VIRTUAL REALITY IN THE ASTRONOMY CLASSROOM

REPORT ON A PEDAGOGICAL DEVELOPMENT PROJECT AT THE FACULTY OF SCIENCE AND TECHNOLOGY AT UPPSALA UNIVERSITY IN 2018

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1. INTRODUCTION

Virtual reality (VR) can be a powerful technique for interacting with 3-dimensional models and for exploring complex data sets. As a pedagogical tool, VR should be especially useful for disciplines such as astronomy – in which the physical environment studied typically remains out of reach and where direct laboratory experiments of many key processes are impossible for practical reasons.

Many misconceptions about astronomy among both students and members of the public can be traced back to problems in extrapolating 2-dimensional representations (e.g. schematic illustrations in a textbook) to our 3-dimensional Universe (e.g. Hansen et al. 2004). Some of the most notorious examples include the failure to understand why solar or lunar eclipses don't happen every month or why there are seasons on Earth. However, many 3-dimensional representations also have severe limitations as pedagogical tools, for instance by having non-intuitive interfaces (e.g. Gazit et al. 2005), by not being sufficiently interactive (e.g. de Paiva Guimarães & Barberi Gnecco 2009) or by failing to properly create the experience of motion parallax (e.g. Eriksson et al. 2014). Immersive VR setups – in which students are allowed to freely explore interactive simulations of planetary systems, stellar systems, galaxies etc. across a vast range of time scales – should allow for the best prospects of developing a solid intuition about the properties of these systems and the astrophysical processes that operate within.

The goal of this project was to develop VR exercise sessions to be carried out in the Ångström Visualisation Lab, inaugurated in 2017, using an Oculus Rift headset and associated hand controls. In these sessions, students get to plan, execute and document simulations in the Universe Sandbox^2 software to learn more about the habitability of planetary systems, the stability of multiple-star systems and the fate of stars that venture close to the supermassive black hole at the centre of the Milky Way.

2. PROJECT DESCRIPTION

Universe Sandbox^2 is a commercial software created for education and entertainment purposes by an ex-astronomer to simulate user-defined astrophysical systems (e.g. planetary systems, star clusters etc.) and to present the 3-dimensional results on the fly in a visually stunning way. The user can zoom in and out through the simulated volume and interactively alter the simulations as they are running, for instance by adding/removing astronomical objects (planets, stars, black holes etc.) or instantaneously altering their properties (mass, orbits etc). It is also possible to speed up or slow down the simulations and to alter the strength of gravity. This is not a research-grade tool, since many astrophysical processes are simplified in order to allow the simulations to respond in a time-frame convenient for instantaneous user interaction. However, it does handle gravitational many-body problems sufficiently well to allow classroom exploration of a wide range of topics relevant for our MSc-level astronomy courses.

The project did suffer a number of setbacks that made it necessary to alter the original project plan somewhat. We initially intended to include elements of data analysis using the VR version of the Gaia Sky software, which allows the user to visualize and navigate the enormous data set (containing on the order of one billion astronomical objects) provided by the Gaia space mission, and various galaxy catalogs as well. However, upon the release of the VR version of Gaia sky in the summer of 2018, it turned out to have severe issues – to the point where it would have felt downright embarrassing to put it into the hands of students. Hence, we were forced to stick to Universe Sandbox^2 for the duration of the project. This also forced us to drop the ambition to develop VR exercises for the Cosmology course, as the capabilities of Universe Sandbox^2 turned out to be poorly matched to the curriculum of that course. Moreover, no VR exercise was developed for the Celestial Mechanics course due to a change of teachers and the lack of time caused by this. VR exercise sessions were, however, successfully designed and implemented for the three courses Physics of Galaxies, Physics of Stars and Physics of Planetary Systems.

2.1. SESSION STRUCTURE

Prior to each session, the students are given a few pages to read on the type of astrophysical environment covered by the exercises. The sessions (3 hours long, one per course and group of 2-4 students) take place in the Ångström Visualisation Lab and start off with a pre-exercise test. After that, about 30 minutes are spent on learning the basics of the Oculus Rift controls and the Universe Sandbox^2 software. The students are then introduced to one or several simulation exercises which they are asked to complete. At the end, one brief exercise report per team needs to be handed in. During the exercises, the students may divide the work any way they see fit. Usually, the students take turns operating the Oculus Rift controls, whereas the others plan the next simulation to be carried out and document the outcome. Since there is currently just one Oculus Rift headset available in the Ångström visualisation lab, only one person has access to the VR view of the simulation at any given time. However, a fraction of the field of view of this person is projected onto a screen for the others to see.

Once an acceptable exercise report has been handed in, a post-exercise test marks the end of the session. The pre- and- post-exercise tests are completed individually and are anonymous, although the students are asked to sign the tests using code names so that the pre- and post-exercise answers can be compared. The instructions make it very clear that no matter how poorly they do on these tests, their course grades will not be affected. In fact, if they wish to consult the text they were asked to read in preparation for the seminar, or the course textbook, then they are perfectly welcome to do so during the tests.

2.2. VR SESSION FOR THE PHYSICS OF GALAXIES COURSE

If there's one fact that even children know about black holes, it's that these objects tend to pull things in. A very common misconception among members of the public and astronomy students alike – no doubt spurred by the common 'space ship sucked into black hole' science fiction trope – is that black holes are extremely efficient at this. In this exercise, the students get to find out just how likely (or not) it is for stars that venture into the central region of the Milky way to end up inside the supermassive black hole (with a mass of about 4×10^6 times the mass of the Sun) that is lurking there. In the pre-exercise test, the students are asked to outline the three most likely fates of such stars, in ranked order. The post-exercise test features exactly the same task, in which they have the chance to correct their replies based on what they have learned during the VR session. In the exercise, the students are provided with a simulation of the star cluster surrounding the central supermassive black hole of the Milky Way, and are asked to inject stars with random trajectories into this region to find out what happens. Of course, any number of things may happen – the star may get trapped inside the star cluster; it may get ejected; it may collide with other stars or be tidally disrupted or completely swallowed by the black hole – but these scenarios are not all equally likely. In fact, as they typically find out during the simulation, getting the star to end up inside the black hole is very, very difficult. The star may end up in a tight orbit around the black hole and could possibly get tidally disrupted (torn out of its spherical shape by the difference in the gravitational pull on its different sides), but having the star completely vanish inside the event horizon of the black hole is a very rare phenomenon. By far, the most likely scenario for the star is instead to either leave the cluster unscathed or become one of its new members.

2.3. VR SESSION FOR THE PHYSICS OF STARS COURSE

When astronomy students reach the MSc level, they usually have the notion that gravitational two-body systems are deterministic and computationally tractable (in fact, the orbits can usually be predicted analytically), whereas three-body or higher-order systems are unpredictable and unstable. While it is true that predicting the orbits of systems involving more than two stars often requires numerical simulations, many seemingly stable systems involving three or more stars are known (in fact, the closest stellar neighbour to our Sun, Proxima Centauri, is a member of a triple-star system). When taking the Physics of Stars course, it seems that many of our students only have a fairly vague idea about how such systems work. Most real-universe trinary, quaternary and quintenary (etc.) stellar systems that have retained stability over long time scales are *hierarchical*. In simple terms, a hierarchical system is what you get if you replace one or both stars in a binary system with pairs of stars on significantly tighter orbits. By recursively exchanging individual stars in this new system with pairs of stars on even tighter orbits, systems of increasingly high hierarchy can be constructed. In this exercise, the students get to explore this concept through hands-on VR experiments. The exercise comes with several subtasks, which involve analysing different kinds of multiple-star systems (both realistic and unrealistic ones) to understand what it is that makes them stable (or at least semi-stable over the time scales simulated). In one of these subtasks, the students also attempt to insert a third star into an existing binary star system to explore what it takes to make it stick. In the pre-exercise test, the students are asked to draw a stable trinary system, to indicate whether a proposed triple-star system is stable and realistic and also to indicate at which point in the orbit of a binary star the Roche lobe (the region within which the star must be contained in order not to lose material due to the gravitational pull from its companion) is the greatest.

2.4. VR SESSION FOR THE PHYSICS OF PLANETARY SYSTEMS COURSE

In the field of astrobiology and exoplanetary research, “habitability” refers to the potential of a planet, moon etc. to maintain environments hospitable to life. For practical reasons, most of the discussion on this topic has revolved around the prospects for these objects to harbour water in liquid form – the prerequisite of life as we know it on planet Earth. A particularly important concept in this field is that of the circumstellar habitable zone – the region around a star in which a planetary surface with sufficient atmospheric pressure would be able to maintain liquid water on its surface. In lower-level courses, circumstellar habitability is often – after numerous assumptions and simplifications – reduced to a simple relation between the luminosity of the star and the distance between this star and a given planet. In this oversimplified picture, the circumstellar habitable zone becomes a concentric zone with dimensions dictated by the luminosity of the star – if a planet on a circular orbit is located too close to the star, the temperature will be too hot and the water will boil away, if the planet is located too far away, the temperature will be to low and the water will freeze; only in a relatively limited range of radial distances are the conditions just right (hence the alternative name “Goldilocks zone”). This simple picture has such allure that it is easy (even for the professional astronomer) to forget the very large number of additional parameters that are expected to affect the surface conditions on exoplanets, yet were ignored in this analysis. In this VR exercise, the students are given the task of analysing a sequence of increasingly complex planetary systems (with planets named after characters, places and creatures from Studio Ghibli anime movies, the J.K. Rowlings Harry Potter franchise, comic books etc.) and figure out which (if any) of the planets are habitable (and possibly even suitable for a human colony), and motivate why this is so. In the process, the students encounter systems for which the simplistic habitable zone concept works quite well, but also systems where it breaks down completely (for instance a system where the surface temperature of planets increases with distance from the host star, i.e. the exact opposite of the typical textbook treatment). The idea is that they – through a bit of detective work and discussion within their team – will develop a better feeling for how the planetary surface and atmosphere properties interact with the overall architecture of the system. In both the pre- and post-exercise test, each student is asked to list the properties that they think affect the habitability of exoplanets. A comparison of the pre- and post-exercise lists (along with an analysis of the comments students make on why changes between these were made) can then reveal how the exercises enriched their understanding of the habitability concept and the complexity of exoplanet climates.

3. EVALUATION

3.1. EVALUATION METHOD

Learning outcome

The impact on student understanding on the topics covered in the VR exercises was gauged using anonymous pre- and post-exercise tests, as described in detail in section 2.2-2.4.

Student satisfaction

As our experience has shown that the centrally administered course evaluations tend to yield too low reply rates, student satisfaction was measured directly on the form used for the anonymous post-exercise questionnaire. The students were asked to grade the VR exercises on a scale from 1 (very bad) to 5 (very good), and were also able to provide free-text comments on the exercise.

3.2. RESULTS – STUDENT SATISFACTION

Our results clearly suffer from small-number statistics, as these VR exercises can – for practical reasons; see section 4 – currently only be used in courses of students of up to ≈10 students. Even so, student satisfaction with these exercises seems to be very high, with average grades of 4.7 (Physics of Galaxies, 2018+2019; 12 students in total), 4.3 (Physics of Stars, 2019; 9 students) and 4.8 out of 5 (Physics of Planetary Systems, 2018; 11 students). Here is a selection free-text comments (both positive and negative) from the student satisfaction part of the form:

- “Extremely engaging, hands-on and entertaining”
- “That was interesting and fun. We had to create hypotheses on why such parameters were too low or too high etc.”
- “Interesting and active learning method”
- “Really great to see an actual simulation and to be able to interact with it and try different ideas. Very worth doing.”
- “It was a lot of fun, the instructions were great and the 'detective character' of the exercises kept the motivation high. Teams of two people would maybe be even better as you'd have more time to experience virtual reality”
- “Allow for individual class to get students to familiarize themselves with controls, then allow more time on analysis of systems”
- “Very instructive and fun. However, it is far easier to manage without the VR set and using the standard Univese Sandbox[2] software instead”
- “The exercises were excellent for insight on motion of multiple bodies, however, the programme was sometimes lacking displaying complex orbits”
- “In this simulation, I got more dizzy and confused than in the other times. Otherwise, the experiments was good and it was insightful to try things out”

Overall, the exercises seem to have been well-received, although a number of practical issues related to the software and equipment could definitely be improved.

3.3. RESULTS – LEARNING OUTCOMES

Our analysis of the pre- and post-exercise questionnaire for the VR exercise in the Physics of Galaxies course indicate that a significant fraction of students altered their perception about how efficient black holes would be in “sucking in” nearby stars. Some also seem to have re-evaluated their perceived likeliness of stellar collisions. After having explored the fate of stars venturing close to the supermassive black hole in the centre of the Milky Way,

≈42% of the students found it desirable to downgrade the probability of the scenario in which these stars would be colliding with the black hole. Another ≈17% kept the same relative position of this scenario in their ranked list (lowest rank), but added a written comment that it was indeed very unlikely. Similarly, ≈33% downgraded the probability that the stars would collide with other stars in the vicinity. Both of these scenarios are indeed quite unlikely, which the exercise seems to have convinced them of.

When asked to draw a stable triple-star system as part of the pre-exercise questionnaire in the Physics of Stars course, ≈44% of the students ended up depicting an unstable system. However, all of these students successfully corrected their mistake in the post-exercise questionnaire, which clearly shows that they have gained some insight on this during the exercises. The additional two questions did not produce any interesting results, as only 1-2 students in the pre-exercise test failed to correctly interpret the stability and realism of the three-stars-in-a-circle system or the Roche lobe evolution. Clearly, these questions were not sufficiently challenging and should be replaced in coming years.

The analysis of the pre-exercise questionnaires for the VR exercises in the Physics of Planetary Systems course shows that the students are typically aware of quite a large number of parameters and effects that may affect planetary habitability already at the start of the session. The median number of student suggestion at this stage is 7, although many of these are not independent (example: the incident flux on a planet is a function of stellar luminosity and distance, but students quite often list all three options). As expected, distance from the star and its planets is the most common parameter listed, but other popular answers include the mass/size/type of the planet (indicating that the planet should be rocky and relatively small, and not a gas giant). A comparison of the pre- and post-exercise tests nonetheless reveals that ≈82% of the students chose to include additional parameters that would be important for planetary habitability at the post-exercise stage. The most common such additions were planetary albedo, tidal locking and angle of planetary rotational axis with respect to the exo-ecliptic plane – all of which were in fact important in one or several of the simulated planetary systems they encountered. Several students also provide enlightening free-text motivations for why they made changes with respect to their pre-exercise answers:

- "After the exercise, the planetary distance appears to be of less importance. The planet's ability to store/lose energy (through atmosphere or reflective surface) seems to play a big role in habitability"
- "As shown in the VR programme, the planets did not always become cooler with distance. Thus, we had to discuss other dominating processes and factors"
- "Seeing the top candidates of our list be crossed off due to planetary properties, as well as seeing planets outside of the habitable zone becoming better candidates than those inside of the habitable zone due to planetary properties"
- One student notes that the parameters in his/her post-exercise answers were "Mostly the same [as in the pre-exercise answers], but I have a better idea of importance and how they combine"

4. DISCUSSION

There are several practical issues to consider when planning and implementing exercises of this type. Already during the instructions, we warn the students about the fact that the software/equipment we are using may trigger photosensitive seizures, and ask that anybody that has been diagnosed with epilepsy reports this to the teacher beforehand. Simulations in Universe Sandbox^2 can occasionally result in rapidly flashing lights, especially prior to mastering the controls. For instance, accidentally locking onto a planet in orbit and speeding up time can feel like being on some extremely intense, stroboscope-illuminated merry-go-round, as this causes the central star to rush past one's field of view several times per second. We also caution students with glasses that it may – depending on the size of their frames – be uncomfortable to wear these inside the headset. In fact, several students have opted to do the exercises without glasses (or contact lenses), even though their reduced eyesight hampers their ability to see the simulated environment clearly.

A highly software-specific issue is the fact that the Universe Sandbox^2 menus map onto the Oculus Rift hand controls in a way that may be perceived as counter-intuitive and take a significant amount of time to learn. In our sessions, we have found it reasonable to set 30-45 minutes aside in order for each team of 2-4 students to learn the basic manoeuvers before getting to work on the exercises. During this time, the teacher acts as a "flight instructor" and walks each student through the controls while the student remains immersed in the VR environment (Example of instructions: "Put your right thumb on the top lever and push forward. Now, while holding the lever in place, push the front button. You should now see the 'Select tool' menu appear in front of you. Please select 'teleport' using the laser and then push the front button again. Good work! Now you can point the laser at whatever planet you want to travel to and get there immediately. Let's try it out!") While a printed version of the architecture of the menus and how they couple to the many levers and buttons of the controls was prepared, this was rarely used by the students, as it was simpler to just ask the instructor for advice or search for the right menus on one's own. Another thing to note (also pointed out by one of the students in one of the free-text answers in section 3) is that the Universe Sandbox^2 software exists in both VR and traditional versions. While not as visually stunning, the latter is by far the more powerful of the two, as it – through a combination of keyboard and mouse input – allows for more options and accuracy. Some features, such as the ability to plot the time evolution of astrophysical properties or check the internal composition of planets, has not been mapped onto the VR hand controls and requires keyboard input. Unfortunately, attempting to provide input via keyboard/mouse while the VR headset is active appears to be a quick path to crashing the software, which means that one temporarily needs to revert to the traditional version (remove helmet and leave hand controls well alone) when doing this.

The fact that the Ångström Visualisation Lab currently only hosts one Oculus Rift headset is of course a major bottleneck, which effectively limits VR exercise sessions of this type to courses of ≈10 students or less. While larger courses could be accommodated by scheduling more sessions, this would clearly be very teacher-intensive. Throughout this project, every session had to be scheduled up to 3 times to maintain no more than 2-4 students per team. This is already quite difficult to schedule, since the Ångström Visualisation Lab is used in several other educational programmes and for general meetings as well. An interesting thing to note is that, while only one student at a time can operate the headset (and hence experience VR in all its glory), this does not seem to make the other team members passive. Instead, there is a continuous discussion on what is going on, what the team should attempt to do next, and these exercises seem to keep everybody engaged throughout the duration of the 3-hour session. Another somewhat surprising aspect of this project is that the set of exercises that got the highest student-satisfaction score (4.8 out of 5; Physics of Planetary Systems) also happens to be the least interactive one. In these exercises, students merely use the VR to study and analyse existing simulations (and occasionally even have to revert to a traditional display to do this efficiently, for the reasons described above) – at no point are they asked to alter the simulated system. As far as we can tell, it is the puzzle aspects of this particular exercise set ("Wait! What? Is that planet *on fire*?! How can that be?") that made it come out on top.

In the future, it would be useful to dig deeper into the question of whether the VR experience itself actually enhances learning, or simply adds a "wow"-factor to a set of simulation exercises that could equally well be carried out using traditional displays and controls. Many of our students still have very little experience of high-quality VR (sometimes no experience, although many have tested setups similar to google cardbox, in which a smartphone is inserted into a pair of crude goggles) when coming to class, and the novelty aspect of it all certainly contributes to their enjoyment (and likely the student satisfaction scores). It would be interesting to see how worthwhile exercises of this type may seem in a few years' time, when good VR headsets may be cheaper and more regularly available to the students at home.

5. SUMMARY AND CONCLUSION

The VR exercise sessions developed as part of this project have been very well-received by students and positive learning outcomes have been demonstrated. Hence, it is recommended that these exercises are kept within the curricula of the relevant courses and are continuously updated.

6. ACKNOWLEDGEMENTS

The authors would like to express their thanks to the following people, who contributed during various stages of the project: Nino Dawod, Martin Sahlén, Kjell Olofsson, James Silvester, Christian Binggeli, Alvin Gavel, Joel Johansson, Ansgar Wehrhahn, Adam Hjort and Sofia Ramstedt.

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