the JS menu would likely fill too much a user's field of view, dominating the system so that the objects themselves become secondary to the menus.

Alternatively, if the menus were developed to be spaceship-style interfaces, possibly like those seen in *Star Trek 2009* (see **Figure 26**), they would require menu components to be much too small for users to comfortably interact with them through the headset and controllers. Unlike glove-like, haptic hand sensors that may give users the dexterity necessary to make modifications via smaller buttons or sliders, the Vive hand controllers are better suited to point-and-click interactions.

Figure 26: "JJ Abrams' Enterprise Bridge from 2009" [105]

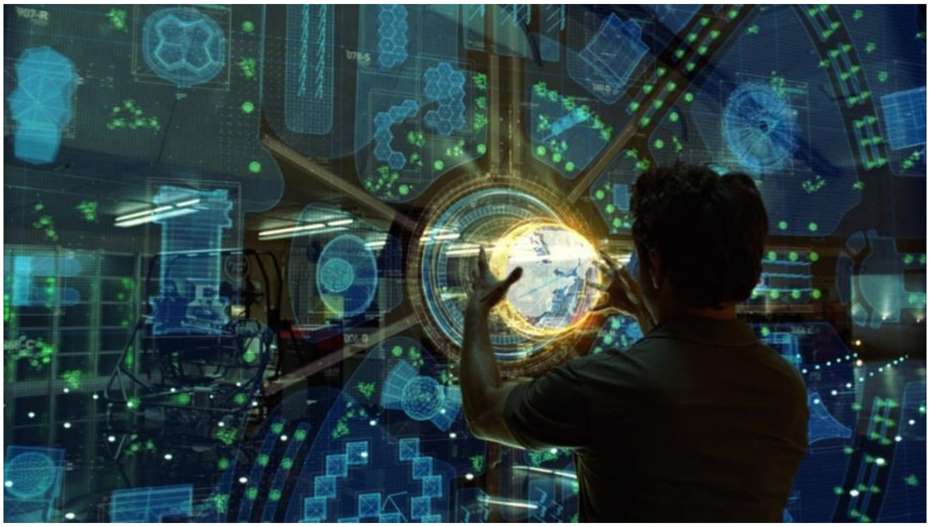
Another science-fiction inspired solution to the challenge of how to let users modify adVantage system parameters came from *Iron Man 2*. We considered programming the HTC Vive controllers to recognize particular movements that a user could make and match those gestures to functions that adjust system parameters. As shown below in **Figure 27 (a, b)** below, a two-hand gesture could be used to select a planet from the adVantage landscape (**Figure 27 (a)**) and gesturing outwards or inwards with both arms could be used to increase or decrease the planet's radius (**Figure 27 (b)**). However, this technique could make precise changes more difficult, and once a student changed a system parameter from its original value, accurately resetting the parameter might prove difficult.

Ultimately, these difficulties associated with allowing users to continue modifying system parameters in the Unity/SteamVR adVantage system as they could in non-immersive adVantage led us to re-conceptualize the system. Rather than being designed like a virtual chemistry laboratory, where the user is given access to a number of chemicals and materials and invited to experiment as they see fit (or in line with provided instructions), the immersive adVantage system more closely resembles a virtual physics laboratory, where the user is given a pre-defined mission (or set of instructions) and invited to make observations as they carry out the task. The MEteor system, described by Dor Abrahamson and Robb Linden in the book chapter

[105] "JJ Abrams' Enterprise Bridge from 2009." *Gizmodo*, April 18, 2013, https://i.kinja-img.com/gawker-media/image/upload/c_scale,fl_progressive,q_80,w_800/18l0t9c4x6lrbjpg.jpg

"Embodiment and Embodied Design" and referenced in the literature review portion of this paper, is a good example of another virtual physics laboratory.[106]

Figure 28 (a, b): (a) Tony Stark Manipulating the Expo Model Hologram in *Iron Man 2*,[107] (b) Tony Stark Manipulating the Molecule Hologram in *Iron Man 2*[108]



[106] Dor Abrahamson and Robb Lindgren, "Embodiment and Embodied Design," in *The Cambridge Handbook of the Learning Sciences*, ed. R. K. Sawyer, 2nd ed. (Cambridge, UK: Cambridge University Press, 2014), 367.

[107] "IM2 PROLOGUE VFX 16" *The Art of VFX*. 2010, http://www.artofvfx.com/IM2/IM2_PROLOGUE_VFX_16.jpg.

[108] "IM2 PROLOGUE VFX 11" *The Art of VFX*. 2010, http://www.artofvfx.com/IM2/IM2_PROLOGUE_VFX_11.jpg.

Navigation in adVantage:

As we considered the implications of removing the parameter manipulation aspect of adVantage, middle-phase development of the system continued with a focus on space travel and, in particular, the challenge of dealing with the scale of space. Because adVantage users need to travel through the expanses of space between WASP-12 and the exoplanet WASP-12b (3,430,288 km.), as well as between WASP-12 and the Earth and Moon proxies included in the system (149, 598,262 km.), the navigation system used must consider a user's time, interest, and attention span while clearly acknowledging the difference between those distances.

The non-immersive adVantage system used a function which divided the current distance between any two objects (Moon and Earth, Earth and WASP-12b, etc.) by a factor of twenty-five with every frame-update to simulate faster-than-light travel in both parts of Mission 2. However, this method of navigation sacrificed accurate representations of relative distance between objects in favor of a quick and visually interesting animation. Because the distance traveled in each frame was scaled to the full distance between pairs of objects, the time (or number of frames) spend traveling between each pair always appeared to be the same. This obscures the truth that WASP-12b is approximately forty-four times closer to WASP-12 than the Earth is to the Sun. In the Unity version of adVantage, it is crucial to find a way to convey relative distance more clearly and intuitively.

Because adVantage is an educational environment geared toward conveying relative size and distances of objects in space, the method of navigation chosen for the system had to be both efficient and educational. Just as the JS adVantage system used axis systems and orbital paths to provide a yardstick for comparison, the Unity/SteamVR adVantage system must find a way to use relevant distances as yardsticks for comparison. To this end, we decided to treat the distances between WASP-12 and WASP-12b, as well as between the Earth and the Moon, as these yardsticks. The WASP-12/WASP-12b distance was selected not only because WASP-12b is the primary subject of adVantage, but also because users are able to visualize the distance when the observe WASP-12b orbiting WASP-12. The Earth/Moon distance, which we did not end up using in the system, was considered because the shorter distance would allow users to travel with more control over their exact path.

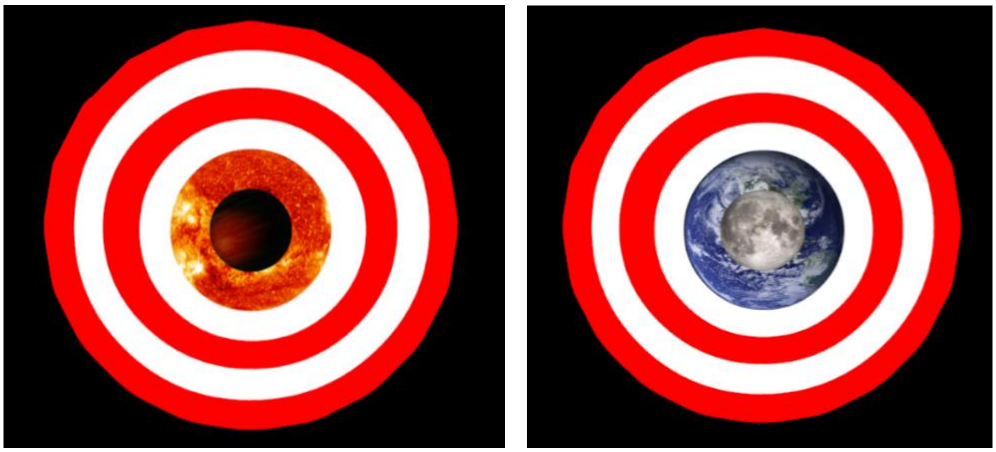
We explored several different means of navigation through space and analyzed how effective those modes of travel were at conveying relative distance.

WASP-12 to WASP-12b and Earth to Moon Targets:

The first method for traveling through the adVantage system used two types of targets that would allow users to "leapfrog" through space. Using the trigger on one of the hand controllers to toggle between a WASP-12 to WASP-12b sized step and an Earth to Moon sized step, users would use on of the touchpads on the controllers to reveal a target indicating the type of step (see **Figure 29 (a, b)**) they were about to take, direct a laser pointer originating from the tip of the hand controller at the target, then release the trigger to travel to the target's location.

Ultimately, although the targets could be used to facilitate users traveling the preset distances through space, this method of travel was rejected because due to the difficulty of balancing the size of the targets with their distance from the user. When the targets were the same size, one was always unreadable. A target size appropriate for the Earth/Moon target's relative proximity to the user was much too small to be legible at the WASP-12/WASP-12b distance from the user. Similarly, a target size appropriate for the WASP-12/WASP-12b target's proximity to the user was much too large at the Earth/Moon distance from the user. We considered making the targets different sizes, but that distortion made an accurate comparison of the two distances difficult.

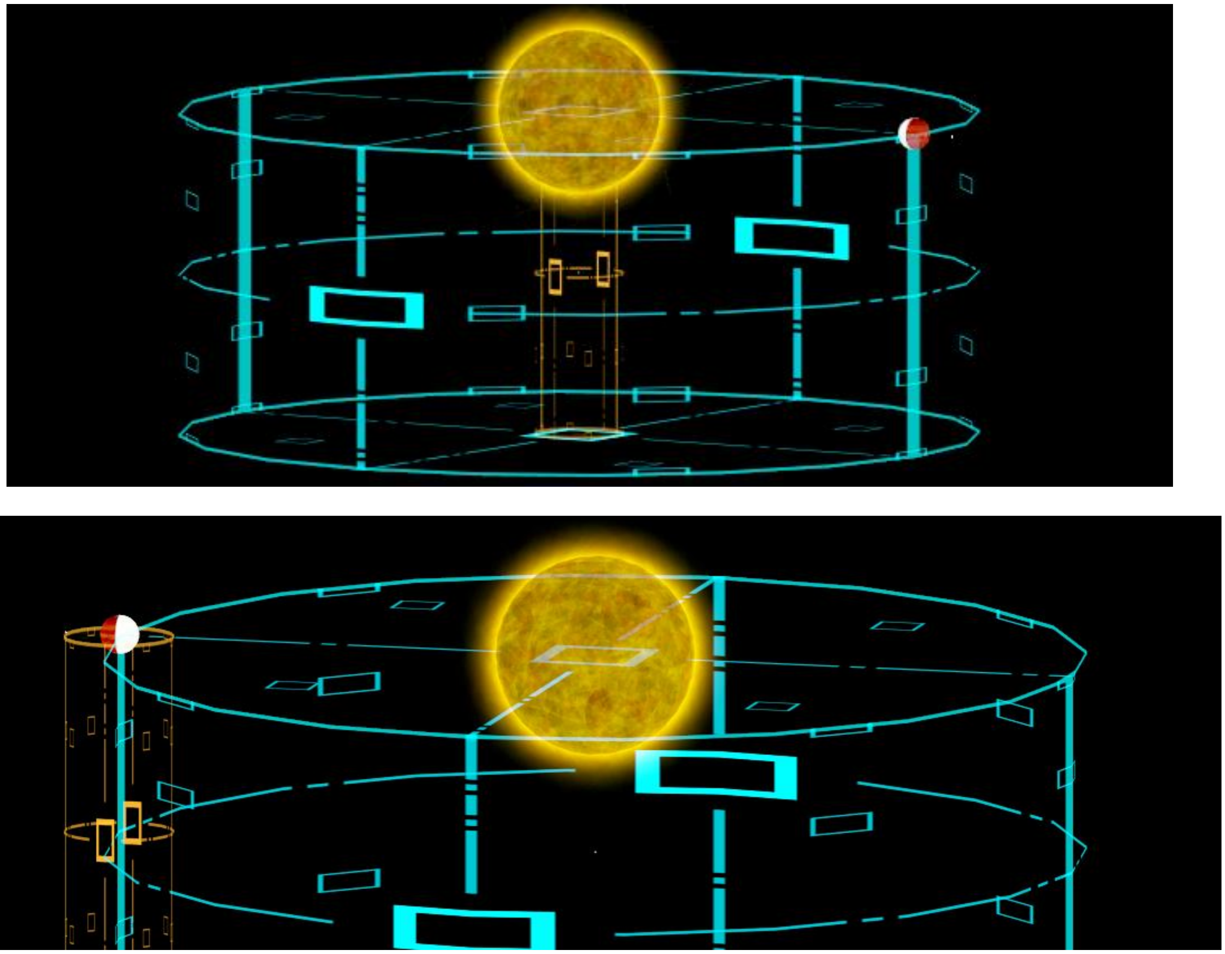
Figure 29 (a, b): (a) A WASP-12 to WASP-12b Target, (b) A Earth to Moon Target



Teleportation Cylinders:

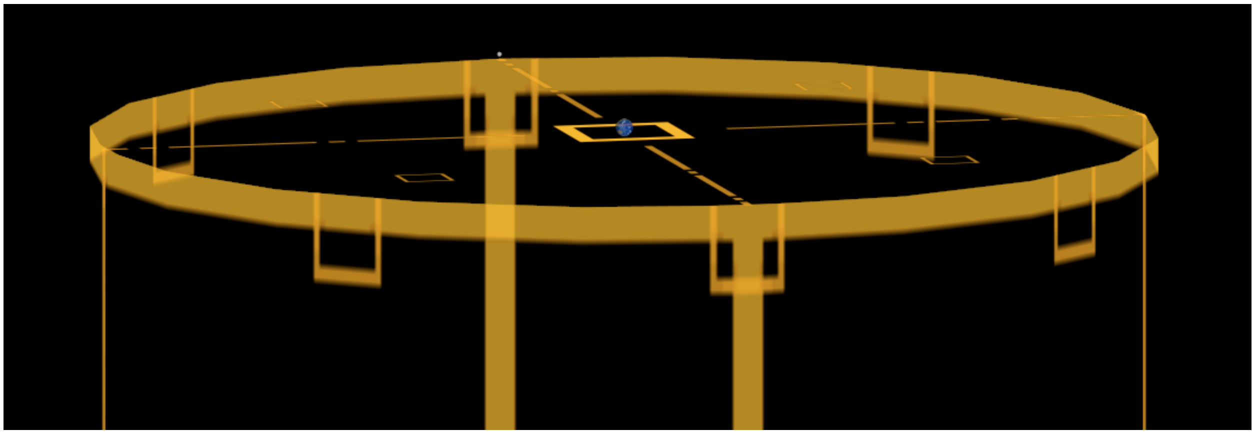
The second style of travel we considered for adVantage was a teleportation system that would show users the outer boundaries of cylinders with radii equal to the size of the step currently being taken. Once again, users would be able to toggle between a WASP-12 to WASP-12b sized step and an Earth to Moon sized step, and the boundary of the cylinder being displayed would give them a better sense of the full, 3D space available for exploration. Users would use a laser pointer originating from the tip of one hand controller to select a point on the teleportation cylinder (which would appear when the trigger was pressed), then release the trigger to travel to that spot. By assigning a separate color to the cylinders based on the step size (turquoise for the WASP-12 to WASP-12b step, and yellow for the Earth to Moon step in the images below), users would be able to easily distinguish the two.

Figure 30 (a, b): Teleportation Cylinders for WASP-12 to WASP-12b (Turquoise) and for Earth to Moon Sized Steps (Yellow)



The teleportation method offered users an additional tool for making comparisons of relative distance. The orbital radii of WASP-12b and the Moon serve as natural, visible yardsticks when the cylinders are aligned with other bodies in the adVantage system. Above, in **Figure 30 (a)**, both a WASP-12 to WASP-12b and an Earth to Moon distance teleportation cylinder are positioned directly below WASP-12. The outer edge of the turquoise teleportation cylinder passes directly through WASP-12b because they have the same (orbital) radius. In **Figure 30 (b)** the turquoise cylinder still sits below WASP-12, but the yellow Earth to Moon teleportation cylinder is positioned directly below WASP-12b. In this position, the outer edge of the yellow teleportation cylinder passes directly through the small, Earth/Moon proxy that orbits WASP-12b because they have the same radius, too. In **Figure 31**, the Earth to Moon teleportation cylinder is shown positioned directly below the Earth, with the Moon just above the outer-edge. Together, **Figure 31** and **Figure 30 (a)** show how the teleportation cylinders would let users draw conclusions about the relative scale of planets and distances – in this case, that the Moon's orbital radius is approximately equal to the half the radius of WASP-12 (384,000 km. vs. 695,700 km.).

Figure 31: Teleportation Cylinder with the Earth to Moon as the Radius With the Center of the Cylinder Positioned Directly Under the Earth with the Moon Over its Outer Edge



However, this method was also ill-suited to scaffolded missions in adVantage, and would be a better choice for a free-exploration mode. The greatest advantage of using cylinders to represent the possible teleportation zones – that the cylinders visually invite users to explore the full, 360° space of the adVantage system – was also the most problematic feature of this method of travel. Because so much of the adVantage system is empty space, and because the orbital radius of the Earth can be traversed in (minimally) forty-four WASP-12/WASP-12b steps or three-hundred and ninety Earth/Moon steps, the risk of students getting distracted or bored as they travel is high. By giving students access to all 360° of the adVantage system through the teleportation cylinder method of travel, we would risk student travel time increasing significantly in number of steps. If a student did not hit precisely the same point on the teleportation sphere with the laser pointer each time they stepped through space, they would find themselves zig-zagging along. Although the teleportation cylinder method of travel is something we would consider reintroducing in a free-exploration mode of adVantage, it is not a precise enough method of travel to be used in missions.

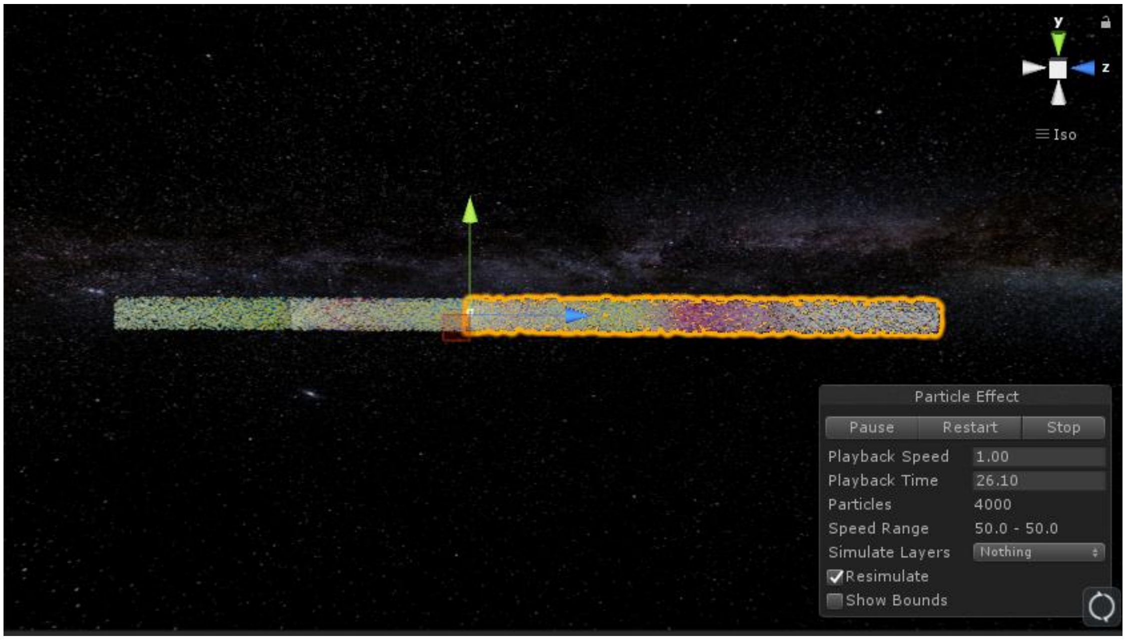
Warp Travel Along Preset Paths:

To avoid the possibility that users would become distracted or lost in the expansive, relatively empty system, and to emphasize perspective points that allow observation of relative size and distance, we decided to set a predetermined path beginning and ending with the most relevant vantage points that adVantage users will traverse: the point directly to the side of the Earth, and the point one WASP-12b orbital radius away from WASP-12. This approach to travel will still incorporate freedom of exploration within a well-scaffolded mission because the system will prompts user to look all around them - making use of the fully immersive, 3D nature of virtual reality simulations - at each stop, and to make observations of how large the various planets and stars appear to be.

To move along a preset mission path, a user will press the upper and lower halves of the touchpad on their right-most hand controller (see **Figure 19 (b)** – the touchpad is element (2) in the diagram). The upper hemisphere of the touchpad is associated with steps "forward", or in the negative X-direction, and the lower hemisphere is associated with steps "backward", or in the positive X-direction. For three reasons, we decided to add a warp-tunnel animation to adVantage: first, because adVantage should keep students engaged even while they are stepping through space; second, because we want to avoid users rapidly pressing the touchpad button to speed up the mission; and third, because we believe it is important that adVantage addresses the impossibility of moving over three-million kilometers through space in one-ninetieth of a second by using an equally impossible method of faster-than-light space travel.[109]

The warp effect created for adVantage is inspired by the special effects in *Star Trek 2009*, and the tutorial video, "Unity VFX - Warp Drive / Hyperdrive / FTL (Particle System Tutorial)", posted by Mirza on YouTube was the primary reference used in the design process.[110] The warp tunnel is made up of six Unity Particle Systems, each shaped like a long, narrow cylinder, and parameters including shape, duration, start size, max particles, and color over lifetime were modified as described in the tutorial video so that the fields resembled warp tunnels. Using two gradients – one made up of blues, purples, and reds, and the other of yellows, oranges, and reds – that were each matched with three of the six Particle Systems, the tunnel was built in overlapping thirds. Two Particle Systems, one blue and one yellow, are layered on top of each other in each third of the tunnel. The middle third of the tunnel covers the second half of the first third of the tunnel, and the first half of the last third of the tunnel. The effect of this layering is that the middle 50% of the tunnel is twice as populated with particles than the first and last quadrants. The warp tunnel is at its most dense in the center because the user will be positioned there during travel, and the ends will appear to be tapered from inside (see **Figure 32**).

Figure 32: Outside the Warp Tunnel, with one Particle System Component in the Third Portion of the Tunnel Selected

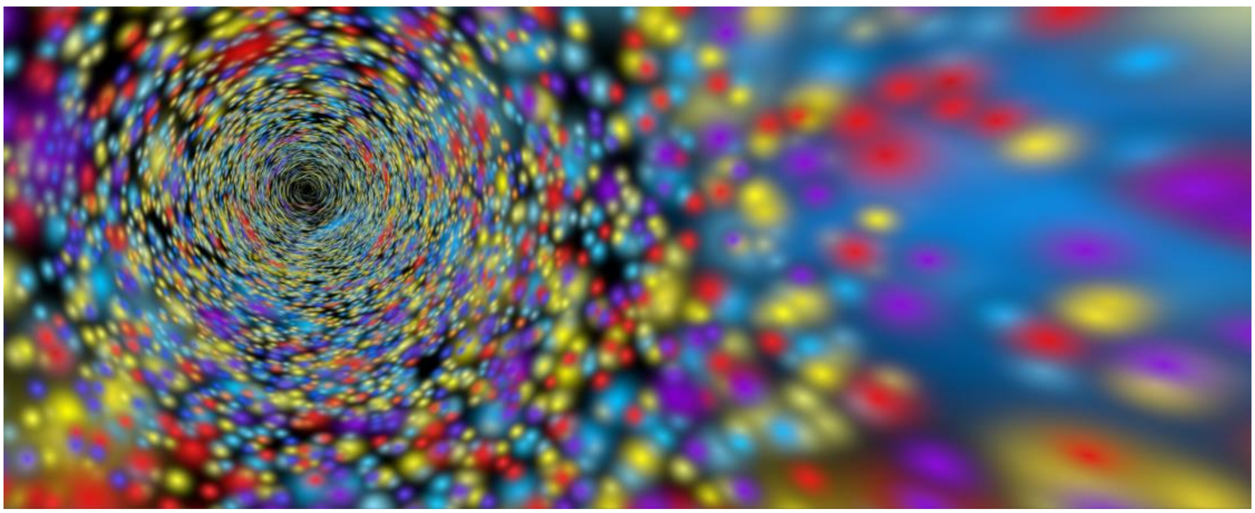


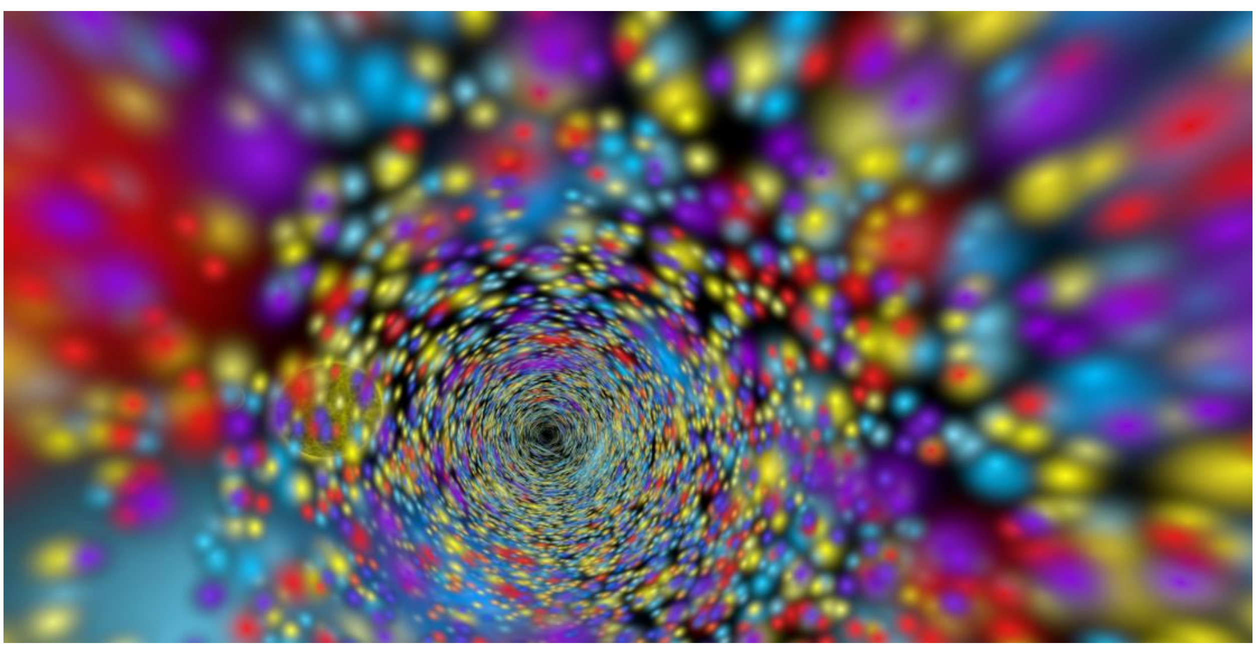
109 Note: Ninety frame updates occur per second in adVantage.

110 Mirza, *Unity VFX - Warp Drive / Hyperdrive / FTL (Particle System Tutorial)* (YouTube, 2017), https://www.youtube.com/watch?v=4hlCOUoc6aQ.

The warp tunnel is controlled by the same C# script that dictates missions in adVantage, and is programmed to run for only three seconds per smaller warp step. After the first two seconds, any objects in the system nearby that were hidden when the warp animation began are added back into the system, adding to the illusion that a user is "dropping out" of warp upon arrival at the target destination (see **Figure 33 (b)**). For longer warp steps, the animation runs for a total of ten seconds, and the objects are added back into the system after the first nine. The warp tunnel varies slightly depending on the direction that the user is traveling. The tunnel is rotated and shifted by the C# script based on which hemisphere is pressed on the rightmost hand-controller's touchpad.

Figure 33 (a, b): (a) Inside the Warp Tunnel During Travel, (b) Preparing to Drop Out of Warp, So WASP-12b and WASP-12 are Visible Outside of the Tunnel (on the Left)



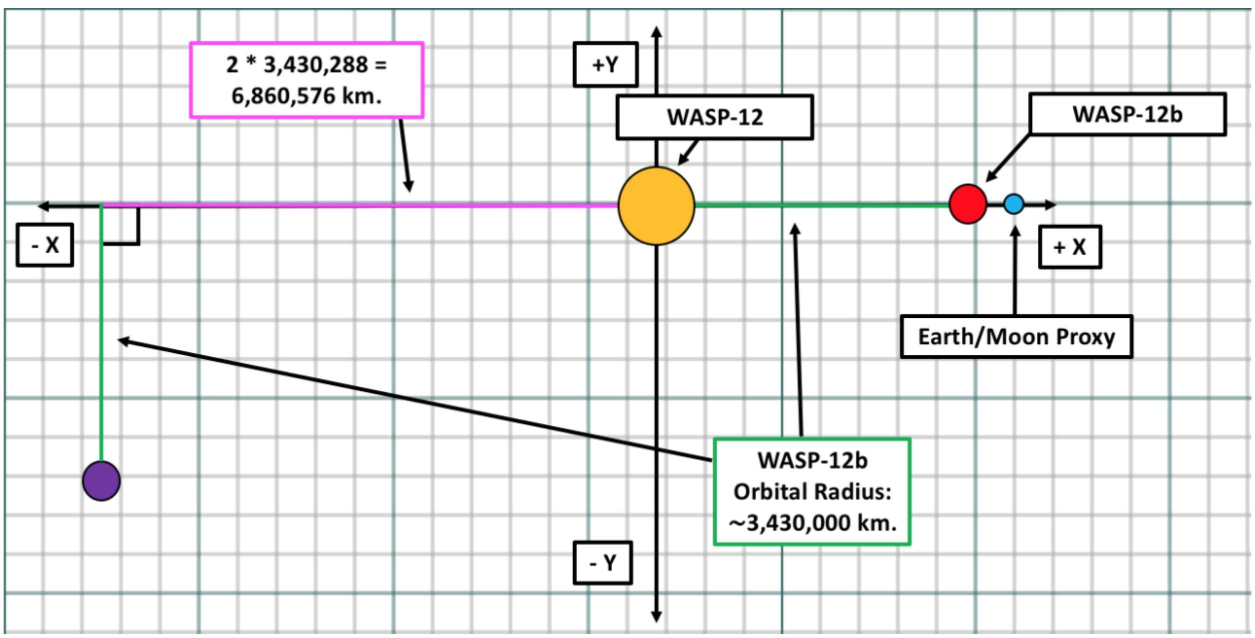


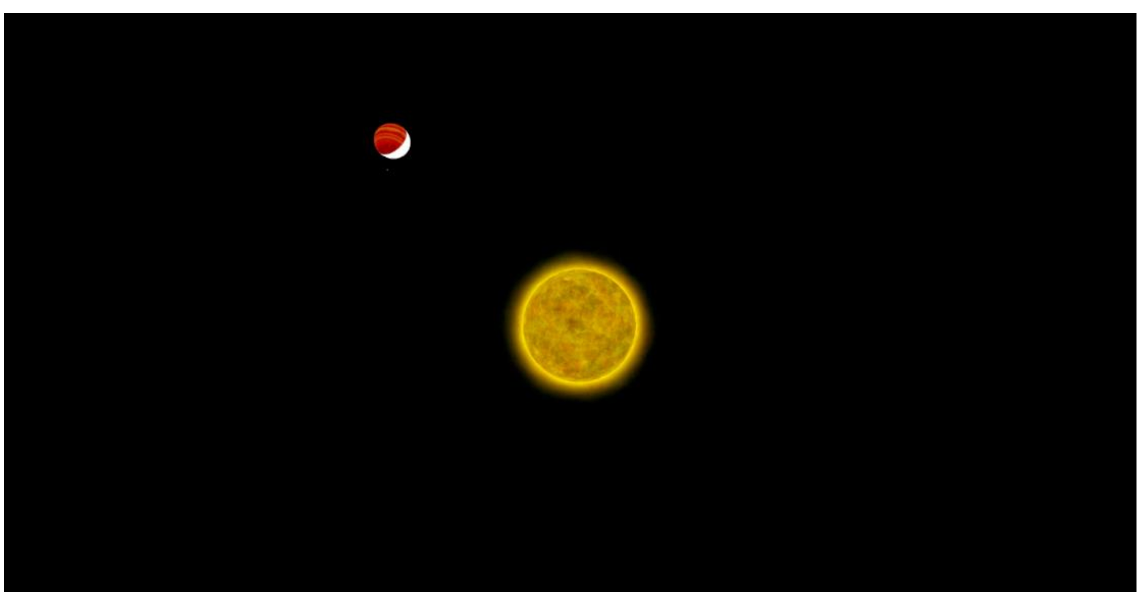
7. ACADEMIC SCAFFOLDING IN IMMERSIVE ADVANTAGE:

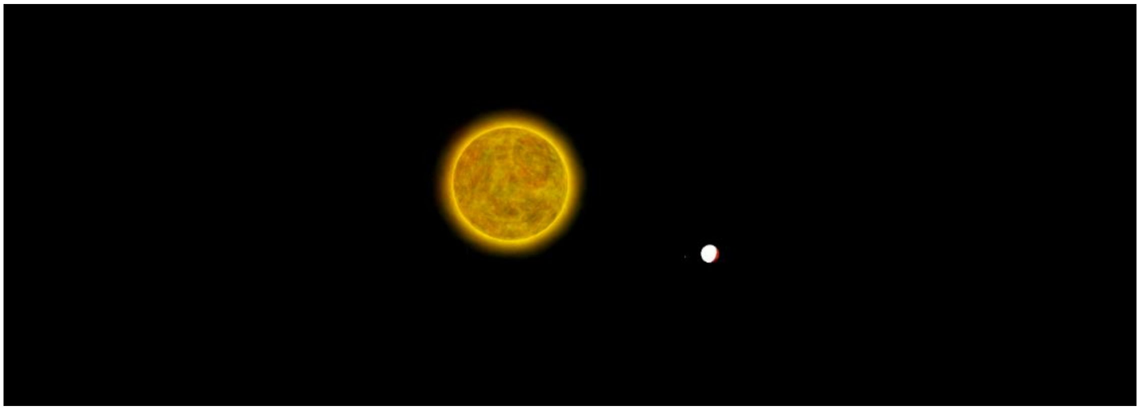
Introducing Immersive adVantage to Users:

Before launching the first mission in adVantage, users begin their exploration of WASP-12 and WASP-12b by watching WASP-12b orbit WASP-12 and the Earth/Moon proxy orbit WASP-12b from an initial vantage point (see **Figure 34 (a, b, c)**). This initial perspective is important because it allows students to get a sense of how far away from WASP-12 the exoplanet, WASP-12b, orbits before they take warp-steps along the pre-set path in Mission 1 of approximately that size.

Figure 34 (a, b, c): (a) Diagram of the Initial Vantage Point and (b, c) Initial Views of WASP-12, WASP-12b, and the Earth/Moon Proxy in the Immersive adVantage System







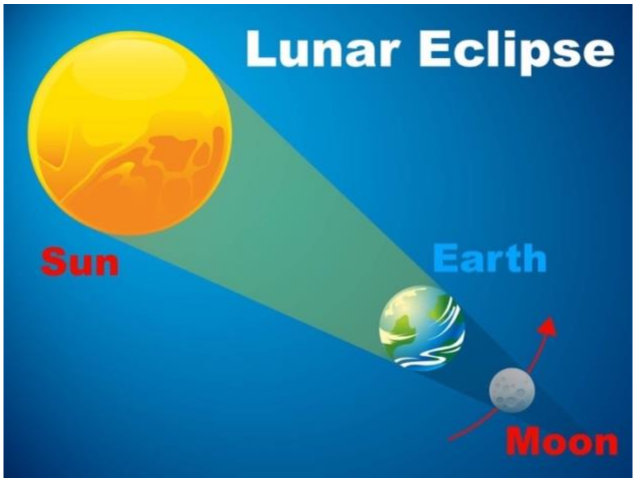
Before a student begins interacting with the system, they will be given two worksheets: the first will introduce WASP-12b and WASP-12 (see **A-2**), and the second will introduce the adVantage and explain the goal of Mission 1, how to launch Mission 1, how to take warp-steps in Mission 1, how long is each warp-step, and how to access the informational panels attached to each object (see **A-1**). With this information in mind, the student will be able to spend however much time they choose at the first vantage point before beginning the first mission by pressing the touchpad on the leftmost hand-controller. This will launch the longer, ten-second warp animation. When the animation ends, the user will find themselves at the starting point for Mission 1.

Mission 1 Trajectory:

The first mission, which became the programming focus for work this semester,[111] begins by dropping the user off directly to the side (in the negative Z-direction) of the Earth. From this first vantage point, the user can see WASP-12 and the Moon on opposite sides of the Earth, positioned as they would be during a lunar eclipse (see **Figure 35**). We selected this point for the mission because the objects visible in adVantage are familiar – the Earth and the Moon will be are inherently familiar to most users, and, in the distance, WASP-12 resembles the Sun – and structured the scene so that it would resemble images taken from the ISS of the Earth and Sun (see **Figure 36**).

[111] Note: All user, activities, interactions, and missions within the adVantage system are controlled by the same C# script: *PlayerInteraction.cs*.

Figure 35: "Lunar Eclipse Diagram" [112]



The initial perspective (see **Figure 37**) is also educational because WASP-12 (a proxy for our Sun) and the Moon appear to be approximately the same size, indicating that the two have similar angular diameters. [113] [114] In order to allow the user time to make observations of the relative sizes of the stars, planets, and moons at each step along the pre-set mission path, we decided to temporarily pause orbital and rotational motion in the system until the mission is complete.

Figure 36: "Sun Over Earth's Horizon" from the ISS [115]

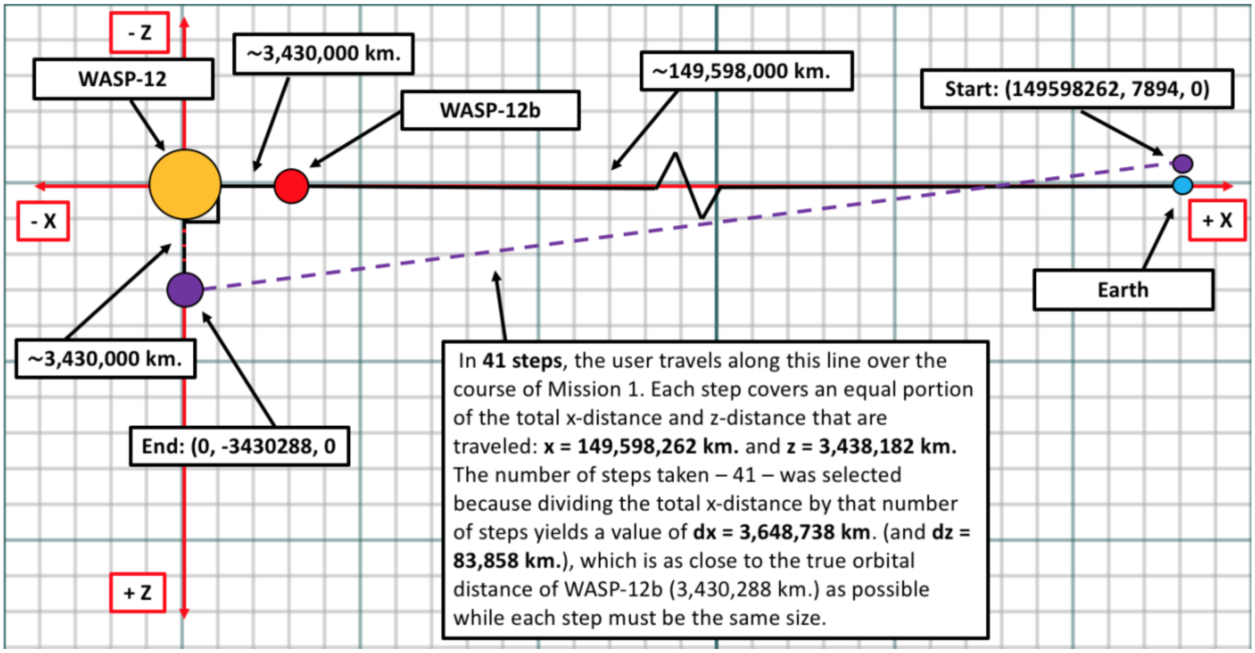
[112] "Lunar Eclipse Diagram," *NASA*, https://www.nasa.gov/sites/default/files/lunareclipse-diagram_0.jpg.
[113] Note: We experience eclipses on Earth because of this relationship: the Sun (here, WASP-12) is approximately 400 times larger than the Moon, but the Moon is approximately 400 times closer to the Earth.
[114] "Angular Diameter," *COSMOS – The SAO Encyclopedia of Astronomy* (Swinburne University of Technology), accessed April 7, 2018.
[115] NASA. "Sun Over Earth's Horizon." *NASA*. August 7, 2017, https://www.nasa.gov/sites/default/files/images/752983main_8905722051_3b553cf223_ofull_full.jpg.

Figure 37: Initial View of Mission 1 in Unity/SteamVR adVantage – Looking Towards WASP-12 (the Yellow Sphere) and WASP-12b (the Dark Spot on the Yellow Sphere) From the Earth

The final vantage point of the first mission is slightly to the side of WASP-12, at a distance in the positive Z-direction equal to the orbital radius of WASP-12b. This positioning allows the user to look comfortably at eye level as they observe WASP-12, WASP-12b, and the Earth-Moon proxy. The journey between these two vantage points spans a total of forty-two points in space (counting the first and last). This number was selected because dividing the orbital distance of the Earth (149,98,262 km.) into 41 steps of 3,648,738 km. is close enough to the true orbital distance of WASP-12b around WASP-12 (3,430,000 km.) that the step-size carries meaning for the user and is observable from prior system interaction (i.e. when users are able to watch WASP-12b orbit WASP-12 before launching the first mission). By keeping in mind that a single step is approximately the orbital distance of WASP-12b, users can count the steps made from beginning to end in the mission to surmise that the Earth's orbital distance is approximately 41 times greater.

Mission 1 was implemented in adVantage by defining a multi-dimensional array in the C# script which was populated with forty-two (x, y, z) coordinates (see **Figure 38**).

Figure 38: Diagram of Mission 1 in the Immersive adVantage System



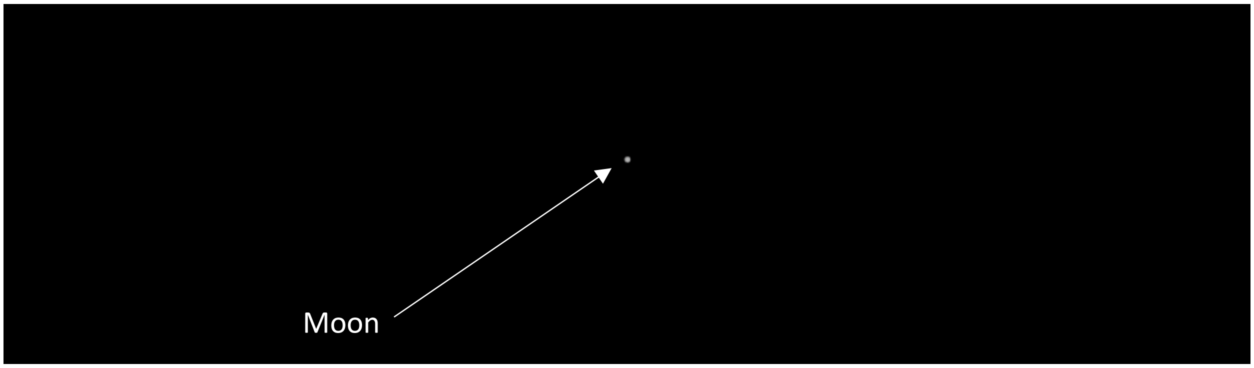
Each time the user presses the rightmost controller touchpad, so long as the desired movement is within bounds, all astronomical objects (planets, star, and moons) are hidden in the system and the warp animation begins. After running for a total of three seconds, the animation ends; the user has been relocated in the system to the next step along the pre-set path in the appropriate direction.

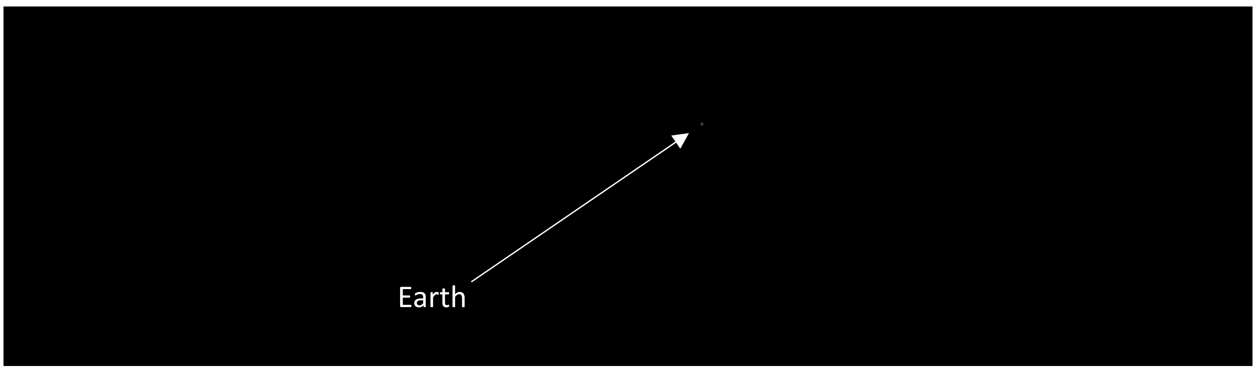
Comparing the Apparent Size of Planets/Moons/Star in Mission 1:

At each vantage point along the pre-set path, users are encouraged to look in both directions and observe the relative sizes of the Earth, the Earth/Moon proxy, WASP-12b, and WASP-12 (the Moon will be too small to see after the after the first step is taken). Building on a user's initial observations of the Earth/Moon proxy orbiting WASP-12b and WASP-12b orbiting WASP-12 (see **Figure 34 (a, b)**), observations that users make during the mission are a primary source of information for users about the relative size of objects (see **Figures 39 and 40**); the number of steps taken to travel from the Earth to WASP-12 (a multiple of the orbital radius of WASP-12b) is the primary source of information for users about relative distance.

The number of images included in **Figures 39 and 40** is itself indicative of the relative size of WASP-12b and the Earth. After traveling to the third vantage point (see **Figure 40 (c)**), the Earth is all but invisible to users. Meanwhile, WASP-12b is visible in silhouette against WASP-12 to some degree from the first vantage point.

Figure 39 (a, b, c): Views along the Positive (toward the Earth and the Moon) X-axis at the First Three Vantage Points From Mission 1 in Unity/SteamVR adVantage





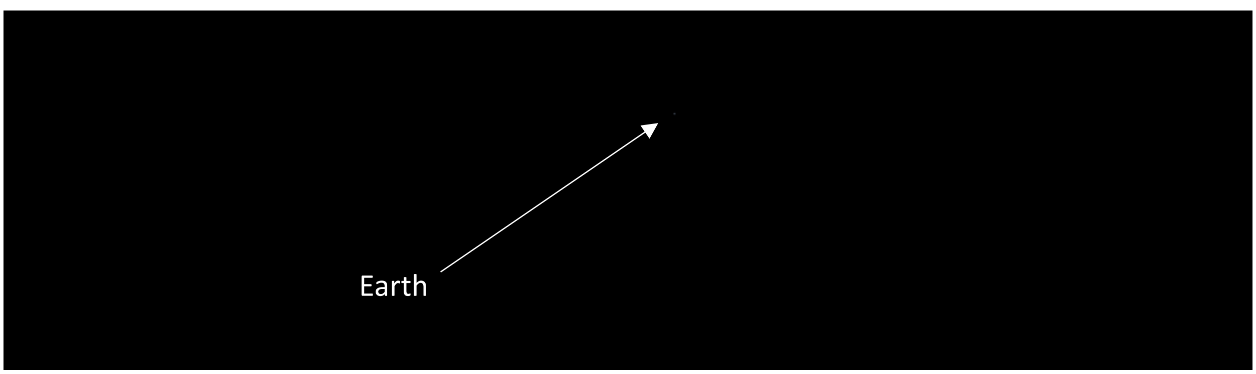
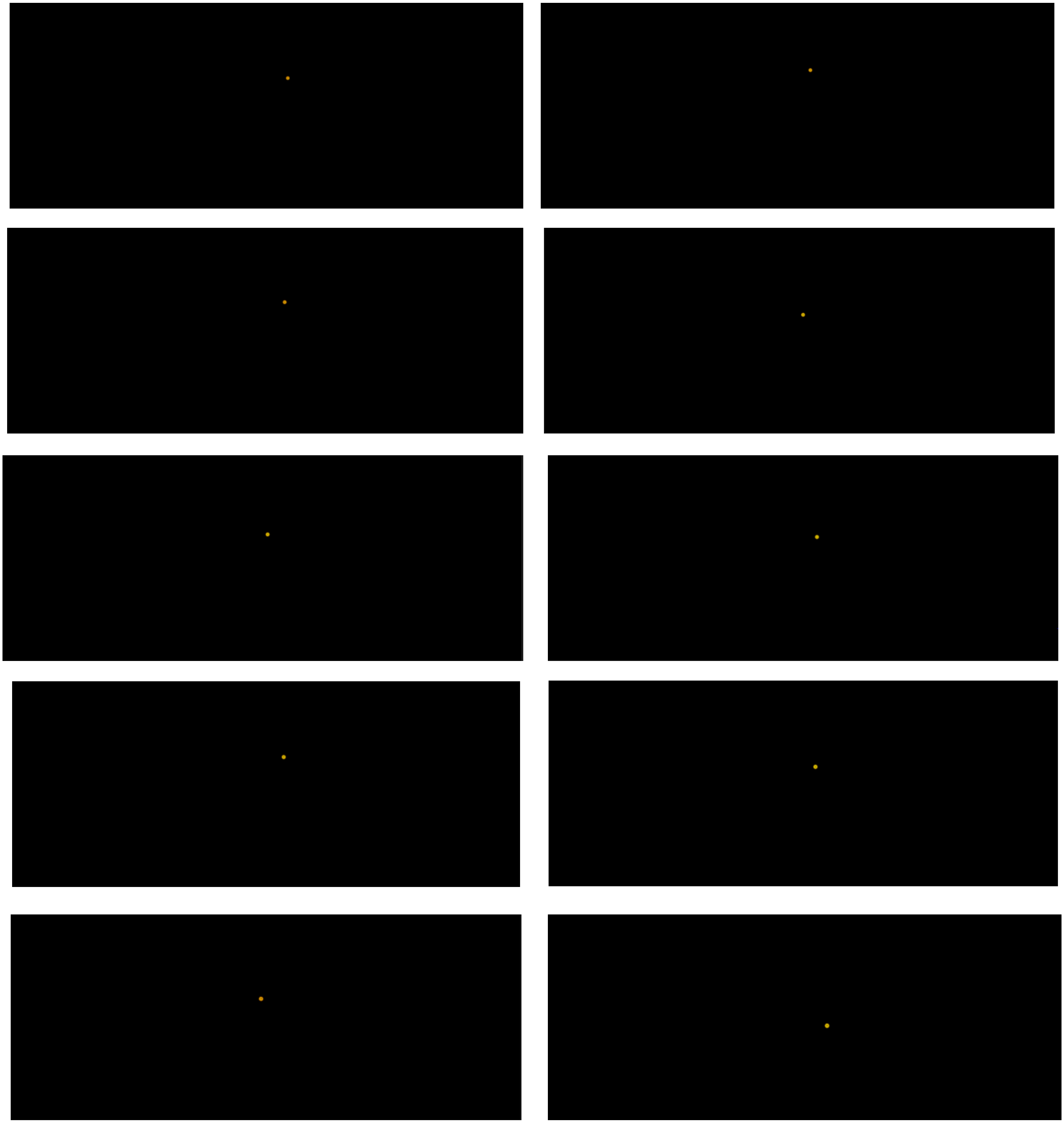
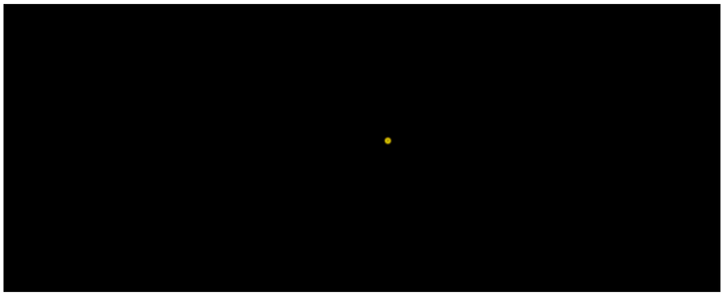
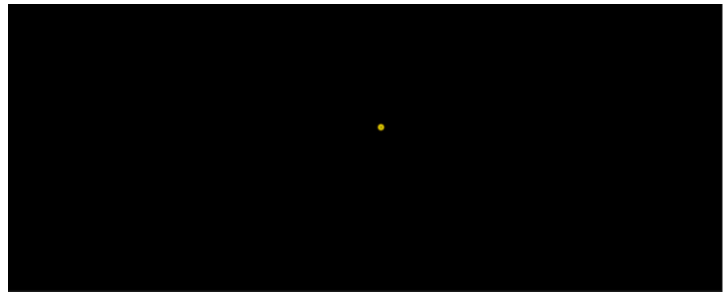
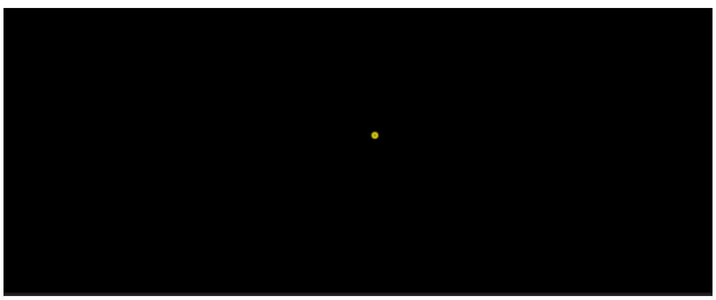
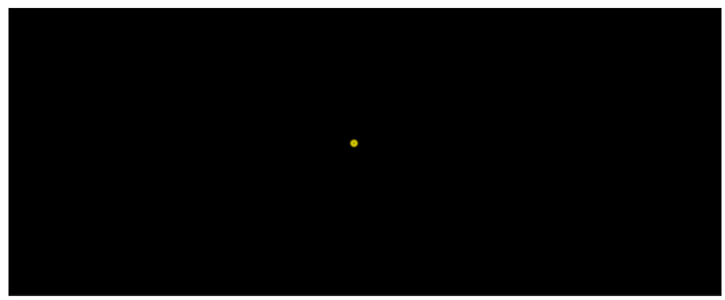
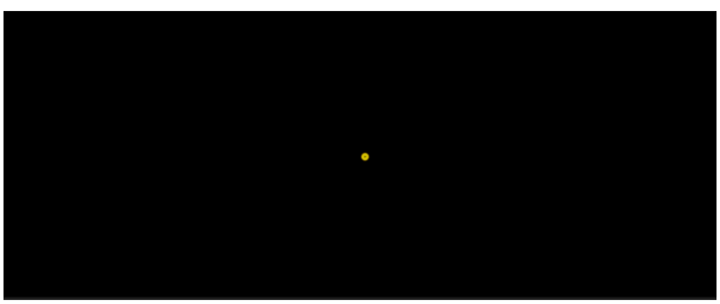
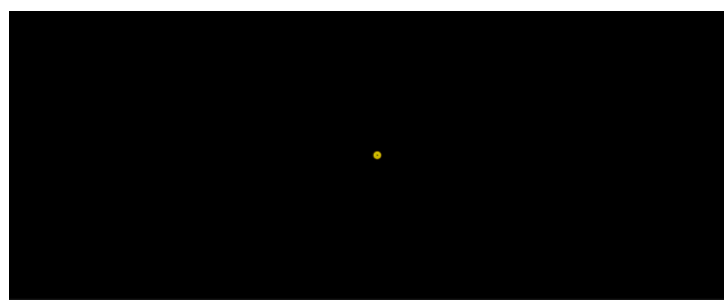
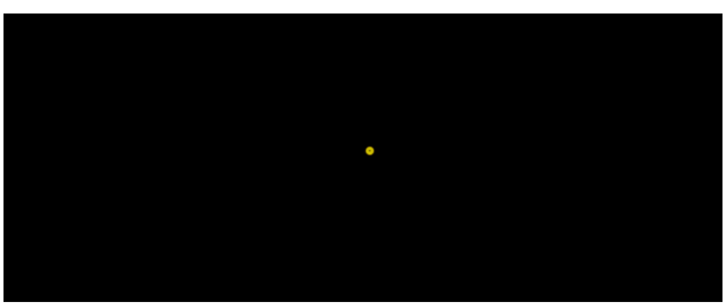
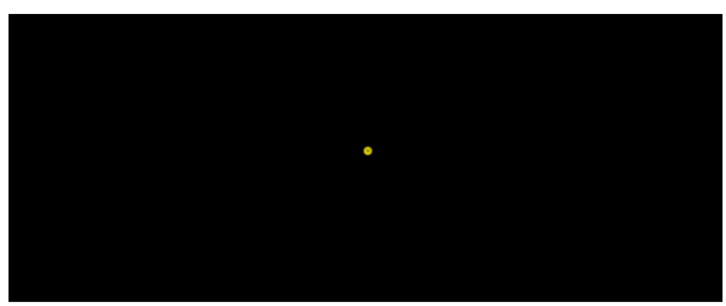
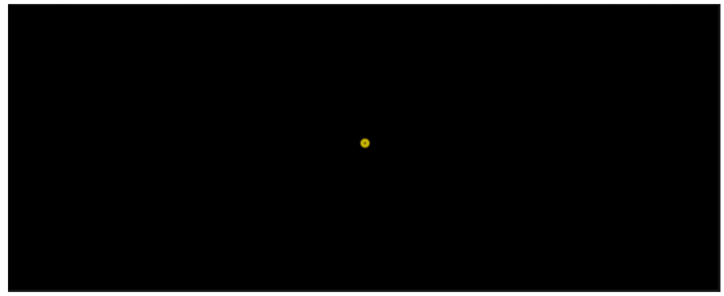


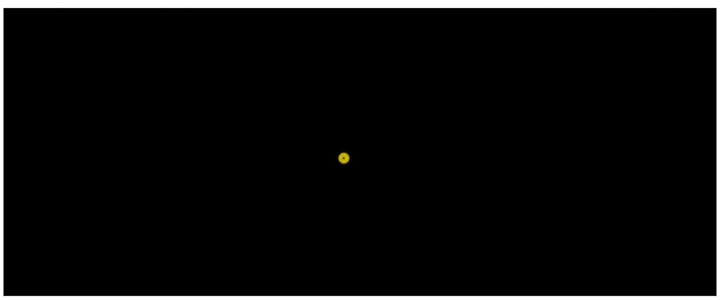
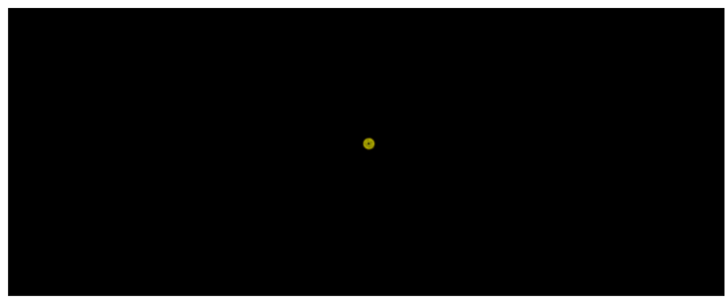
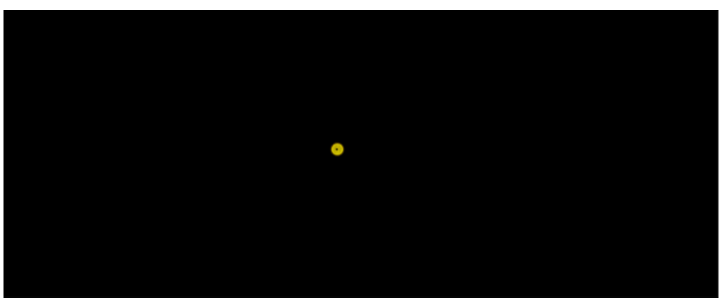
Figure 40 (a, b, c, d, e, f, g, h, i, j, k, l, m, n, o, p, q, r, s, t, u, v, w, x, y, z, aa, ba, ca, da, ea, fa, ga, ha, ia, ja, ka, la, ma, na, oa, pa): Views along the Negative (toward WASP-12) X-axis at Each Vantage Points From Mission 1 in Unity/SteamVR adVantage (Ordered Left to Right, Across then Down)

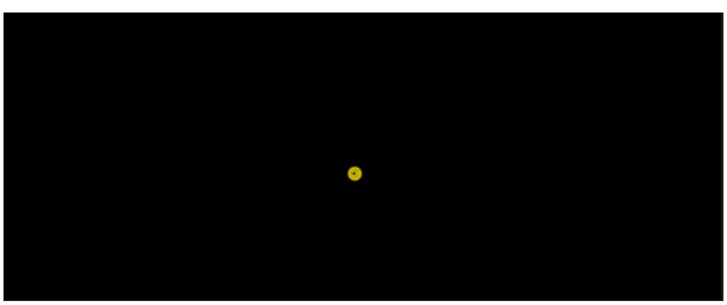
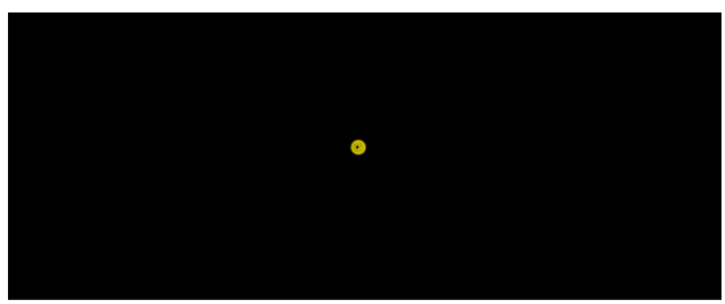


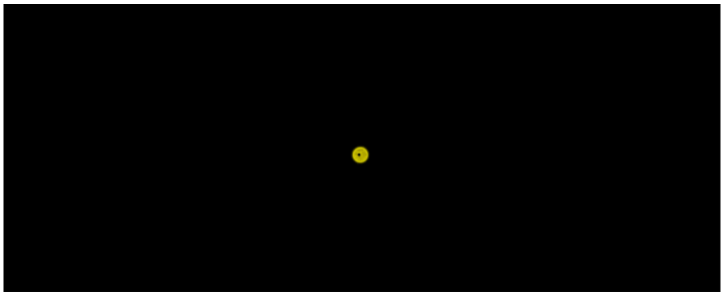
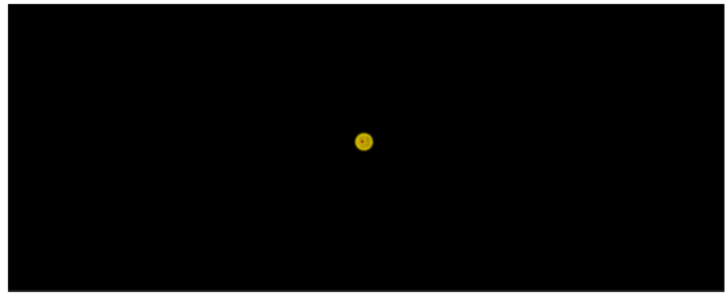
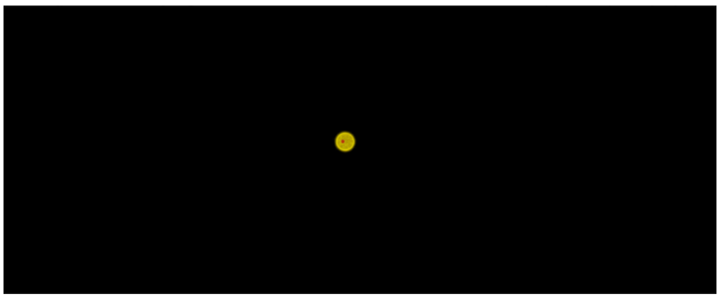
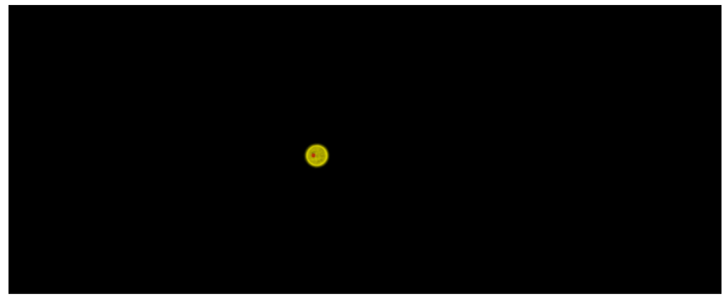
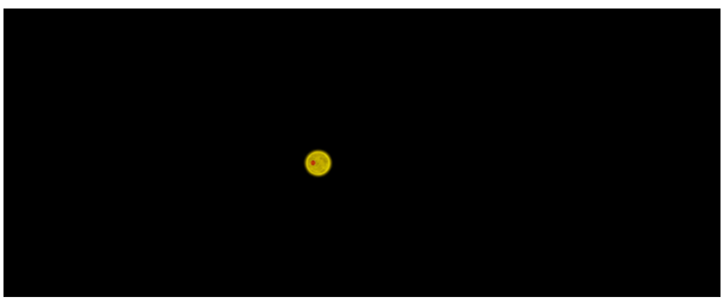
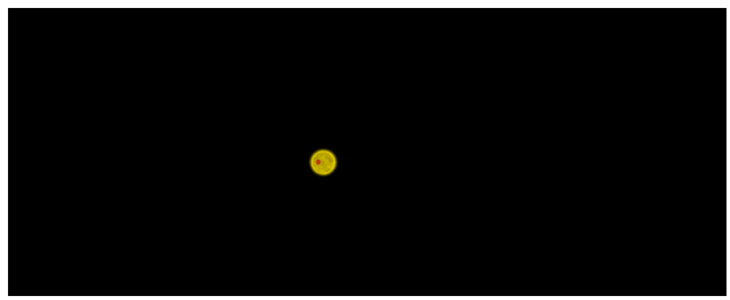
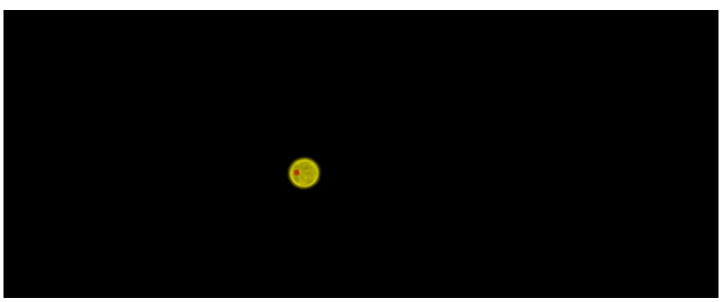
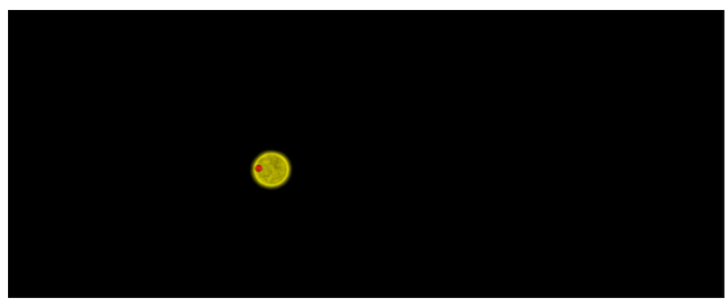
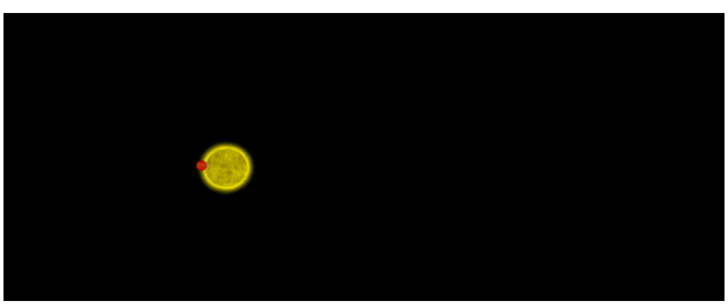
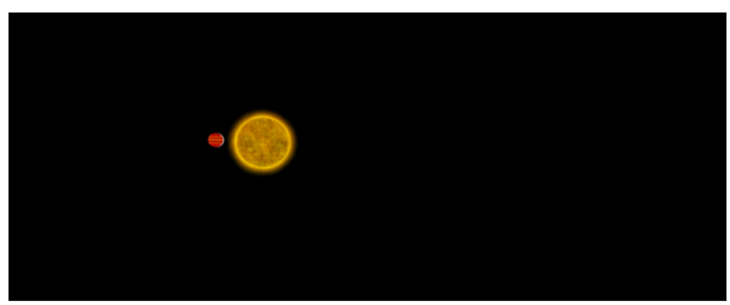



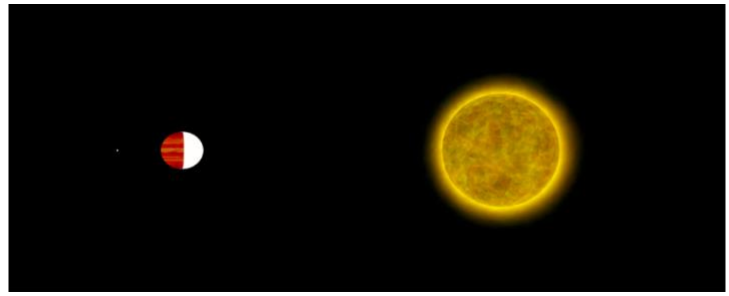










Tools Available to Users in the System:

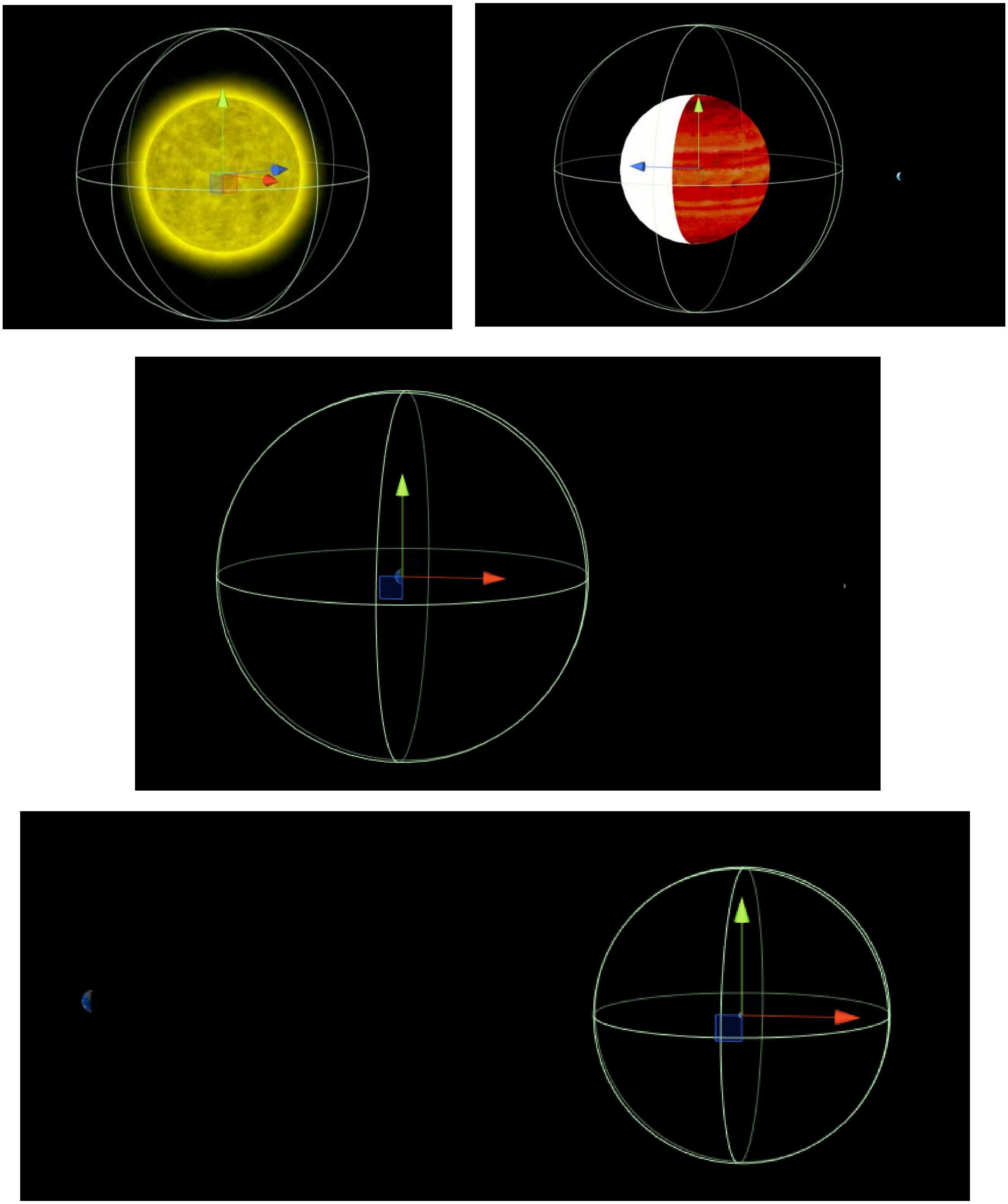
As users progress through the mission, they will be able to make use of two tools pairs with different input sources on the HTC hand controllers in the Update() method of the C# script controlling user activities (*PlayerInteraction.cs*). These tools are a laser pointer that can reveal informational panels linked with the subjects of the adVantage system, and a radar map that shows the position of a player in three-space relative to the orbiting planets and moons in adVantage.

Laser Pointer and Informational Panels:

The C# code used to implement the laser pointer tool comes from the tutorial blog post "HTC Vive Tutorial For Unity", written by Eric Van de Kerckhove.[116] To see an informational panel, the user must point the rightmost hand controller at the object it describes (e.g. WASP-12, WASP-12b, etc.) and press the trigger. If the ray originating from the hand controller and traveling in the direction the controller is pointed collides with any of the five objects that have associated informational panels, then the panel will be displayed at an angle above the user until the trigger is released. Each object is also surrounded by a collision shell – another, invisible sphere that expands surface area with which the ray can collide (see **Figure 41**). This is particularly important for the Moon, because the user will never be close enough to it while navigating the Mission 1 path to direct a ray precisely into the object. The collision sphere makes the Moon information panel accessible, and are similarly useful for accessing the Earth and Earth/Moon proxy panels. If the ray collides with an object (if the user is within its collision sphere) or with a collision sphere, a red "laser" beam appears between the controller to the collision point and will remain on the screen for as long as the trigger is pressed. The text content on each panel includes basic information about the objects, including features like name, radius, orbital distance, galactic coordinates, temperature, etc. as appropriate (see **Figure 42**). The information will ideally pique the interest of students about exoplanets like WASP-12b, and also provide useful, contextual information about the system. Citations for the sources of images and information used to fill the panels are included in this paper.

[116] Eric Van de Kerckhove, "HTC Vive Tutorial for Unity," raywenderlich.com, December 22, 2016, https://www.raywenderlich.com/149239/htc-vive-tutorial-unity.

Figure 41 (a, b, c, d, e): Collision Shells for (a) WASP-12, (b) WASP-12b, (c) the Earth Proxy, (d) the Moon Proxy, and (e) the Earth/Moon Proxy



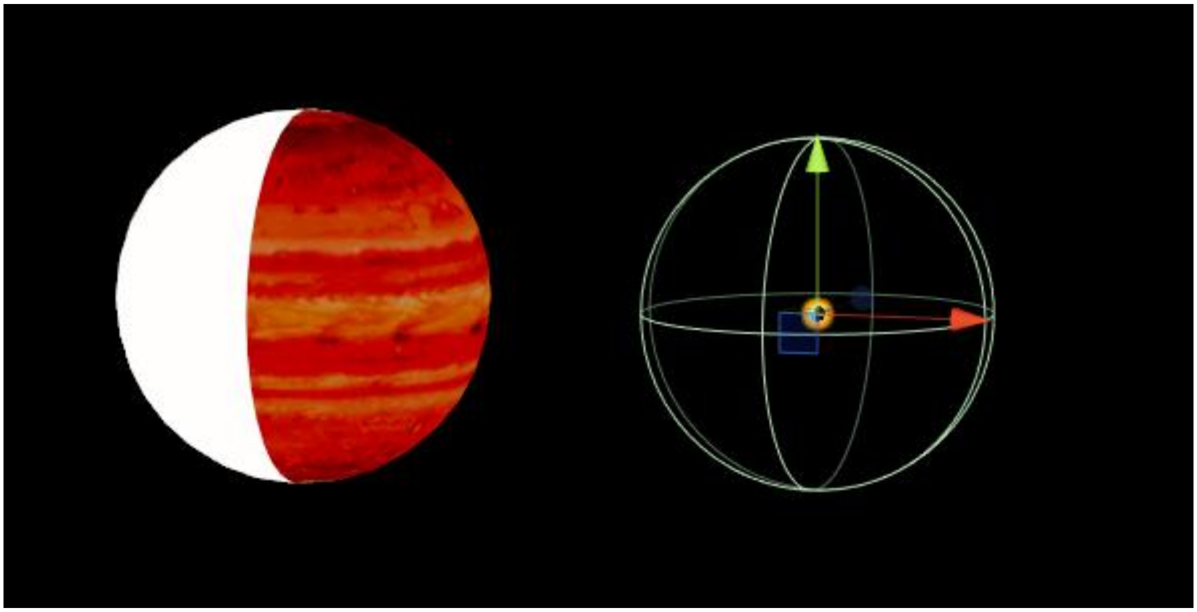
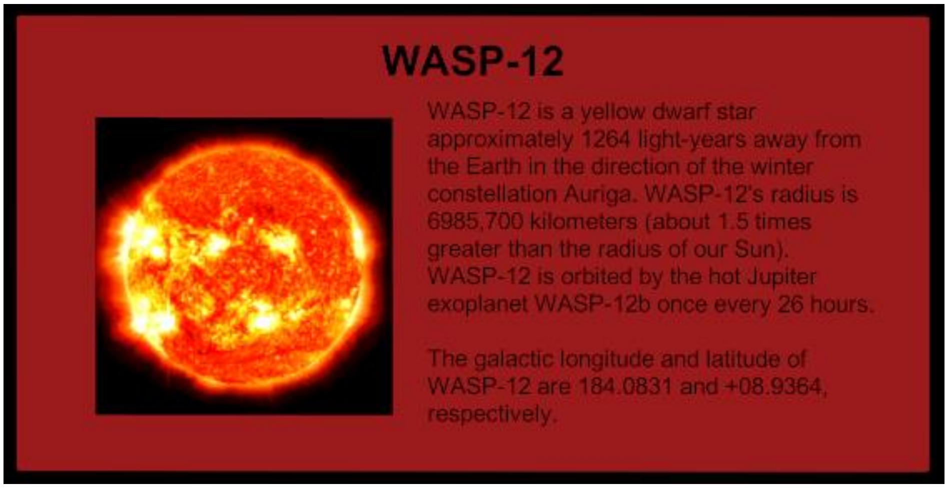


Figure 42 (a, b, c, d, e): Informational Panels for (a) WASP-12, (b) WASP-12b, (c) the Earth Proxy, (d) the Moon Proxy, and (e) the Earth/Moon Proxy [117] [118]



[117] Image Sources: (a) NASA/SDO. 2012. "The sun emitted an M6 solar flare on Nov. 12, 2012 – blend of one image showing the sun in the 304 Angstrom wavelength and one in the 193 Angstrom wavelength." *NASA*. November 12, 2012, https://www.nasa.gov/sites/default/files/706436main_20121114-304-193blend_m6-orig_full.jpg., (b) ESA/C Carreau, "Very Hot Jupiter," *Universe Today*, October 15, 2008, https://www.universetoday.com/19774/hottest-ever-exoplanet-discovered-wasp-12b/., (c) NASA's Earth Observatory. 2002. "Blue Marble West." *NASA*. 2002, https://www.nasa.gov/sites/default/files/thumbnails/image/1-bluemarble_west.jpg., and (d) NASA/Goddard/Lunar Reconnaissance Orbiter. 2015. "Christmas 2015 Full Moon." *NASA*. December 17, 2015, https://www.nasa.gov/sites/default/files/thumbnails/image/christmas2015fullmoon.jpg.

[118] Note: In future iterations of adVantage, measurements like the radii and orbital radii that are included on the informational panels (e.g. WASP-12b's radius and orbital radius) should either be rounded or be reported with uncertainties.

WASP-12b

WASP-12b was discovered in 2008 in the United Kingdom's Wide Area Search for Planets (WASP). The exoplanet's radius is 134,851.4 kilometers, and it orbits the star WASP-12 at a distance of 3,430,288 kilometers. WASP-12b completes one full orbit and rotation every 1.09 Earth days (approximately 26 hours).

Because WASP-12b is so close to its star, WASP-12, the surface temperature on its star-facing side is over 4,700 degrees Farenheit.

Earth (Proxy)

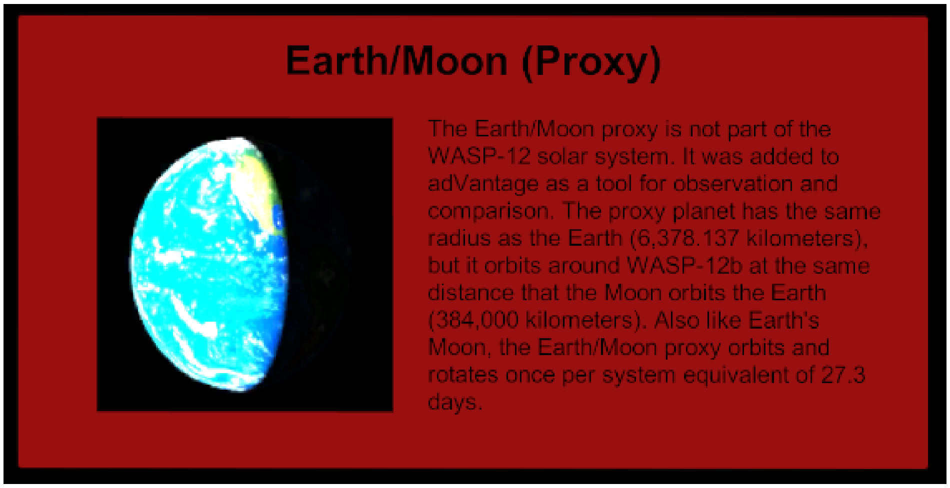
The Earth is the largest terrestrial planet located in our Solar System with a radius of 6,378.137 kilometers. It is located 149,598,262 kilometers away from the Sun. It takes the Earth 23.9 hours to complete one rotation, and 362.25 days to complete one orbit around the Sun.

The Earth is not part of the WASP-12 solar system. It was added to adVantage as a tool for observation and comparison, and here orbits around WASP-12 as it actually does the Sun.

Moon (Proxy)

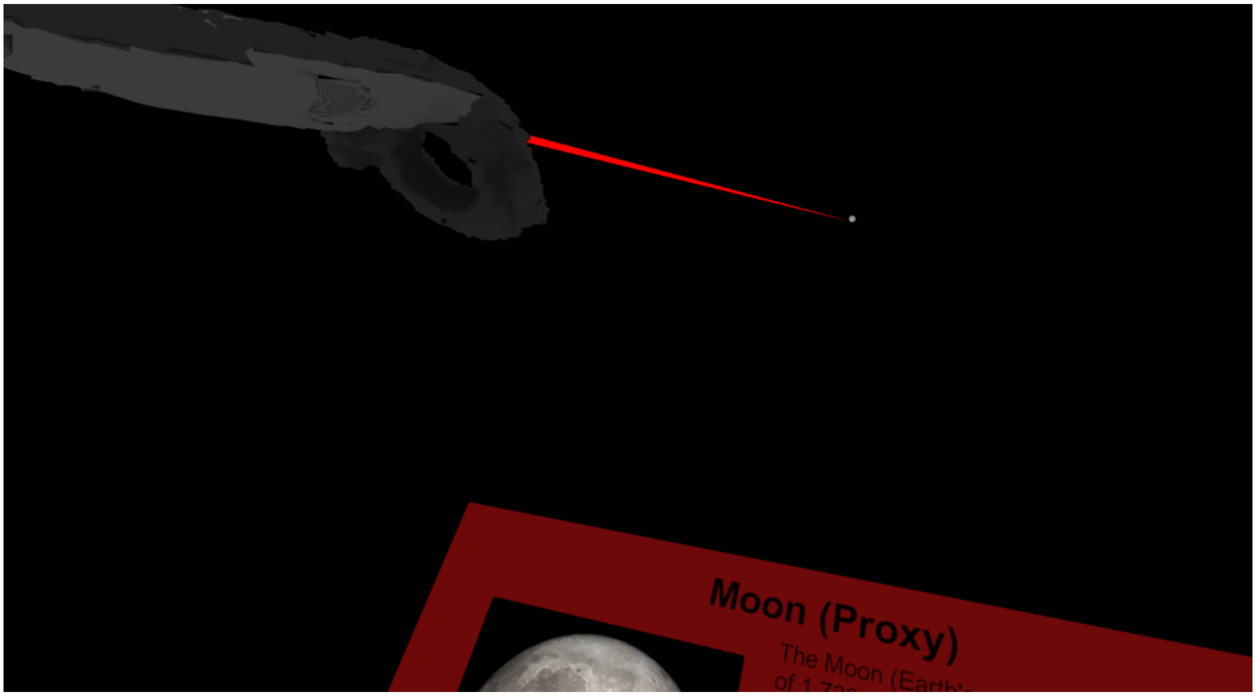
The Moon (Earth's only moon) has a radius of 1,738.1 kilometers. It orbits the Earth at a distance of 384,000 killometers. Because the Moon is approximately 400 times closer to the Earth than the Sun, but is also approximately 400 times smaller, the Moon and Sun have similar angular diameters - we experience eclipses on Earth because of this relationship.

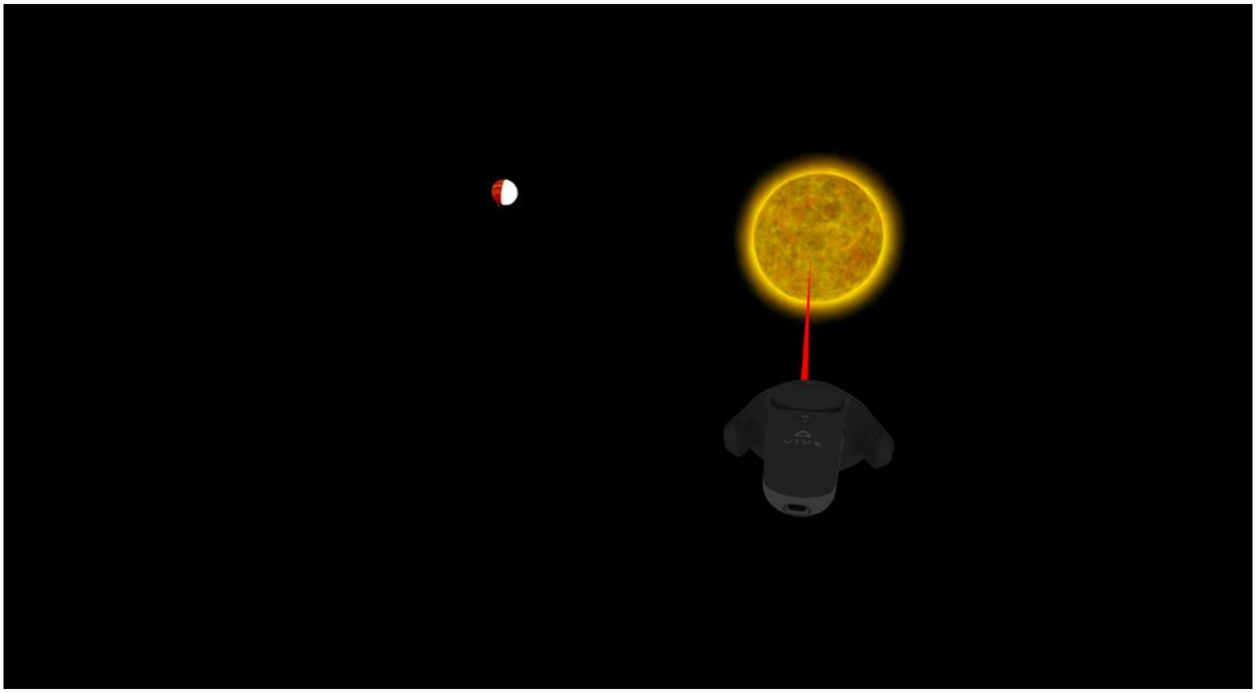
The Moon is not part of the WASP-12 solar system. It was added to adVantage as a tool for observation and comparison.

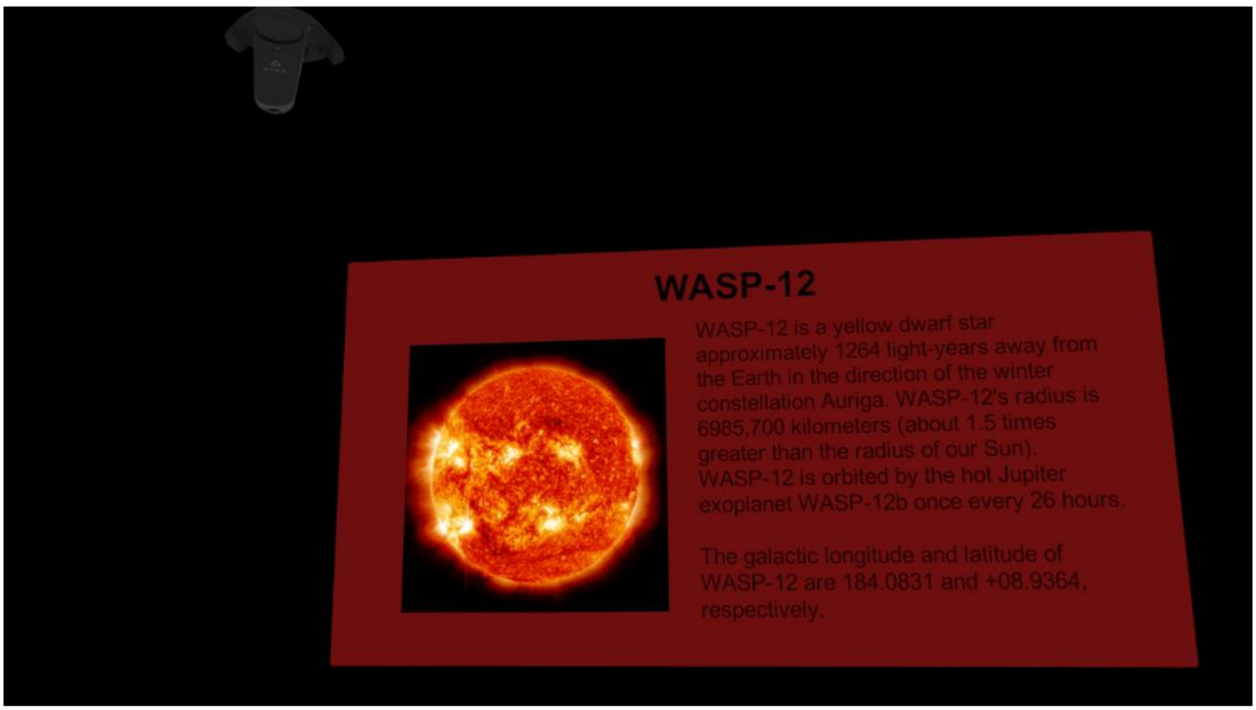


These panels always appear in the same position relative to the user: they are rotated to improve readability, and are placed below the user in the positive Z-direction. By looking down and in the direction of the Earth, a user will be able to read the short fact-files about each object without the panels colliding with any objects (see **Figure 43 (a, b, c)**).

Figure 43 (a, b, c): (a) The Laser Tool Directed at the Moon in Mission 1, Revealing the Moon Panel in the Bottom Right Corner; (b) the Laser Tool Used to Access the Informational Panels Directed at WASP-12; and (c) the Informational Panel for WASP-12







Celestial Radar Map:

The other tool available to adVantage users, the celestial radar map, is still under development and will be described in the Future Work – Continued Development section of this paper.

8. IMMERSIVE ADVANTAGE PILOT STUDY:

After the first mission was implemented in immersive adVantage, an informal pilot study was carried out to get preliminary feedback from students about the system. Because part of the goal of the adVantage system was to foster an understanding of relative distance in space by representing larger distances as multiples of smaller distances (e.g. WASP-12b is approximately 42 times closer to WASP-12 than the Earth is to the Sun), the pilot study investigates whether :

(i.) Students are able to successfully navigate adVantage by warp-steps and access the information panels paired with each object in adVantage;

(ii.) Students understand the significance of the size of each warp-step (approximately the orbital distance of WASP-12b around WASP-12) from reviewing the introductory materials;

(iii.) Students look back and forth between WASP-12 and the Earth/Moon (in the negative and positive X-directions, respectively) to make judgements about the apparent size of the planets, moons, and star from each vantage point;

(iv.) Students kept track (or were able to accurately approximate) both the total number of warp-steps taken in Mission 1 and the number of steps taken before the Earth disappeared from view; and

(v.) Students are able to describe the relationship of the distances between WASP-12 and WASP-12b, and between the Sun and the Earth (approximately 1:42) as a ratio, as well as the relationship between the radii of the Earth and WASP-12b (although this will likely be more a qualitative understanding than a quantitative one).

Research Methods and Design:

The pilot study had four participants, all of whom were Wellesley seniors with no astronomy background. Each participant signed an informed consent waiver which outlined potential risks and benefits of participation in the study; granted me the right to use any quotations from the post-interaction interviews in papers, posters, etc. about adVantage; and me permission to use video footage of participants interacting with adVantage in academic contexts. To protect the identities of the participants, the following pseudonyms will be used in this paper: Aries, Virgo, Taurus, and Sagittarius.

The research process involved giving the participant two worksheets to review before interacting with the system. One worksheet introduced the adVantage system, outlined the goals of Mission 1, and described how users should interact with the system using the HTC Vive hand-controllers (see **A1** and **A2**). After reading the worksheets and asking me about any misunderstandings, the participant sat in a chair in the center of the play-space for interaction with a Unity/SteamVR game, put on the HTC Vive headset, and took hold of the hand-controllers. I then started the adVantage system, recording what the participant saw with a video screen-capture and how the participant moved with a video-camera and tripod. After the participant completed the mission, they completed a post-interaction interview with me that was recorded and transcribed for inclusion in this paper. The template used to structure these interviews is included in the Appendix (see **A-3**). Although I intended to let participants interact with adVantage without any intervention, I instead talked with the participants throughout their interactions with adVantage to clarify any confusion about how to interact with the system, and about the contents of the system.

Conclusions from the Pilot Study:

Of the data collected in the study, the most valuable resource for improving adVantage was the interviews conducted with each participant after they interacted with the system. Observations made as participants carried out the mission (recorded by the screen-capture and video of those interactions) supplement the suggestions and feedback documented in the interviews. In the sub-sections below, quotations from Aries, Virgo, Taurus, and Sagittarius's interviews will be used to support my conclusions from this study.

System Improvements:

All four participants in the adVantage pilot study successfully completed the first mission, but each suggested several improvements to make using the environment a better experience. The primary source of confusion about adVantage, which became apparent in the post-interaction interviews, was the actual size of each warp-step. None of the four participants remembered that the size of the warp-steps was approximately the same as the distance between WASP-12b and WASP-12, even though it was explicitly stated in the explanation of Mission 1 on the introductory worksheet (see **A-2**). From this fundamental misunderstanding, which became clear quickly during the post-interaction interviews, we can conclude that either that the first mission of adVantage will fail fundamentally at conveying the scale of space, or that the mission (and the system, more generally) will require much more in-system instruction and reminders of relevant information.

In each interview, I clarified with the participant the actual size of the warp-steps so that they would be able to better understand the total distance between the Earth and the Sun (represented in the system by WASP-12). This revelation provoked varied responses from the participants, and helped them draw conclusions about the system. The quick acceptance of information about the size of warp-steps coupled with the conclusions drawn by the four participants during our conversations suggests that the adVantage system can be improved with additional instruction during interaction. Virgo's reaction to the size of the warp-steps was to invert the comparison; after considering the division of the Earth-to-Sun/WASP-12 distance into steps of WASP-12b's orbital radius, they imagined how much space a step of the Earth's orbital radius (around the Sun) would cover:

> **Virgo:** Okay, that makes sense. So each step is the orbital distance, like, the distance between those two planets [**Interviewer:** Yeah.] or is it… oh, okay, alright, alright – got it. Ummm… so it was that many of those. From my experience… oh that's, wow… the distance is a lot less than the distance between, ummm, WASP-12 and WASP-12b is a lot less than the distance between the Earth and the Sun… [**Interviewer:** And our sun.] Yes, that makes

sense, yeah, because then, yeah, because we had… if each step was the orbital distance between the Earth and the Sun then it would have been fewer steps, I imagine. I mean I… yeah. [**Interviewer:** That's true.] I mean, yeah, okay, that's cool.

Taurus, who had estimated that they had only taken approximately ten warp-steps to travel from the Earth to WASP-12, immediately used the clarification of the warp-step distance to comment on the proportional relationship between the WASP-12/WASP-12B and Sun/Earth distances:

Taurus: It seemed like around ten.

Interviewer: Around ten? [**Taurus:** Yeah.] Okay. And what would that tell you about the distance between the Earth and the Sun compared to the distance between WASP-12b and WASP-12?

Taurus: That we're, like, much further out from the Sun than WASP-12b is from its star.

Interviewer: Do you remember the significance from the worksheet of the size of each of those warp-steps?

Taurus: Uhhh, they were all, I mean they were all the same size, right? [**Interviewer:** They are, yeah.] Uhhh, that's it.

Interviewer: So they were also, ummm – do you remember when you started the mission you saw WASP-12b orbiting WASP-12? *[sound of agreement]* Each warp-step is the same distance of that orbital distance. [**Taurus:** Ohhhh.] So every time you took a step you were crossing [**Taurus:** Wow.] just about the same distance. Yeah…

Taurus: So it's like ten-times, the Earth is ten-times as far from the Sun… that's really cool.

Aries, after learning the true size of warp-steps, addressed the issue of mission scaffolding directly:

Interviewer: Twelve? Okay. Ummm, and then do you remember from the worksheet what the significance of the, the size of each warp-step was? [**Aries:** No.] Okay, so if I told you that every step you took was about the same distance that WASP-12b is away from WASP-12… [**Aries:** Oh.] So, where you could see that distance initially as it was orbiting. Is that surprising? That every step was that same distance? [**Aries:** Yeah.] Okay. Ummm, and without thinking about this… numeric specifics… what does that kind of tell you about the Earth versus WASP-12b for proximity?

Aries: Ummm, the Earth is like, really, really, really far away.

Interviewer: Exactly, yeah. Awesome. [**Aries:** That's cool.] Is there anything that you think maybe would have encouraged you to look back and forth more in the system to check in with the Earth? Like if the system prompted you: hey, where's the Earth right now?

Aries: Yeah, I think that… yeah. [**Interviewer:** Okay.] Because that would have been, that would have been something cool to look at, I just didn't think…

Interviewer: Awesome, so that's, that's definitely something you would appreciate? The system being like: "Hello Astronaut!"

Aries: Yeah, yeah, ummm, and I think also, to like, make people… Because I feel like, well, I didn't read this closely, but I feel like people in general don't really read things closely. So, I think, I think I would have thought to look back if I had remembered that it was, like, orbiting WASP-12. You know what I mean? [**Interviewer:** Yeah.] Because I was like, I'm going to a new place, but that's not the right way to think about it.

Although the introductory worksheets contain all relevant information for interacting with adVantage, there is no guarantee that a student will read carefully and remember important details. Because the size of the warp-steps is crucial for understanding the ratio of WASP-12/WASP-12B distance to Sun/Earth distance, that information should be readily available to users within the system throughout the mission.

The combination of two solar systems – ours and the WASP-12 system – in adVantage was also a source of confusion for students that should be clarified within the system. Like the size of warp-steps, this information was available to users in the introductory worksheet (see **A-2**), but both Aries and Taurus were confused by the distortion of reality:

Interviewer: So can you describe any preconceptions you had about scale of space before interacting with adVantage? Ummm, for example – this could be how you thought about the relative sizes of the Sun, the Earth, and the Moon, or the distances between, like, the Sun and the Earth, or between the Earth and the Moon?

Aries: Ummm, yeah pretty much – no preconceived notions whatsoever about how big space is. Uhhh, it was definitely, like, more… I don't know, I guess, like, the system definitely gave an impression on me as to how far this solar system is from ours, ummm, and…

Interviewer: I should add a quick caveat. [**Aries:** Yeah.] So, ummm, the system puts two systems together, [**Aries:** Okay.] so, ummm, WASP-12 and WASP-12b are a totally separate system. We're using the WASP-12, that star, as a proxy for our Sun, so, it's like, Earth at a distance it is from our Sun away from WASP-12, if…

Aries: … I think that makes less sense…

Interviewer: Okay, I can explain that better, so WASP-12 orbits WASP-12b… WASP-12b orbits WASP-12. [**Aries:** Yeah.] And then our Earth orbits its Sun. [**Aries:** Yes.] And so in this, both the Earth and WASP-12b are orbiting WASP-12 at the distances [**Aries:** Ohhhh, I see what you're saying.] So, oh yeah, it's two separate systems, but is kind of like, superimposed on top of each other.

Aries: Oh interesting, oh, that's kind of cool, oh, oh, so the point was, like… that WASP-12b is so much closer to the sun then we are to our Sun. [**Interviewer:** Yeah. Exactly.] Okay, got it, [**Interviewer:** I just wanted to make sure…] that makes a lot more sense now.

Interviewer: So, would that be something more explanation at the front end about how that's all being…

Aries: No, I think that I probably just should have read this [carefully]… Because I think, now, now that I'm thinking about it, I think that I did read that… Ummm…

Taurus: Ummm, I think I knew, I had seen, ummm, like, visuals, that put in, like, two-dimensions, like, the sizes of the Sun, the Earth, and Moon, so I knew that the Sun was like, way, way, way bigger than the Earth, which is way, way, way bigger than the Moon, but I think seeing it in, like, three-dimensions, like, the Earth and Moon, was cool, because then I realized, like, how small the Earth was, I guess, ummm, like actually, like how small the Moon was compared to the Earth. And then, the other thing that was really surprising was the, like, how far this, like, star and exoplanet were, because you said there, it was like 1,300 light-years, ummm, and that's like really far…

Interviewer: Ummm, okay, so – I'll clarify really quickly. So the solar system, the WASP-12 solar system, is about 1,300 light-years away from our solar system. [**Taurus:** Ohhhh, okay, not from the Earth.] Not from the Earth, no. [**Taurus:** Even then…] Ummm, well I guess, from our Solar System, and the, this, the Earth is it's distance away from the Sun away from WASP-12. [**Taurus:** Okay.] Yeah, so, as if you are orbiting the Sun, but WASP-12 instead. [**Taurus:** Yeah.] …

Another improvement suggested by both Sagittarius and Virgo is including more background to the adVantage system – specifically, stars besides WASP-12:

Sagittarius: Stars, would be cool. [**Interviewer:** Okay.] I felt that there weren't a lot of stars, and I feel like it's just like a cool added touch you could have, ummm, especially because those are sort of tangible things that you can locate then in the night sky, so if you can see, like, oh, Orion's over there, like, we're going in this direction, because there's not real sense of direction that I have, particularly.

> **Virgo:** Ummm, I have the sense that there's a lot of empty space, I think, pre-thinking about scale, and particularly the geosciences class, I thought that there were just kind of like, stars scattered everywhere that were all in like little neighborhoods… [**Interviewer:** A little bit, we did just omit stars.] Right, that's true, but uhhh – seeing, seeing like a diagram of our solar system, I think lead me to believe that they are just kind of like, that you can kind of like wave at them, that they're pretty close [**Interviewer:** Yeah.] to one another, which, I mean, in relative, relative to the distance, ummm, WASP-12 and the Earth I suppose they are, but, ummm, yeah, I'm just struck by how much, like, space there is between [**Interviewer:** Empty space?] yeah, empty space…

Sagittarius's comment suggests that adding more information to the system could support a greater feeling of familiarity. The ability to identify constellations like Orion's Belt, which a student can observe outside of a VR environment, may help ground adVantage users in the system. As Virgo comments, seeing more stars is also familiar from diagrams of the solar system that many students interact with as children and in schools. However, because stars are much further apart than Virgo implies, adding more stars to adVantage with information about their distance from a user's current location could promote a greater understanding of scale outside of the immediate adVantage system.

More generally, Virgo also recommended that more instructional guidelines be included in the system.

> **Virgo:** Ummm, *[long pause]* I think, uhhh, as maybe as some sort of instructional guidelines as you're, while you have it on, so you can say like, wait I think you did do this but like, there's the Earth, and like, but say like, this is this, this is this, and you step forward with this. Ummm, or maybe a test before you put on, before the participants put on the [VR headset] so that we know, that if you're testing, you're wanting to test how well you recall…

While testing students on the information on the introductory worksheets before they interact with adVantage may not be the best solution, as Aries commented and Virgo suggests, there is no guarantee that users will carefully read worksheets without incentive. Distributing reminders of important information throughout the system, and making that information available on demand throughout interaction, would better support learning in adVantage.

Technical Issues:

One technical issue with adVantage that repeatedly came up in testing was the differentiation of the two hand controllers based on their position relative to each other – that is, the *leftmost* controller is matched with certain user functions in the system, and the *rightmost* controller is matched with other functions. The problem with this system is that, whenever a user crosses their hands or arms during system interaction, the leftmost and rightmost assignments to controllers are reversed. No matter how the controllers were positioned relative to one another, users generally appeared to use the laser pointer (which is activated by pressing the trigger on the rightmost controller) by pressing down the trigger under their right index finger. In future versions of adVantage, it is important to find a better way to distinguish the controllers while a user is interacting with adVantage, possibly by distinguishing the controllers initially by relative position, then permanently associating each controller with tasks appropriate to their initial positions. Another possibility is to find a way to prevent users from crossing their arms or hands during the simulation.

Another technical issue, which will be addressed in greater detail in the "Future Work – Continued Development" section of this paper, is the apparent shakiness (or flickering) of the hand controllers at the outer reaches of the system. Sagittarius commented on how the effect impacted their experience with adVantage by making it more difficult to see the in-system representation of a user's thumbs on the hand controllers (small gray circles, lighter than the rest of the controller model):

> **Sagittarius:** Umm, I think it sometimes wasn't clear whether the last pointer was supposed to be coming out of the left controller or the right controller. [**Interviewer:** Okay.] Ummm, and the shakiness with the controllers made it kind of hard to see where my thumbs were at a certain point [**Interviewer:** Gotcha] but I understand that's a bug in the code and that might take some… tricky fix-its.

Virgo and Taurus were also both frustrated by the laser-pointer tool when they tried to access information panels for WASP-12b and the Earth/Moon proxy. Virgo was unable to see the Earth/Moon proxy panel, and Taurus was unable to unlock either of the panels mentioned above. Although the collision spheres that surround each object make it somewhat easier to "hit" the planets/collision spheres with the laser-pointer tool, the users' difficulties accessing the information panels suggest that this tool can and should be improved in future iterations of the system.

Successes with Scale and Immersive VR:

Although there are certainly improvements that should be made to adVantage to address both conceptual and technical issues the four participants had while using the system, the interviews suggested that the immersive adVantage system does convey relative distance well, and relative size reasonably well.

Sagittarius and Virgo's reflections on the proximity of WASP-12 to WASP-12b after interacting with adVantage demonstrate how seeing something can be more effective than reading at conveying information:

> **Interviewer:** Awesome. So you began your interaction with adVantage from a vantage point where you could see WASP-12b orbiting WASP-12, and the Earth/Moon proxy orbiting WASP-12b: were you at all surprised by the planet's proximity to its star?
>
> **Sagittarius:** Ummm, a little bit, yeah. Eh, or, maybe only now that you're asking me that I'm surprised, now that I think about it. I'm like – dang, that's a really big planet or a really small star and they're very close together.

> **Virgo:** … But okay my preconceptions [about the scale of space] were, I had anticipated that there would be less space between the planets and moons, or you know the, uhhh, the, the… would you say planets?
>
> **Interviewer:** Planet… uhhh, yeah… [**Virgo:** the WASP?] WASP-12b, yeah, [Yeah.] and then it's star is WASP-12 [**Virgo:** Okay, yeah.]. That made editing fun, I'll tell you that…
>
> **Virgo:** Ummm, yeah I imagined that they'd be far away, or far apart from one another, but, yeah, I also imagined that the, uhhh, [WASP-12-b] would be further away from the sun equivalent than it was, ummm, even though it said in the paper it'd be pretty close, like, that's really close.

Sagittarius elaborated on how exploring adVantage gave them a better sense of the distance between planets and stars later in the interview:

> **Sagittarius:** It's so big. I don't know, I think that's kind of the only big conclusion I can draw from it: that space is so big. And that's not something you can really conceive of in terms of just reading, like, oh it's x-many light-years away from some textbook or something. I think it's, it's cool to see that relative distance in real time.

When asked about looking back (in the positive X-direction) to see whether or not the Earth had disappeared in the distance, Sagittarius and Virgo commented on how they were surprised that the planet disappeared so quickly while WASP-12 appeared unchanged at the beginning of the mission:

> **Interviewer:** Gotcha. So after you began Mission 1, umm, when did you notice that you could no longer see the Earth?
>
> **Sagittarius:** Probably like four or five warp steps.
>
> **Interviewer:** Okay, and did you find it helpful to look back and forth trying to locate WASP-12 and WASP-12b as you warped through space?
>
> **Sagittarius:** Umm, a little bit, yeah. [**Interviewer:** Okay]. Mostly trying to orbit – like, locate the distance between – like seeing the Earth shrink but seeing WASP-12 and WASP-12b not really grow that much.
>
> **Virgo:** Yeah, ummm, I feel like it was, maybe, four – that's my guess – because I looked back after a while and then it was just darkness, and I can't remember how many steps I took in total, but I remember it being at one of the beginning ones. And, well, it felt like the, uhhh, 12b, you know … total system, the system that I was trying to engage with, that it wasn't growing that much at first. And I was like, am I doing

> this right? But, ummm, yeah, I think it just demonstrates the scale even more, but, ummm, I imagine four, [**Interviewer:** Awesome.] that's my guess.
>
> **Interviewer:** But fewer than you thought it might be?
>
> **Virgo:** Yeah! Yeah, I thought that I might be able to just look back the entire time and see a… [**Interviewer:** A little speck there?] Yeah. [**Interviewer:** There's home.] Yeah, exactly.

And Taurus noted that the ability to look back and forth while making judgements of relative size was unique to a VR environment:

> **Interviewer:** Okay. Did you find it helpful looking back and forth to try to locate WASP-12/WASP-12b and the Moon and the Earth [**Taurus:** Yeah.] to orient yourself?
>
> **Taurus:** Yeah, that was really cool. And I think that's like really unique to this system, because you can't do that on paper.

Aries, Taurus, and Sagittarius all expressed their surprise on how much space existed between the Earth and the Sun (represented by WASP-12) after interacting with adVantage. Sagittarius's conclusions about the voyage took the form of a criticism of reality in science fiction:

> **Sagittarius:** It took so many warp steps to get [to WASP-12].
>
> **Interviewer:** Umm, how many warp steps do you think it took in Mission 1? [**Sagittarius:** Like… twenty?] Like twenty? Okay. What does that tell you about the distance between the Earth and the Sun, compared…
>
> **Sagittarius:** Star Wars lied.
>
> **Interviewer:** Star Wars lies a lot.
>
> **Sagittarius:** Star Wars makes it seem like it's real short, but it took sooo long to get there.

Like Sagittarius, the other three participants also underestimated the total number of warp-steps they took while traveling from the Earth to WASP-12. Although Aries confessed to being irritated by the number of times they had to press the button that launched warp-steps, they believed that the mission had only lasted about twenty-five steps:

> **Aries:** Ummm, I think, the, the, like, continuously pressing the steps forward, ummm, was, like, became kind of irritating, but… it's also. Like, that's kind of the point, right? Is it's so far? I think maybe, if, if it was kind of a thing where it's like, we're going to warp for a while, and then you warp for a while, like, forward or whatever,

and then it says: "Hang on, like, let's check to see where the Earth is", or whatever, like, if it wasn't, like, you have to press it twenty-five times, ummm, but it was instead, like, oh, we're going to go this way and now we're going to stop you and, like, have you look back at where the Earth is now, and then, like, go you a little farther. And then, I don't know. Something like that, [**Interviewer:** Okay.] I think, ummm, might give the same impression, without being, like, without becoming irritating. *[laughter]* Ummm…

Interviewer: If I told you, you actually did press it forty-one times, would you be surprised? [**Aries:** Did I really!] It was forty-one steps! [**Aries:** That's wild!] Yeah. [**Aries:** Okay cool.] It's been interesting, so far all three of y'all who tried it so far have been estimating in the, in the teens to twenties, [**Aries:** Yeah.] but no, it's, it's forty-one times…

Aries: Forty-one times… that's fascinating. Ummm…

Interviewer: It's interesting that you did kind of low-ball your guess but it was coming across as being irritating.

Aries: Yeah, yeah, that's interesting… I think, well, we were talking, well, this is a side conversation, *[laughter]* you don't want to, you don't have to transcribe this, but I'm reading this book about framing and stuff, and how people use reference points and, ummm, often underestimate or overestimate things based on what they're reference point is…. Anyway, don't bother…

Like Aries, Taurus was also surprised to learn how many times they had pressed the button:

Interviewer: Awesome. Umm, so if I told you that you'd actually taken forty-one steps in the system, [**Taurus:** Whaaaat?] would you be surprised? Yeah.

Taurus: Whaaaat? It seemed like only ten! [**Interviewer:** Oh yeah, it's…] Wait, I clicked forty times?

Interviewer: You clicked forty-one times.

Taurus: Whaaaat? Whaaaat? Wow, yeah, yeah. That's cool. That means it's, like, engaging. And I didn't realize how much I was clicking, yeah.

Analysis of Results:

The pilot study clearly indicates that adVantage needs significantly more in-system guidance for users to extrapolate the proportional relationships of distance and size from the planets, moons, and star, but the interviews with study participants suggest that the system is promising as an academic resource. Addressing the five topics investigated in the pilot study (listed above):

(i.) With some guidance from the interviewer, all of the participants were able to navigate Mission 1 in adVantage by taking warp-steps and most were able to access the information panels;

(ii.) None of the participants remembered the significance of the size of each warp-step from the introductory worksheet, but most were able to draw conclusions about the distance between the Earth and the Sun after learning the size of the steps;

(iii.) Most participants looked back and forth to make observations about the appearance of the Earth versus the appearance of WASP-12 at different distances;

(iv.) Most participants were able to approximate the number of steps taken before the Earth disappeared from view, but all four participants significantly underestimated the total number of steps between the Earth and WASP-12; and

(v.) Participants were able to make general comparisons about the relative sizes of the Earth and WASP-12b, and the distances between the Sun and Earth, and between WASP-12 and WASP-12b after interacting with adVantage.

Without understanding how the size of warp-steps related to the orbital radius of WASP-12b, and without counting the exact number of steps taken while completing the mission, the participants were unable to specify the proportional relationship between the WASP-12/WASP-12b and Sun/Earth distances as we hoped. Still, the system seemed to impress upon all four participants the scale of space, and the distance between the Earth and Sun surprised them all. Even more promising for future iterations of the study was Taurus's conclusion that the Earth is ten-times further away from the Sun than WASP-12b is from WASP-12 after learning that each step was approximately WASP-12b's orbital radius. Although Taurus significantly underestimated the total number of steps taken, they were still able to extrapolate a concrete ratio of the distances between planets and their stars by coupling their experience with adVantage and the new information.

Adding more guidance for students in the system is crucial for future development. Creating menus and tools that give students constant access to information about the size of warp-steps, about their position in the system relative to its contents, and about the total number of steps taken at any point during the mission should improve both a student's experience, and the likelihood of the student completing the mission with a proportional understanding of relative size and distance in adVantage.

The success of adVantage at conveying the scale of space during the pilot study is perhaps best summarized by Sagittarius and Taurus. Scale and proportional distance can be known by reading, but are understood by seeing and experiencing. As Sagittarius said, "[the scale of space is] not something you can really conceive of in terms of just reading, like, oh it's x-many light-years away from some textbook or something".

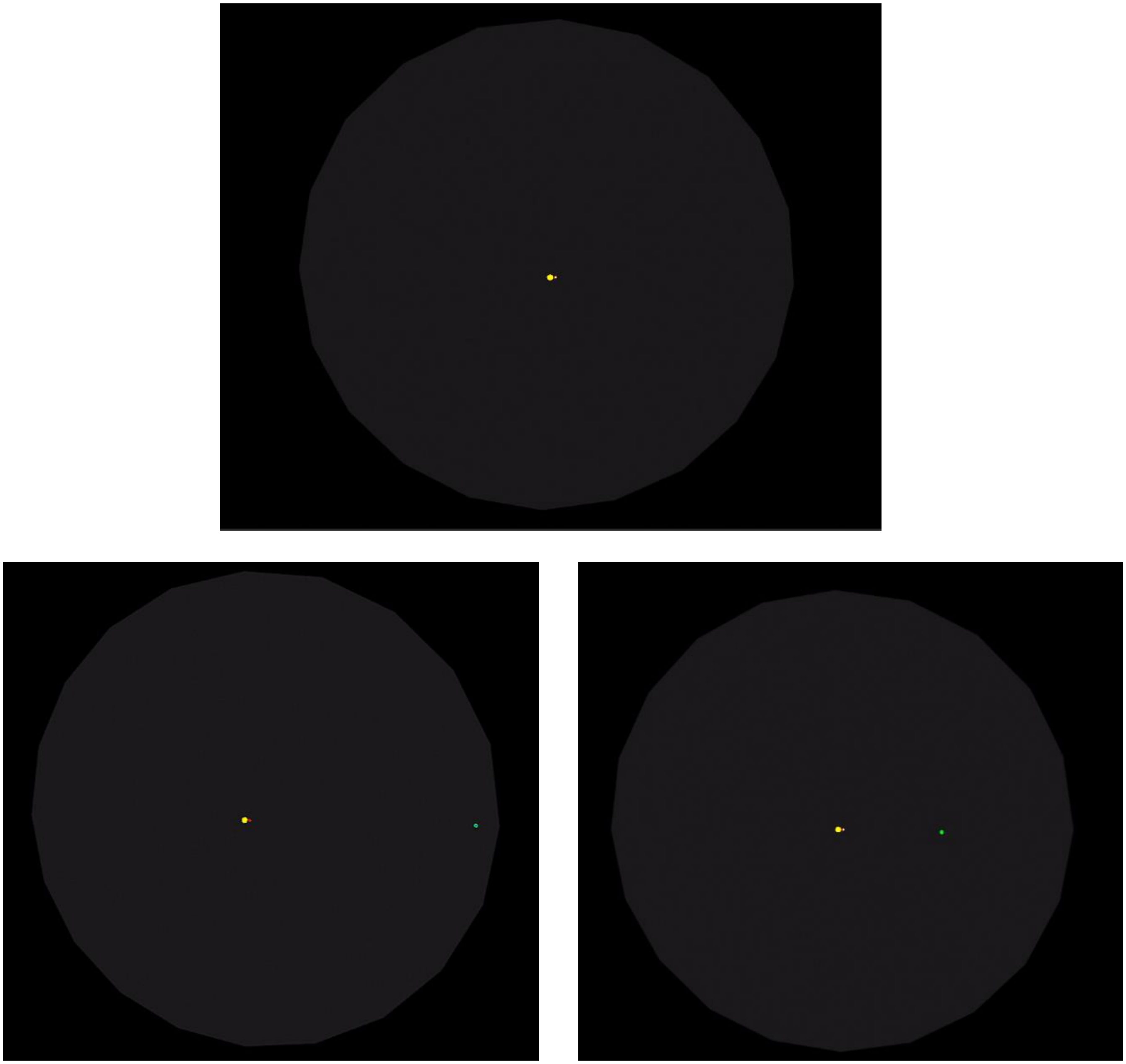
9. FUTURE WORK – CONTINUED DEVELOPMENT:

Continued work developing the Unity/SteamVR adVantage system will prioritize the development of more missions to the system, the inclusion of a free-exploration mode that allows users to travel through space using a more realistic flight simulation coupled with the teleportation cylinders described in the "Unity Development" section of this paper, and the addition of other astronomical objects (e.g. stars) to their appropriate locations in space. Other additions to the system may include revisiting the adjustable parameter feature used in JS adVantage, adding capabilities to show orbital paths and axis systems for each planet, and developing a dome-shaped space-ship window and control panels that would surround users. Further development, particularly of more missions, will follow initial, informal testing of the Unity/SteamVR system and will be based significantly on feedback from student users.

Before other features are added to adVantage, the celestial radar map tool that has been partially implemented should be debugged and deployed in the system. The celestial radar map was designed to resemble submarine radar maps, and is meant to show users where they are in the adVantage system with reference to the other planets, star, and moons. Each object in the system, including the Player, is represented on the map by a small, colored circle. Using a method that translates the X- and Z-coordinates of each object into map coordinates, the positions of the colored circles are updated constantly to reflect changes in the system. The leftmost hand-controller is programmed to replace the in-system model of the controller with the radar map when a user presses the trigger. Because the radar map is then paired with the position and direction of the controller, the user should be able to move the map around as they explore each vantage point.

Currently, the radar map does not show all of the map-icons consistently. The icons closer to the origin of the map – particularly the yellow icon (for WASP-12) and the red icon (for WASP-12b) – are usually visible, but the green icon (for the Player), the blue icon (for the Earth), the pink icon (for the Moon), and the turquoise icon (for the Earth/Moon proxy) do not appear consistently. By angling their wrist at various angles, a player is able to find the icons on the outskirts of the map. This is impractical, though, and will hopefully be corrected by identifying what is causing the issue (i.e. the Y-dimension of each map-icon, etc.). Still, because the C# method correctly translates system coordinates into map coordinates (see **Figure 44**), we are optimistic about debugging the radar map and adding it to an adVantage user's toolkit.

Figure 44 (a, b, c): The Celestial Radar Map (a) Without the Outer Icons, Viewed from Straight Ahead; (b) With the Player and Earth Icons Visible from the Initial Vantage Point in Mission 1, Viewed at a Slight Angle; and (c) With the Player Icon Visible at the mid-Vantage Point in Mission 1, Viewed at a Slight Angle



Another, concrete issue that should be addressed immediately in future development of adVantage is the flickering appearance of the HTC Vive hand controllers when a user is placed too far away from the origin in the system (see **Figure 45**).

Figure 45: Flickering Hand Controllers at the Initial Vantage Point in the First Mission of Unity/SteamVR adVantage

Extensive testing of the C# script dictating user interaction with adVantage, of the impact of relocating of the system's main camera to each point specified in the multi-dimensional array of Mission 1 coordinates in three-space by moving its parent, and of the settings for anti-aliasing effects in Unity, we determined that the cause of the flickering was the distance of the controllers from the origin. Why the controllers flicker so badly when the planets positioned at the same X-distance away from the origin are not affected remains a mystery. As a user moves along the pre-set path of Mission 1 toward the center of the system, the controllers stabilize and appear to be more solid. Understanding the exact cause of this effect and correcting the issue is a priority for developing future versions of adVantage.

10. FUTURE WORK – EVALUATING ADVANTAGE:

The initial goal of this study was to show that, for investigations of relative sizes and distances between objects in space, immersive VR models explored with a Head Mounted Display (HMD) and hand controllers are more effective than those presented on a computer monitor, and both the non-immersive and immersive adVantage systems are more effective than traditional, 2D learning materials. To this end, I propose that future work on the adVantage project would include quantitative and qualitative evaluation of the benefits of VR in model-based learning through comparison of the two versions of adVantage (JS and Unity/SteamVR), and of traditional, two-dimensional classroom aids (e.g. textbook illustrations). Evaluations of adVantage would likely echo methods used by researchers in the Virtual Playground study, in which analysis followed "a qualitative approach based on observation (aided by a think-aloud protocol) and informal interviews with [the participants]" that were focused on identifying conceptual changes that occurred as a result of interaction with the VR environment, additive knowledge (as opposed to changes in knowledge), and changes in behavior.[119]

[119] Maria Roussou, Martin Oliver, and Mel Slater, "The Virtual Playground: An Educational Virtual Reality Environment for Evaluating Interactivity and Conceptual Learning," *Virtual Reality* 10, no. 3–4 (December 2006): 229.

System evaluation could be done by dividing participants into three cohorts – immersive adVantage, non-immersive adVantage, and 2D materials – and allocating time for each participant to interact with the learning materials assigned to their cohort. After interaction with the learning materials, each participant could complete a multiple-choice post-test to assess their understanding of scale and relative distance in space. The post-test could include a series of questions about the students' interest in WASP-12b, WASP-12, and exoplanet research following their interactions with the learning materials. After the post-test is complete, each student could participate in a recorded interview and be asked to explain the reasoning used to decide each multiple-choice answer.

The Wellesley participants best suited to assessing the value of Unity/SteamVR adVantage, JS adVantage, and 2D materials as learning aids for introductory, undergraduate astronomy are students with little to no prior exposure to the field who are enrolled in either ASTR 101: Introduction to Stars, Galaxies, and Cosmology, or ASTR 100: Life in the Universe (both of which are courses offered by Wellesley's Astronomy department). The identities of all participants in evaluations of adVantage will be protected by the use of pseudonyms in written analyses of the study, papers, or presentations.

The data collected from the adVantage study could come from the multiple-choice questions on a post-test completed by each participant (see **A-5**), and from an interview conducted after each student completes the post-test. The crucial differences between the adVantage systems and the 2D material condition will not only be the addition of knowledge, but the degree of presence each system fosters in a student and the level of interest in WASP-12b, WASP-12, and exoplanets that the systems inspire. As presence is difficult to quantify, the interview questions should probe the qualitative benefits of VR systems, both viewed on a computer monitor and through a HMD. By emphasizing the basis for a student's reasoning when answering a question on the post-test, and by inquiring after student interest in continued research about exoplanets and hot Jupiters, the interview questions could focus on each student's experiences, impressions, and continued interest rather than on details of the systems. These questions will likely include:

For all cohorts: *Can you explain why you selected the answer that you did from the options in the problem? How did you eliminate the other answers?*

For all cohorts: *Did the provided materials (worksheet or VR system) impact your decision?*

For all cohorts: *If so, was there a particular diagram or mission (as appropriate to the cohort) that influenced your choice? Which one?*

For all cohorts: *Describe the ways that the diagram or mission impacted your understanding of WASP-12b's distance from WASP-12 or its size?*

For the non-immersive and immersive adVantage cohorts: *What did you learn from Mission 1 – Finding Earth about the respective sizes of WASP-12b and the Earth? What did you learn about their respective distances from WASP-12 and from the Sun?*

> ***For the non-immersive and immersive adVantage cohorts:*** *What did you learn from the two parts of Mission 2 – Into the Depths of Space and Space Scales – about the respective distances of the Moon from the Earth, of the Earth from the Sun, and of WASP-12b from WASP-12? What did you learn about the respective sizes of those four objects: the Moon, the Earth, WASP-12b, and WASP-12?*
>
> ***For the 2D cohort:*** *What did you learn about the respective sizes of Earth and WASP-12b from the diagrams provided? How did you relate the WASP-12b and Jupiter diagram to the Solar System diagram? What did you learn from the orbital-distance diagram about the distance of WASP-12b from WASP-12 as compared to the distance of the Earth from the Sun?*
>
> ***For all cohorts:*** *Would you be interested in learning more about WASP-12b?*
>
> ***For all cohorts:*** *Would you be interested in learning about other exoplanets, particularly hot Jupiters like WASP-12b?*
>
> ***For all cohorts:*** *Do you think that the US Government should provide NASA with additional funding to continue researching exoplanets like WASP-12b?*

The methodology for data collection could proceed as follows: each participant would be provided with a worksheet introducing WASP-12b and WASP-12 to be read before interacting with one of immersive adVantage, non-immersive adVantage, or 2D materials (see **A-2**); the participant would spend an allotted amount of time, likely thirty-minutes, interacting with the system assigned to their cohort; and, upon completing interaction with the assigned system, the participant would be administered the post-test and would complete an interview recorded for transcription (with the participant's consent). I would also take notes during participants' interactions with Unity/SteamVR adVantage, JS adVantage, and 2D materials. The contents of these notes would be, primarily, observations about the order in which participants interact with different materials, missions, etc., the time that participants dedicate to interacting with different portions of the system/materials, and an frustrations expressed about the experience. Students in the immersive adVantage and non-immersive adVantage cohorts would use either a HTC Vive headset and controllers, or a computer monitor and keyboard to interact with the respective systems. The students in the 2D materials cohort would be provided with a worksheet of images/diagrams that illustrate the size of WASP-12b and its distance from WASP-12 (see **A-5**).

Participants in the Unity/SteamVR adVantage cohort would be briefed before interaction with the HTC Vive about important safety information (see "HTC Vive Safety and Regulatory Guide" PDF document), and would be asked to complete a waiver indicating that they have read the safety information and are willing to continue their participant in the Unity/SteamVR adVantage cohort.[120] Any participants uncomfortable with interacting with Unity/SteamVR adVantage who still would like to participate in the adVantage study could be reassigned to

[120] "HTC Vive Safety and Regulatory Guide" (HTC Corporation, 2016), http://dl4.htc.com/vive/safty_guide/91H02887-08M%20Rev.A.PDF?_ga=2.241901058.1255309278.1512853866-1513990621.1512853866.

another cohort, and openings in the Unity/SteamVR cohort could be filled by other participants. Additionally, every participant in adVantage would be asked to sign a waiver indicating their consent for the inclusion of results from the post-tests, quotations from interviews, and observations of their interactions with the systems in written analyses of the study, papers, or presentations following the conclusion of the project. As stated above, all participant identities would be protected by a pseudonym.

The documents described above, which will be used for evaluation of adVantage, are included as appendices (excluding a participation waiver). The solutions to the proposed post-test questions and their accompanying explanations are also provided in the appendices.

11. CONTRIBUTION AND CONCLUSIONS:

The challenge of building an academic environment vast enough to hold WASP-12, WASP-12b, the Earth, and the Moon mirrored the original problem we sought to address with the adVantage system: how do you negotiate the astronomical distances involved with a space simulation in a way that is both efficient and educational? We experimented with several methods of space-travel within the simulation that used steps of constant and observable sizes, all of which were designed to maximize student learning while minimizing loss of interest. The navigation method we selected for the first immersive adVantage mission was warp travel along a pre-set path. Much like three-dimensional scale models of our solar system that use items of various sizes (e.g. sports balls, fruits, seeds, etc.) to demonstrate how far away the Earth is from the Sun, the adVantage mission provided users with a static environment to make observations of size and distance with an added immersive element. Initial testing of the first mission in a pilot study revealed that, while more information about the system and mission must be made readily available to users for adVantage to be useful as an educational tool, it does allow users to extrapolate a concrete ratio of the distances between planets and their stars.

While a free-exploration method of space travel would allow adVantage users to see more of the solar system, it would also subtract the opportunity to make proportional judgements about relative size and distance. We chose to prioritize comparison over exploration in adVantage, to the effect that the adVantage system resembles Maria Roussou, Martin Oliver, and Mel Slater's "Virtual Playground" environment, which teaches children about fractions through activities with virtual playground equipment,[121] more so than it does the VSS systems like *Touch the Sky, Touch the Universe*, which emphasizes exploration of a dynamic solar system.[122] adVantage contributes to the field of educational virtual reality a unique method of investigating the scale of space. Ultimately, it wasn't the opportunity to manipulate variables that set adVantage apart from its predecessors, but the method of navigating space by taking steps of constant and observable sizes.

[121] Maria Roussou, Martin Oliver, and Mel Slater, "The Virtual Playground: An Educational Virtual Reality Environment for Evaluating Interactivity and Conceptual Learning," *Virtual Reality* 10, no. 3–4 (December 2006): 227.

[122] Yoav Yair, Rachel Mintz, and Shai Litvak, "3D-Virtual Reality in Science Education: An Implication for Astronomy Teaching," *Journal of Computers in Mathematics and Science Teaching* 20, no. 3 (2001): 298.

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APPENDICES:

A-1: adVantage Explanation, and How to Use the Immersive adVantage System

Welcome to the adVantage Task Force!

By now, you will have traveled almost 1264 light years from home in the direction of the constellation Auriga, and will soon arrive in the solar system of the G-type yellow dwarf star, WASP-12. Your mission is to observe both the star, WASP-12, and the exoplanet that orbits the star, WASP-12b, then to report back to Mission Control. We've added a packet of background information about the star and the exoplanet for you to peruse before you begin your first exploratory mission with the adVantage team.

Because your first mission with adVantage is launching you into an unknown solar system, we've provided you with some useful tools to better understand environment. We've equipped the screens of your space-ship to display proxies for our Earth and Moon in the WASP-12 system. In addition to the star and exoplanet, you'll also find a proxy planet the same size as the Earth orbiting WASP-12 like the Earth orbits the Sun. You'll also find a proxy-moon the same size as the Earth's Moon orbiting the Earth-proxy. Closer to WASP-12b and WASP-12, you'll find another proxy planet that combines characteristics of the Earth and the Moon. This final proxy planet is the same size as the Earth, but orbits around WASP-12b like the Moon orbits around the Earth (e.g. orbital radius, orbital speed).

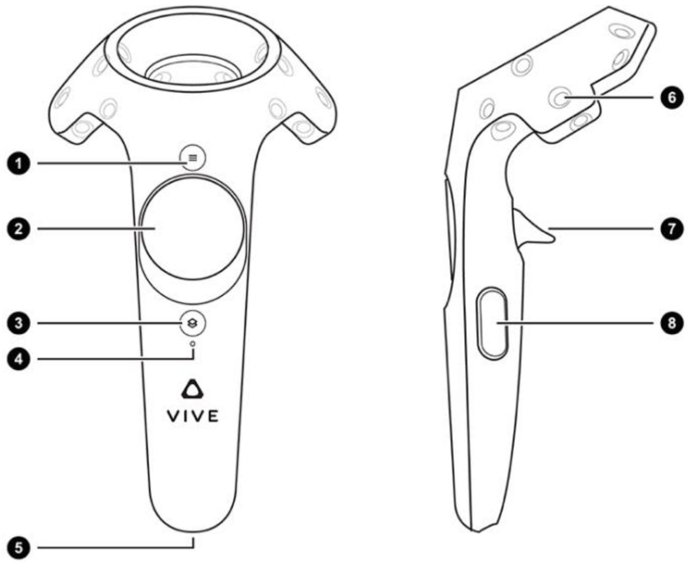
We hope you'll find these proxies useful as you're making observations about the characteristics and contents of the WASP-12 solar system, particularly for making comparisons about the relative sizes and distances of objects in our Solar System and objects in the WASP-12 system. We've also programmed your space-ship to make the planets and moons appear to be still while you're carrying out Mission 1.

Mission 1:

Your first mission with the adVantage Task Force is to travel at warp speed from your first vantage point near WASP-12 and WASP-12b to the first vantage point for Mission 1. When you drop out of warp, you'll find yourself near the Earth proxy we added to the system. From this point, you'll be able to see WASP-12 and the Moon on opposite sides of the Earth, in the configuration of a lunar eclipse.

Starting at this first point, we'd like you to travel back towards WASP-12 in steps of a constant size. Make sure you pay attention to WASP-12 and WASP-12b before you warp to the starting point of your first mission – each warp-step that you take during Mission 1 will be approximately the same size as the orbital radius of WASP-12b! As you warp from the Earth to WASP-12, pay attention to how large the planets, moons, and star appear. We'd like you to observe and report on how the size of WASP-12b compares to the size of the Earth, and on how much further away the Earth is from the Sun than WASP-12b is from WASP-12. Good luck, adVantage! We're counting on you to collect this data! To learn more about WASP-12b, check out your planetary factsheet. To learn more about how to navigate in the adVantage system, turn the page.

How to Use the Immersive adVantage System:



(Vive VR System," *Vive*)

To Show Informational Panels: Point the rightmost hand-controller at a star, planet, or moon. Press and hold the trigger **(7).** If the laser beam cast by the hand controller has collided with either the object or its collision shell, you will see a laser beam connecting the hand controller and the collision point. Look down and in the +X direction (toward Earth) to see the informational panel. Release the trigger **(7)** to hide the panel.

To Launch Mission 1: Press and release the touchpad **(2)** on the leftmost hand-controller.

To Take Warp Steps in Mission 1: The touchpad **(2)** of the rightmost hand controller is split into two hemispheres – the upper hemisphere is the top half of the touchpad, and the lower hemisphere is the bottom half. To take a warp-step in the -X direction (toward WASP-12), press and release the upper hemisphere. To take a warp-step in the +X direction (toward Earth), press and release the lower hemisphere. If you are trying to step off the Mission 1 path (i.e. past the Earth in the +X direction), pressing the touchpad **(2)** will have no effect.

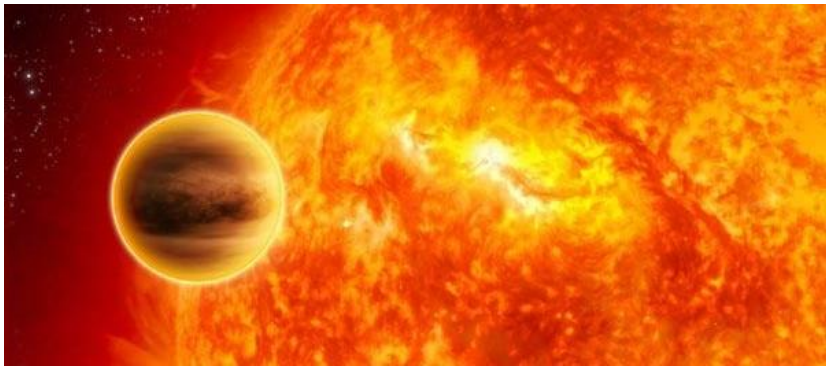
Good luck!

References:

“Vive VR System.” *Vive*. https://www.vive.com/media/filer_public/8f/ef/8fef879f-c986-4c89-a0b3-12126e8ba6f7/vive-pdp-hero-desktop-031918-v3.jpg.

A-2: An Introduction to the Exoplanet – WASP-12b

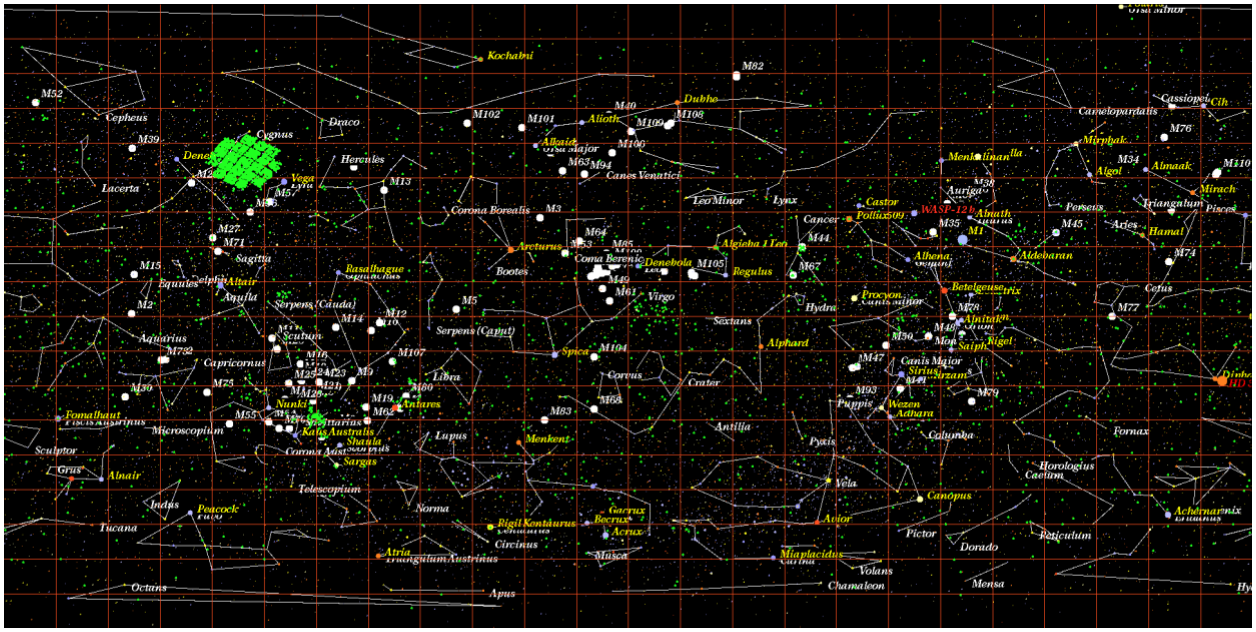
An Introduction to the Exoplanet – WASP-12b



(ESA/C Carreau. 2008. "Very Hot Jupiter.")

WASP-12b was first discovered in 2008 by the United Kingdom's Wide Area Search for Planets (WASP) (Minard). The exoplanet, which orbits WASP-12 once every 26 hours, has a surface temperature of over 4,700 degrees Fahrenheit due to "a combination of heat from the star and from a gravitational tug-of-war called tidal heating" (Minard). This extreme temperature may be the cause of the exoplanet's abnormally low albedo which, according to Taylor Bell, the lead author of a recent paper, "The Very Low Albedo of WASP-12b from Spectral Eclipse Observations with Hubble", published in *The Astrophysical Journal Letters*, is at most 0.064. An albedo measurement close to zero indicates that the body in question is nearly "a pristine black body that absorbs all light" (Quach). WASP-12b's temperature may be the cause of its low albedo, as the star-facing side (which never changes) is too hot for molecules to survive. This dynamic relationship between planet and star "is most likely preventing clouds from forming and reflecting light back into space" so that the light is, instead, "absorbed … and converted into heat energy" (Lazzaro). Notably, the side of WASP-12b not facing its star is over 2,000 degrees Fahrenheit cooler than the star-facing side (Lazzaro).

In addition to its albedo, and closely related to the extreme temperature of WASP-12b's surface, the exoplanet is also distinguished from its fellow hot Jupiters by its close orbit of WASP-12, its elongated shape, and its outpouring of atmospheric material to WASP-12 (Quach and "Hubble Finds a Star Eating Planet"). The star that WASP-12b orbits is WASP-12, "a yellow dwarf star … in the winter constellation Auriga", approximately 1260 light-years away ("Hubble Finds a Star Eating Planet"; Ryden, 2003; "Query : WASP-12"). The similarity of WASP-12 to the Sun only enhances the relevance of the WASP-12b/WASP-12 system as subjects for study. WASP-12b orbits its star at a distance of 3,430,000 kilometers, "approximately 44 times closer … than the Earth is to the Sun" (Quach). The orbital path is far from standard, orbiting eccentrically rather than circularly due to a changing gravitational pull exerted on the exoplanet by WASP-12. This eccentric path may, in fact, be evidence that WASP-12 has a neighboring, smaller body whose gravitational pull is influencing its orbit (Minard).



(“Position in Stellar Map of star WASP-12 and its Exoplanet WASP-12 b.”)

The extreme temperature of the planet causes significant expansion to the extent that, with only 1.4 times Jupiter’s mass, WASP-12b has six-times Jupiter’s volume. Gas from the planet’s atmosphere that is “pushed out so far from the planet… [may be] getting caught in the star’s gravitational pull”, forming a ring around WASP-12. Evidence of this ring does not yet exist, but researchers recommend that observers watch for a ring or disk of gas, which a team led by astronomer Shu-lin Li of Peking University calculated to be as hot as 7,200 degrees Fahrenheit, emitting detectable infrared radiation (Minard). The loss of atmosphere is unique in that the exchange of matter not uncommon between “two stellar objects … in close binary star systems”, but was unseen in a planet-star system before WASP-12b (“Hubble Finds a Star Eating Planet”). Furthermore, the exchange of atmosphere means that, in an estimated ten million years, WASP-12b will be absorbed entirely by WASP-12 (“Hubble Finds a Star Eating Planet”).

It should also be noted that WASP-12b does not actually appear to be reddish or orange-yellow as it does both in the artistic renditions above and in the adVantage system. The exoplanet should appear blindingly white due to its proximity to WASP-12.

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ESA/C Carreau. 2008. "Very Hot Jupiter." *Universe Today*, October 15, 2008. https://www.universetoday.com/19774/hottest-ever-exoplanet-discovered-wasp-12b/.

Lazzaro, Sage. 2017. "Hubble Spots a 'Pitch Black' Hot Jupiter Planet That EATS Light instead of Reflecting It." *Daily Mail*, September 14, 2017. http://www.dailymail.co.uk/sciencetech/article-4885982/Hubble-spots-pitch-black-planet-hot-eats-light.html.

Minard, Anne. 2010. "Star 'Eating' Superhot Planet's Atmosphere." *National Geographic News*, February 24, 2010. https://news.nationalgeographic.com/news/2010/02/100224-wasp-12b-hot-jupiter-planet-ring/.

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Quach, Katyanna. 2017. "Hubble Catches a Glimpse WASP-12b, an Almost Pitch-Black Exoplanet." *The Register: Sci/Tech News for the World*, September 14, 2017. https://www.theregister.co.uk/2017/09/14/wasp12b_almost_pitchblack_exoplanet/.

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Ryden, Barbara. 2003. "HOW FAR IS A STAR?" The Ohio State University Department of Astronomy. January 13, 2003. http://www.astronomy.ohio-state.edu/~ryden/ast162_2/notes6.html.

A-3: Pilot Study Template for Post-Interaction Interviews

Can you describe any preconceptions you had about the scale of space before interacting with adVantage? For example – how did you think about the relative sizes of the Sun, Earth, and Moon? What about the distances between the Sun and Earth, and between the Earth and Moon?

You began your interaction with adVantage from a vantage point where you could see WASP-12b orbiting WASP-12, and the Earth/Moon proxy orbiting WASP-12b: were you at all surprised by the planet's proximity to its star? Did you notice the Earth/Moon proxy orbiting WASP-12b?

After you began Mission 1, when did you notice that you could no longer see the Earth? Do you remember how many warp-steps had you taken?

Did you find it helpful to look back and forth to try to locate WASP-12/WASP-12b and the Earth in the distances as you warped through space?

How many warp-steps did you take in Mission 1? If you don't remember exactly, just approximate! What does this tell you about the distance between the Earth and the Sun compared to the distance between WASP-12b and WASP-12?

Was it helpful to you that the planets and moons were frozen in place during Mission 1? Why or why not?

What are you conclusions about scale in space – particularly about the relative sizes of the Earth and WASP-12b, and the relative distances between WASP-12 and WASP-12b and between the Sun and the Earth after completing Mission 1?

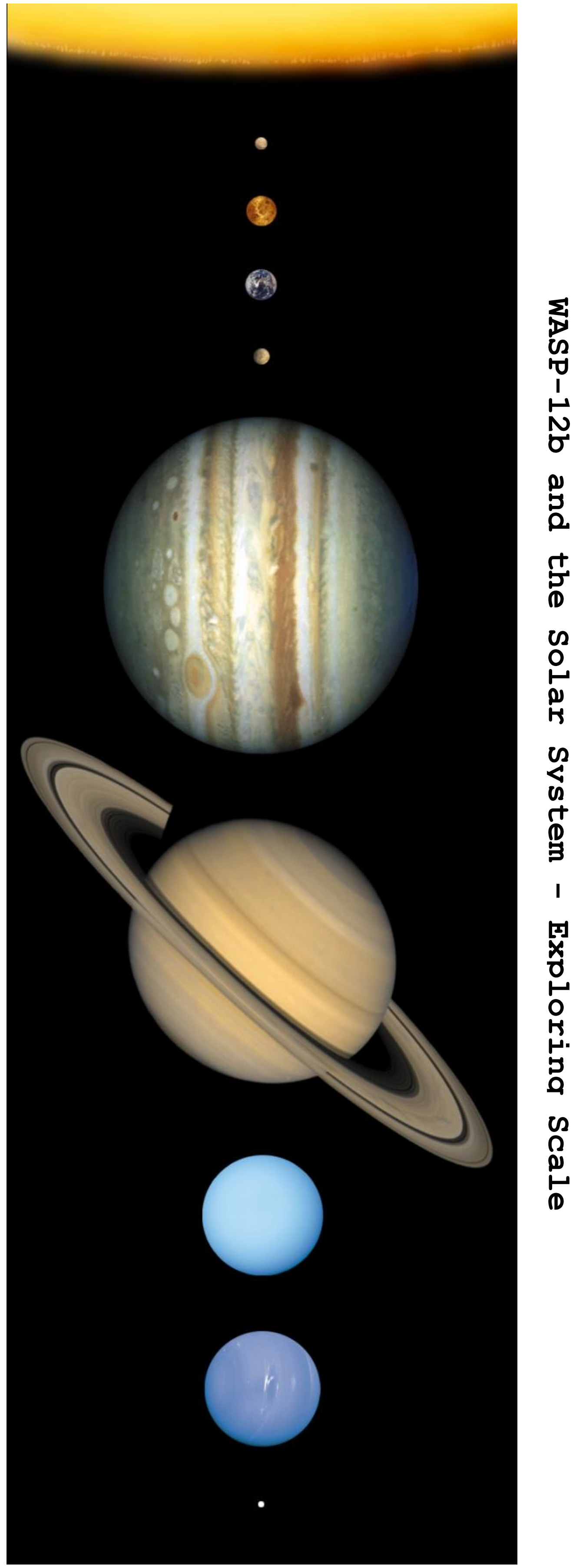
Did you enjoy exploring the adVantage learning environment? What about the system did you like? What didn't you like? Are there any changes you'd recommend that we make to the system?

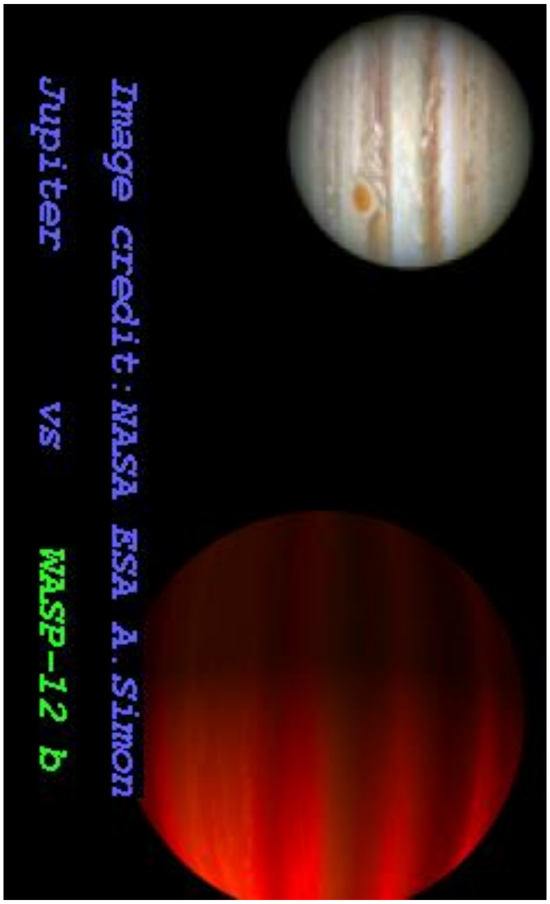
Would you be interested in learning more about WASP-12b?

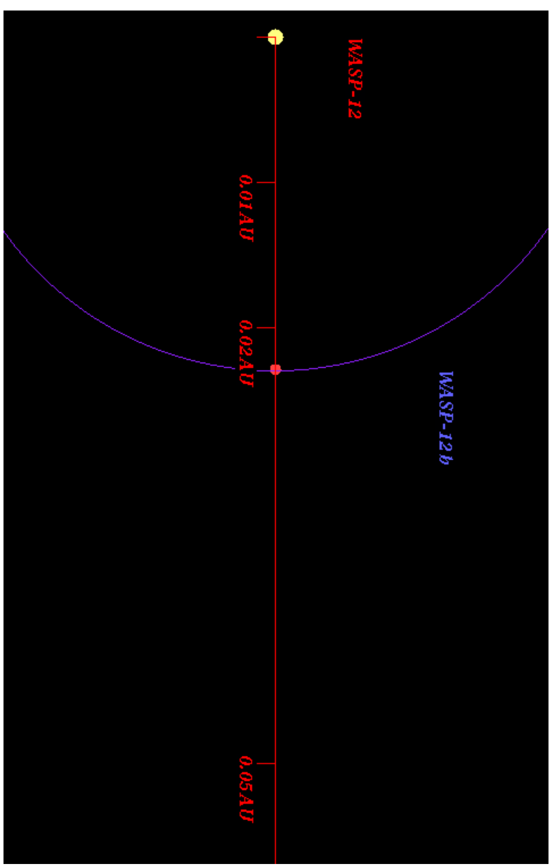
Would you be interested in learning about other exoplanets, particularly hot Jupiters like WASP-12b?

Do you think that the US Government should provide NASA with additional funding to continue researching exoplanets like WASP-12b?

A-4: WASP-12b and the Solar System – Exploring Scale







References:

NASA. 2003. "Solar System Scale." *NASA*. https://solarsystem.nasa.gov/images/galleries/solarsys_scale-browse.jpg.

NASA/ESA/A. Simon. "Jupiter vs. WASP-12b." *Extrasolar Planet's Catalog*. Kyoto University. http://www.exoplanetkyoto.org/exohtml/WASP-12_b_CJup.png.

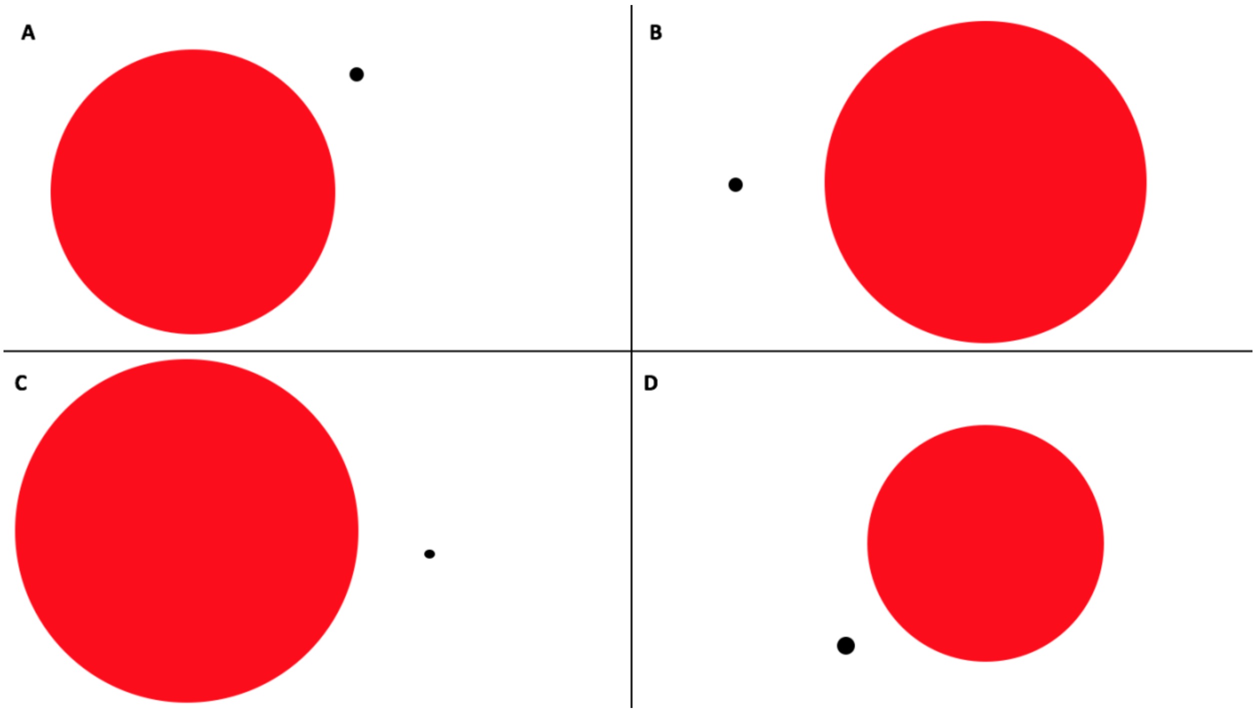
"Position in Stellar Map of star WASP-12 and its Exoplanet WASP-12 b." *Extrasolar Planet's Catalog*. Kyoto University. http://www.exoplanetkyoto.org/exohtml/WASP-12_b_STZ0.png.

"WASP-12b's Orbital Distance." *Extrasolar Planet's Catalog*. Kyoto University. http://www.exoplanetkyoto.org/exohtml/WASP-12_b_Orb.png.

A-5: Scale and Relative Distance Post-Test

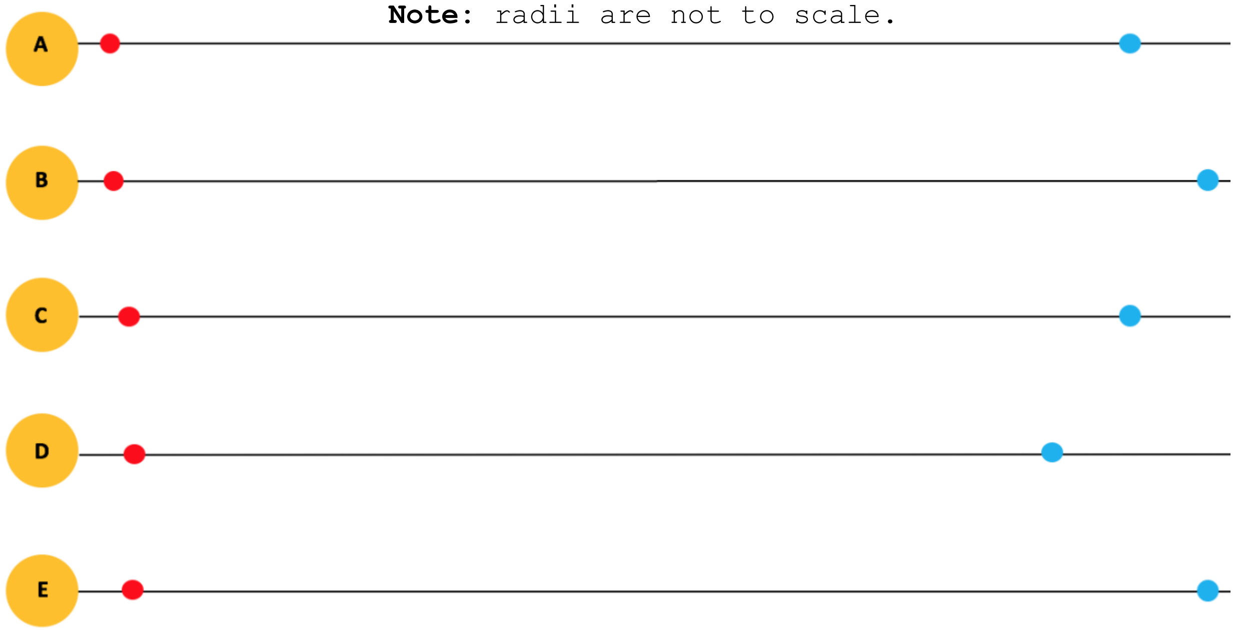
adVantage – Exploring the Solar System: Scale and Relative Distance Post-Test

1. Let the **black circles** represent the Earth and the **red circles** represent WASP-12b. Which of the following pairs best expresses the **relative sizes** of the two planets?



2. Let the **yellow circles** represent WASP-12/the Sun, the **red circles** represent WASP-12b, and the **blue circles** represent the Earth. Which of the options below best expresses the **relative distances** of the two planets from their suns?

Note: radii are not to scale.



Scale and Relative Distance Post-Test Solutions:

1. The radius of WASP-12b is 135851.4 km, and the radius of Earth is 6378.137 km. The approximate ratio between these values is 21:1. The best choice of the solutions is **(a)**. The ratios are:
   a. 3.00:0.14 ≈ 21:1
   b. 3.40:013 ≈ 25:1
   c. 3.62:0.12 ≈ 30:1
   d. 2.50:0.17 ≈ 15:1

2. The distance between the Earth and the Sun is 149,598,262 km, and the distance between WASP-12b and WASP-12 is 3,430,288 km. The approximate ratio between these values is 44:1. The best choice of the solutions is **(b)**. The ratios are:
   a. 10.87:0.21 ≈ 50:1
   b. 11.68:0.27 ≈ 44:1
   c. 10.87:0.43 ≈ 25:1
   d. 10.05:0.50 ≈ 20:1
   e. 11.68:0.39 ≈ 30:1

References:

NASA. 2003. "Solar System Scale." *NASA*. https://solarsystem.nasa.gov/images/galleries/solarsys_scale-browse.jpg.

NASA/ESA/A. Simon. "Jupiter vs. WASP-12b." *Extrasolar Planet's Catalog*. Kyoto University. http://www.exoplanetkyoto.org/exohtml/WASP-12_b_CJup.png.

"Position in Stellar Map of star WASP-12 and its Exoplanet WASP-12 b." *Extrasolar Planet's Catalog*. Kyoto University. http://www.exoplanetkyoto.org/exohtml/WASP-12_b_STZ0.png.

"WASP-12b's Orbital Distance." *Extrasolar Planet's Catalog*. Kyoto University. http://www.exoplanetkyoto.org/exohtml/WASP-12_b_Orb.png.