TU WIEN Informatics

Visualizing and Explaining Space Weather Phenomena in Virtual Reality

Visualization and Storytelling

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BACHELOR'S THESIS

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at the TU Wien

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Vienna, 19th August, 2023

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Alexandra Irger

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Wien, 19. August 2023

Alexandra Irger

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Kurzfassung

Diese Arbeit präsentiert ein Konzept für eine Virtual-Reality-Anwendung, die Nutzerinnen und Nutzer über Weltraumwetter informiert. Sie bietet eine Zusammenfassung von Forschungsergebnissen zum Weltraumwetter mit Fokus auf den damit verbundenen Phänomenen und Risiken für uns. Dabei wird ein Ablauf festgelegt, der alle wichtigen Handlungspunkte einschließt. Das Konzept ist in Szenen unterteilt, wobei für jede Szene Implementierungsdetails angeführt werden. Es wird auch diskutiert, ob die Elemente der Szenen reale Daten, simulierte Daten oder klassische 3D-Modelle enthalten sollen. Die Rolle von VR sowie Implementierungsdetails werden beschrieben. Abschließend wird ein Storyboard-Mockup besprochen.

Abstract

This thesis presents a concept for creating a virtual reality application that educates users about space weather. It provides a summary of space weather research focusing on the phenomena and the risks they carry for us. A storyline is created that captures all the key messages. The concept is divided into scenes, containing implementation details for each scene. Scene elements are discussed, as to whether they should integrate real data, simulated data, or standard 3D models. How VR plays a role as well as implementation details are stated. To conclude the concept, a narrated storyboard mockup is discussed.

Contents

CHAPTER 1

Introduction

As early as in the 18th century, scientists have observed indications of solar activity directly affecting the Earth. Auroras have been the most evident signs of the interconnection between the sun and our planet. While it remained relatively insignificant to humanity for a long time, it now poses a great threat to modern society.

The telegraph was one of the first well-known examples of technology directly affected by solar activity. With the advancement of technology over the past two centuries, a much greater part of our lives is at risk of being compromised. This ranges from satellites in outer space and in orbit, to planes, to all kinds of electronic devices.

Space weather is being studied in great detail, and the sun's activity is closely monitored. Through the 2012 near-miss event, scientists have been able to learn a lot about the possible impact an event of such magnitude could have. This thesis goes into detail about the different kinds of phenomena and their impacts on us.

1.1 Motivation

There is relatively little public coverage on the risks, and the public is not educated well on the topic. To create awareness and educate people, the European Space Agency commissioned a project called CosmoWeather. While other institutions including the DLR developed an expert prototype for space weather research in VR, the VRVis took on developing an educational prototype. The following thesis presents the foundation for developing this VR application.

1.2 Goal of Thesis

The main goal of this thesis is to create a full concept for a virtual reality (VR) prototype that educates users of the general public about space weather. It touches on the general foundation of space weather, why it forms, and how it physically impacts earth, as well as the history and state-of-the-art of the research area, and the socioeconomic threats space weather phenomena pose.

The concept is based on a storyline guiding the user through the topic. Based on the key concepts of storytelling research, multiple scenes are defined to create a journey. These pose important visualization questions, as measured data is difficult to obtain on this scale. The tradeoff between using immersive technologies and the capacity for complex visualizations of huge datasets is another matter of consideration.

To finalize and evaluate the concept, the scenes are paired with the narration of the storyline into a final storyboard mockup. After the final implementation, a detailed reflection follows on the concept as well as on how realistic the fully detailed implementation is in a limited scope.

1.3 Structure of Work

Starting with an overview of state-of-the-art work in space weather visualization and storytelling, both related to VR, in Chapter 2, we then introduce space weather phenomena in Chapter 3. We establish and detail the storyline in Chapter 4 and follow up with a detailed description of scenes in Chapter 5. As VR is a main component of the prototype, its impact, as well as implementation details are outlined in Chapter 6. To finish up the thesis, we present the storyboard mockup in Chapter 7 and reflect on it and future work and challenges in Chapter 8.

CHAPTER 2

Related Work

The related work can be categorized in three groups. The base for the project is research done on space weather itself. It then builds upon visualization methods, as well as storytelling.

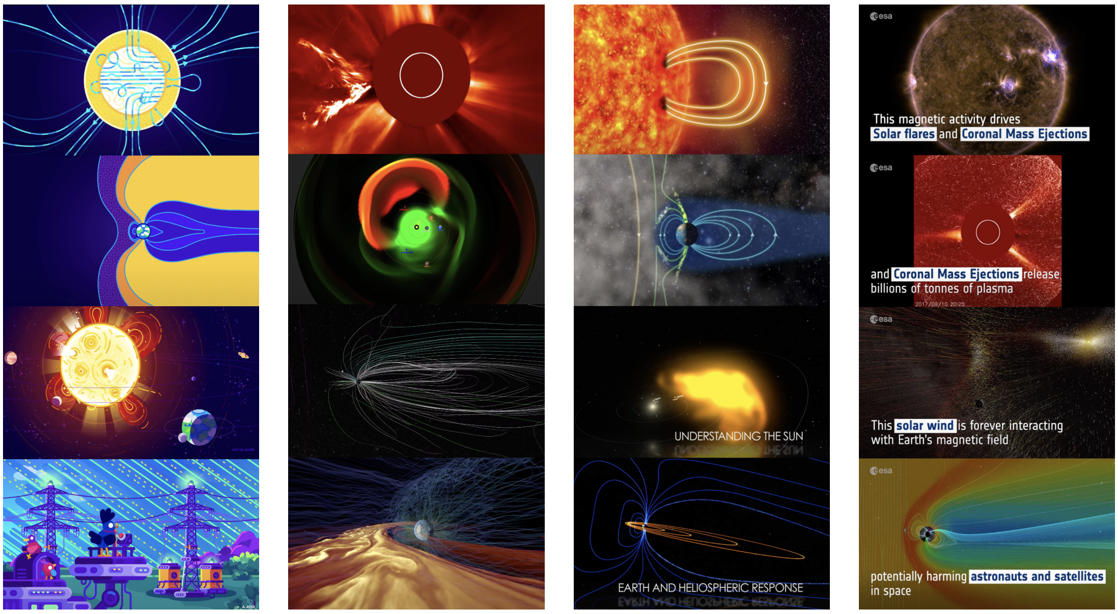
2.1 Space Weather Science

An Introduction to Space Weather [Mol08] provides the theoretical background to space weather. It describes the mechanisms of the sun, the events, and the impact on earth — physical as well as on our technologies. Additionally, Echer et al. [EGG+05] discusses specifics for the distinct phenomena. The Carrington event is discussed by Carrington [Car59], Cliver [Cli06], and Green et al. [GBO+06]. For the 2012 event, Baker et al. [BLP+13] provides a resource. Predictions and estimates about future events are made by Jyothi [Jyo21] and Eastwood et al. [EBH+17]. A condensed introduction summarizing the majority of these topics is given by McIntosh et al. [McI19].

2.2 Visualization

2.2.1 OpenSpace

OpenSpace is a visualization software for visualizing space phenomena. Törnros [Tö13] introduces volumetric rendering with Voreen for integrating the rendering of space weather models in OpenSpace. Bock et al. [BAB+17] introduce OpenSpace as an "open source interactive data visualization software designed to visualize the entire known universe and portray our ongoing efforts to investigate the cosmos". Novén and Carlbaum [CN17] add interactive and time-varying solar data as well as time-varying field lines to OpenSpace. Berg and Grangien [BG18] introduce support for visualizing 3D magnetohydrodynamic CME simulation data.



(a) [Kur20] (b) [Spa15] (c) [NAS13b, NAS13a] (d) [Eur18]

Figure 2.1: Various scenes from the respective videos.

2.2.2 Virtual reality

Visualization in immersive environments is explored in Donalek et al. [DDC+14]. Liu et al. [LLW19] implements real-time magnetic field visualization in augmented reality. Sicat et al. [SLC+19] introduces DXR, a toolkit for immersive data visualization in Unity.

2.3 Storytelling

2.3.1 Space Weather

There are multiple resources that educate about space weather. *About Space Weather* [Spa] is a collection of online articles that offers concise explanations of the phenomena, their impact, and the stakeholders. It utilizes text for the majority of the information and some images, as well as hyperlinks and some graphics. It serves as a general guide on how to break complex topics down into smaller, still informative bits.

More similar to our prototype are educational videos about the topic. Kurzgesagt — In a Nutshell [Kur20] is an illustration-based concise explanation video that covers the topic in under 9 minutes. It uses 2D animations, as seen in Figure 2.1a. SpaceRip [Spa15] focuses on the 2012 and the Carrington event, specifically how it physically impacts earth. It uses a combination of real images taken, 2D and 3D visualizations of measured and simulated data, and 3D illustrated scenes, as seen in Figure 2.1b. NASA published two videos concerning the topic. One specifically focuses on Heliophysics [NAS13b] and one focuses on space weather and Earth's Aurora [NAS13b]. They both use 2D and 3D animations, real images, and simple visualizations of model data, as seen in Figure 2.1c. The video on Heliophysics is unique as it does not take the standard journey from the sun to earth. ESA's video [Eur18] comes in the shortest, explaining the topic in under two minutes. It is the only video of the five examples, that uses text on the screen instead of spoken narration. Its visuals consist of images, with short clips of animations and visualizations in-between, as seen in Figure 2.1d.

2.3.2 Virtual reality

Utilizing VR for boosting the understanding of a global scientific problem is explored by Markowitz and Bailenson [MB21]. They analyze the connection between VR and climate change in terms of psychology and add recommendations for creating and improving those VR experiences.

CHAPTER 3

Space Weather

> » **Space Weather** is caused by conditions on the Sun and in the solar wind, the magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can affect human life or health. « — *Glover et al.* [GDHB02]

The following chapter lays out the foundation of what we know about space weather, which is needed to craft an engaging storyline subsequently. What follows is a summary of the key concepts and phenomena.

Space weather encompasses a variety of areas and is not limited to the interrelation of the sun and the earth. As these are out of the scope of this thesis, phenomena like Galactic Cosmic Rays will not be discussed here. Further information can be found in Mark Moldwin's *An Introduction to Space Weather* [Mol08] and in the *About Space Weather* glossary by the Space Weather Prediction Center [Spa].

3.1 Sun Phenomena

All weather relevant to this project originates in the sun. The following section details the different phenomena and how they form.

3.1.1 The Sun

Within the sun's core, protons are fused together to form Helium. This process releases energy. The resulting temperature and ionization also create a strong and dynamic magnetic field (as seen in Figure 3.1), which makes up the base for space weather formation [Mol08]. Traces of this have been observed since Galileo in around 1609, as regions of strong magnetic field are cooler and therefore darker – known as Sunspots [Mol08].

3.1.2 Solar Flares

The areas around sunspots are also called active regions. Around those, the surface magnetic field tears, twists, and reconnects, making it unstable. These events cause rapid energy releases [Mol08, EGG+05]. Solar Flares are an example of this, releasing energy as great as "hundreds of millions of megaton hydrogen bombs exploding at the same time", all within a few minutes. Particles from the solar atmosphere shoot into space, reaching up to light speed. Additionally, X-rays are emitted [Mol08].

It takes around 8 minutes for the effects to reach earth. The electromagnetic radiation impact lasts 1-2 hours [EGG+05]. This makes the flare the fastest type of weather to reach earth, making any anticipatory action close to impossible.

3.1.3 Solar Wind

Another surface phenomena are coronal holes. They appear where the field lines are open and do not reconnect in the heliosphere [EGG+05, Sch71]. Through those holes, streams of high-speed solar wind are emitted. The solar wind is a plasma (charged particles), consisting mostly of protons, helium nuclei, and electrons, all of which have high enough velocities to escape the sun's gravitational pull. It carries the sun's magnetic field with it, and can be described as "magnetized plasma" [Mol08].

As the solar wind flows continuously, it influences the magnetic fields around planets. Its speed averages 400 km/s, reaching the earth in 4-5 days [EGG+05, Mol08].

3.1.4 Coronal mass ejections

Reconfigurations of the magnetic field can cause large portions of the corona to blast away all at once. These are called coronal mass ejections, short CMEs, and are large-scale magnetic structures, consisting of up to over 10^9 tons of coronal material [Mol08].

As they move faster than the background solar wind, their velocity can exceed 1000 km/s, very fast CMEs can reach the earth in less than one day [Mol08, EGG+05]. They are the primary reason for geomagnetic storms, making them one of the most important phenomena in the space weather discourse [Mol08].

3.2 Impact on Earth

The different sun phenomena impact the earth in different ways. In the following section we will discuss the physical impacts as well as the implications for society in the past, present, and future.

3.2.1 Physical impact

Because of the amount of iron inside of the earth and its movement, our planet is surrounded by a strong magnetic field. As opposed to the sun's, the magnetic field of the

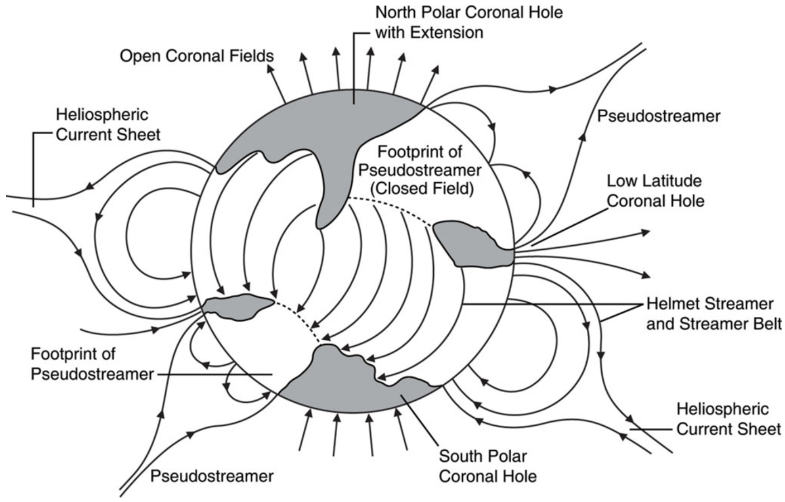


Figure 3.1: Visual representation of the sun's magnetic field [LLR+11]

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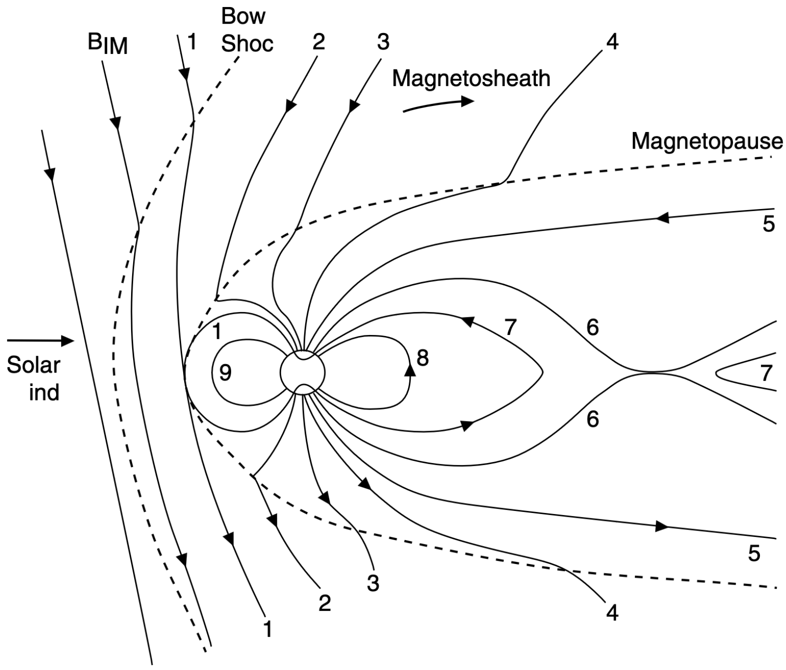


Figure 3.2: Visual representation of the earth's magnetic field [Mol08], adapted from [KR95].

Earth is a dipole magnetic field, which is similar to that of a regular magnet, having two poles - one where the magnetic field extends outward and another where it goes back into the Earth [Mol08].

As seen in Figure 3.2, the magnetic field is stretched into a tail shape, due to the interaction with solar wind. When plasma approaches the earth, a shock wave is formed, and the plasma is then diverted around the magnetosphere. It leaves behind a tail, similar to a wake in a stream. However, it is not as simple as a fluid analogy, as we have to factor in magnetization. When two magnetic fields pointing in opposite directions are brought together, they subtract. Additionally, magnetized plasma can interact in a new way and form new field lines. This happens in a process called magnetic reconnection. The process occurs twice, first when a field line connected to the solar wind magnetic field on both ends touches a field line connected to both poles on earth (see (1) in Figure 3.2). They produce two new field lines (2), one connected to the north as well as to the south pole of the earth. On the tail side, a similar reconnection happens when two oppositely directed open field lines (6) reconnect and form a closed field line as well as a field line connected to the solar wind (7) [Mol08].

If the energy transferred from the sun to the earth's magnetosphere increases rapidly, it is called a geomagnetic storm. With these storms, the auroral oval on both poles rapidly expands and brightens, causing aurorae, commonly known as northern and southern lights [Mol08].

3.2.2 Impact on society

As we are dependent on satellites for modern-day communication, we are directly affected by space weather affecting them. Various radiation effects affect satellite materials as well as their electronics and signals. These effects vary by the satellite's orbiting distance [Mol08].

As geomagnetic storms alter the density of the ionosphere, which acts as a medium for radio waves, radio communication is disturbed. This most notably impacts communication for ships and commercial aircrafts, as well as the Global Positioning System (GPS) [Mol08].

Large geomagnetic storms alter currents on the ground. They induce currents within long conductors, therefore affecting power lines, telephone lines, as well as metal pipelines. This causes corrosion and device failure by overloading, impacting electrical components connected to those lines. Damage to the power grid due to an overload of voltage can cause major blackouts, damaged and destroyed transformers could take years to replace [Mol08].

3.2.3 Past Events

Carrington Event

The first ever reported solar flare dates back to September 1st, 1859 [Cli06]. While sunspots were discovered earlier — by Galileo Galilei and others in the 17th century —

Richard Christopher Carrington joined by Richard Hodgson discovered the flare in his daily sunspot observation [Cli06, Car59]. He described it as "two patches of intensely white and bright light [breaking out]" [Car59]. The flare was accompanied by what is said to be the largest ever observed geomagnetic storm on September 2nd, 1859. [Cli06] There are several eyewitness reports, detailing the night sky turning red and hearing rushing sounds they believed to be "loose winds". Telegraph lines ceased to work for around 8 hours, and an economic impact was noted [GBO+06].

2012 Solar Eruption

On July 23rd, 2012 a severe space weather event directly hit the satellite STEREO-A. If the storm had occurred a week earlier, the CME would have targeted earth directly instead. It is believed, that the 2012 event defines a "worst case" solar storm scenario, comparing the magnitude to the previously introduced Carrington event. It provided researchers and policymakers with data for further research as well as emergency preparedness purposes [BLP+13].

3.2.4 Future Outlook

A powerful solar superstorm could massively disrupt the internet, and earth being hit by one is estimated to be 1.6 – 12% in the next decade. Multiple important questions regarding infrastructure design, as well as preparation and recovery plans, remain [Jyo21].

While the physical impact is understood well, a solar event hitting earth also brings an arguably big economic impact. Lack of agreement over the exact technological impact makes quantifying the effect on affected industries — such as satellite, aviation, power, and navigation systems — challenging [EBH+17].

Both from an economic, as well as a technological standpoint, researchers are anticipating and urging more action to be taken to provide better solutions for the posing threat [EBH+17, Jyo21, BLP+13].

CHAPTER 4

Storyline

While the previous introduction to space weather already only scratched the surface of the research subject, it must be further simplified and structured, for the interested user to understand the topic. While there are two main implementation goals — the educational prototype without interaction and the exploration prototype with interaction — the scenes will be similar. In this chapter, the educational prototype will be the main focus.

4.1 Storytelling

The main task here is to pack the most relevant information into a story, that explains the concepts, dangers, and effects of space weather to a user without background knowledge in the field. Kurzgesagt — In a Nutshell [Kur20] provided an approach that is similar in length to our project.

The natural way to go about this is to start at the origin of (most) space weather, the sun. The story follows different phenomena through space, where they reach the magnetosphere and eventually earth. The impact on our technology is showcased there.

The integration of the topic of space weather history, such as the Carrington event, as well as the 2012 near miss, pose a bigger challenge. As a solution, the concept of a control room, showcasing multiple sources of further information, is established.

There are two main constraints for the number of scenes. The first being VR. The more scenes we have, the more transitions are necessary. As the prospective users include people, who have never experienced VR before, avoiding motion sickness is a key aspect. It is simply impractical to include more short scenes and transitions for minimal amounts of information and contributions to the story. Hence the control room is established, to give more space to topics not important enough to have their own distinct environment. The second constraint is the development. Each additional scene requires additional composing and modeling. Having more scenes may not be achievable in the limited timeframe of the project.

This is the reason why additional scenes were omitted for this iteration of the project. Examples of supplementary scenes that could be included are non-solar space weather, the ionosphere, depicting the recollections of the Carrington event, illustrating the CME impacting STEREO-A, and detailing the ionosphere. We opted to include details about these topics in the control room, which is especially relevant for the exploration mode, where additional information could be requested about those topics. As the ionosphere and non-solar space weather are not vital to the narrative, they have been omitted from the main educational prototype. The Carrington event as well as the STEREO-A event are included in the control room but do not have a distinct scene to match.

As the educational prototype runs without interaction, the concept follows a movie-like structure. In order for the user to grasp the connections between the scenes, the decision to refrain from cuts was made, so the whole sequence runs without any cuts and abrupt changes in position. This constrains the storyline and creates the need for parallel running storylines, such as for the different types of weather flying through space at the same time. All things happening at the same location have to happen at similar times, which contrasts the scene switching seen in all exemplary info videos described in Section 2.3.1. Similar to the majority of the videos, the visuals are accompanied by a narration guiding the journey.

These requirements make staying true to scale impossible. In order to minimize motion sickness from transitions, the scales are adjusted, making the earth bigger and placing it closer to the sun. The technology portion is also adjusted in scale.

4.2 Scenes

In the following section, all of the scenes and their contribution to the storyline are described.

4.2.1 Surface of the Sun

As mentioned prior, the story starts with the sun. This scene gives us the opportunity to explain how the sun releases energy, show the magnetic field around the sun, and various surface phenomena, such as sunspots. It transitions into showing an example of a flare, CME, and solar wind. The examples cover the main talking points and also leave room for exploration — walking through the magnetic field or showing the inner workings of the sun being two possible ways to extend the scene. There are also multiple other phenomena such as for example coronal holes and coronal rain that can be included in a later version.

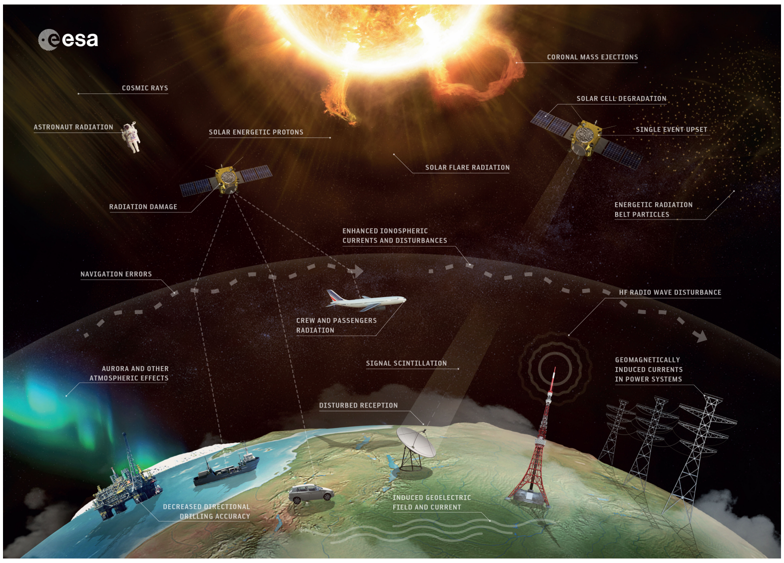


Figure 4.1: Overview of technology being impacted by space weather. Image courtesy of ESA [ESA18].

4.2.2 Journey to Earth

The narrative continues with the third and slowest phenomenon, which is the solar wind. It then accelerates to catch up with the CME and eventually the flare. Finally, earth comes into view in the far distance.

4.2.3 Earth from Space

The earth is shown surrounded by a visualization of the magnetosphere. A CME is shown impacting earth, causing magnetic reconnection. This scene could be extended by also including the ionosphere, however, it is not needed for the narrative.

4.2.4 Impact on Technology

This scene ties up the direct effects of space weather, by showing the affected technology. The composition is based on Section 4.1 and the narration guides through the effects of the flare and the CME. By the time each piece of technology is impacted, it turns "off" until the whole scene is dark. The blackout creates a suspenseful scene, supporting the central thesis of the prototype — educating about the risks and dangers of space weather.

4.2.5 Control Room

What follows afterwards, is a control room with multiple screens. An example of how that could look like can be seen in Figure 4.2. The screens are filled with dashboard space

Figure 4.2: Control room scene example. Image generated using OpenAI's DALL · E [ID23]

weather data, additional visualizations, and original documents of the Carrington event. For the exploration prototype, the scene provides the opportunity to create interactive screens with interactive visualizations. It is also an opportunity to integrate live data into the prototype. The information on display can also consist of forecasts, information about the current solar cycle, and sunspot data.

4.2.6 Epilogue — Auroras

To tie the story together, it ends with an outdoor setting, showcasing auroras — a phenomenon caused by solar wind that is familiar to the majority of people. It provides space to include credits, sources, and references for further information. This scene can be combined with the control room too if needed. For example, the screens can be set up in the scene directly, leaving the sky and backside open, showcasing the phenomenon in the night sky.

CHAPTER 5

Visualizations

The visualizations are a core part of the prototype. We want to incorporate them with manually generated 3D models into one cohesive scene. We aim to incorporate as much real data as the constraints permit.

5.1 Goals

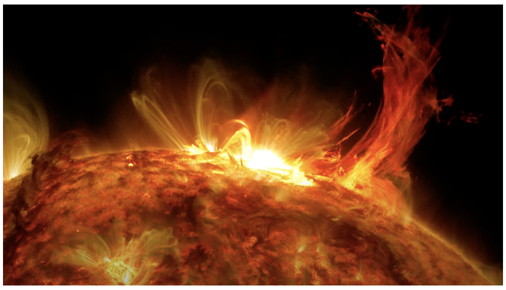
The main decision we have to make for most of the scenes is what we use measurement data for, what we use simulation data for, and what we use standard 3D models for. This also strongly poses the question of what data is available in general, and what data is 3D and suitable for our VR application.

5.1.1 Constraints and Tradeoffs

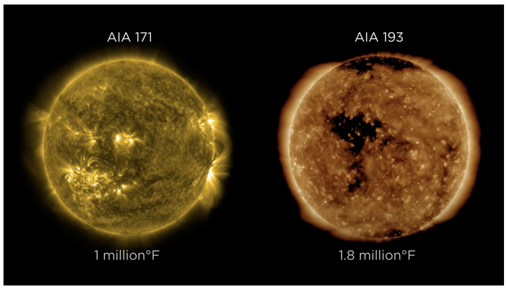
The concept for the visualizations takes multiple factors into account. The first component we have to consider is the hardware. The prototype targets low-cost VR devices, therefore computing power is limited. In order for high-quality volume visualizations to run at >90Hz, this computing power is vital. Since it is not planned to offload the rendering onto computers directly, volume visualization will be difficult to put into practice. As data analysis is not necessary for this prototype, we will resort to multiple pre-computed displays of visualizations.

The second main consideration is the user. As mentioned before, the prototype provides a short introduction to the topic, so the visualizations target education rather than expert analysis. The visualizations should therefore be easily understandable and aid the scene and storyline.

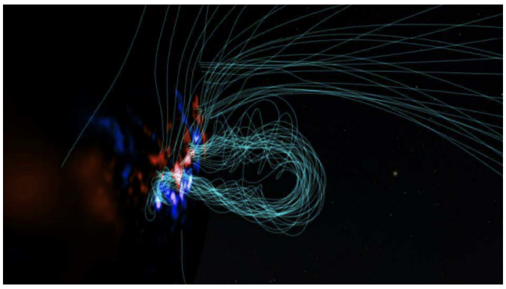
Thirdly, the project runs over a limited timeframe. Consequently, not all aspects can be implemented in a complex manner. The tradeoff here is finding the right combination of



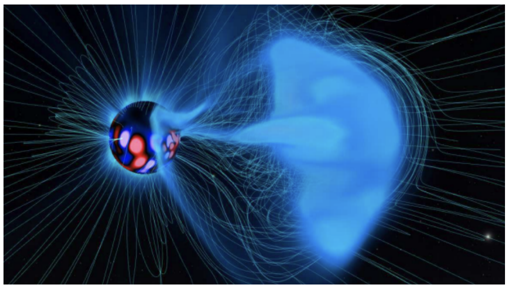
(a) [NAS21]



(b) [NAS21]



(c) [BG18]



(d) [BG18]

Figure 5.1: Various visualization examples for the sun scene.

using pre-made models for efficiency and simplicity, modeling phenomena after simulation data, precomputing visualizations, and visualizing data on the hardware directly.

5.1.2 New Challenges

As discussed in Chapter 2, the topic has already been visualized for educational purposes in various ways through videos [Kur20, Spa15, NAS13b, NAS13a, Eur18]. The challenge for this project is to create an application with a similar feel that works in an immersive 3D environment. The goal is to steer away from 2D images and animations, such as satellite images, unless it is absolutely necessary. There are 3D expert tools for space weather data analysis available, examples include openSpace [BAB+17, Tö13, CN17, BG18], as well as the proposed CosmoWeather expert prototype. Those tools however target specific hardware and an advanced level of expertise on the topic. Our challenge is to find the balance between the educational 2D approach and the expert 3D visualization approach. The goal is to combine aspects of both into a new application.

5.2 Scene 1: Surface of the Sun

The surface of the sun itself can be displayed with animated textures. As there are plenty of images and videos of the sun, events on the horizon could be displayed through video animations on geometry. Example (video) textures are shown in Figure 5.1a and Figure 5.1b. The phenomena we see up close have to be visualized differently. Multiple models exist for simulating the sun's magnetic field, resulting in magnetohydrodynamic simulations (MHD). MHDs were introduced to OpenSpace through Berg and Grangien [BG18]. They visualize a time-variant dataset of a flare followed by a CME using a combination of field lines for the magnetic field and volume rendering showing the mass, as seen in Sections 5.1c and 5.1d.

Vital to this scene is some kind of visual representation of the magnetic field, and the plasma that moves along its field-lines. A volume visualization might not be feasible. For demonstrating mass, geometry is the simpler alternative.

5.3 Scene 2: Journey to Earth

As this transition scene is neither to scale nor introduces any new physical objects, no new visualization is necessary. The particles following streamlines can be followed from the previous scene, the same goes for the mass of the CME. As traveling fast with the flare — suggesting the speed of light — is the final step of this transition, fast particle geometry is the proposed solution.

5.4 Scene 3: Earth from Space

This scene contains the most significant visualization. Aside from the earth itself — a textured sphere — the magnetosphere will be visualized. All reviewed educational videos about space weather impacting earth include this part. It is done either based on 2D simulations or modeled animations, as seen in Figure 2.1.

For this type of visualization, data is available through the Community Coordinated Modeling Center (CCMC) [Kuz00]. The standard model used for storing simulation data is the BATS-R-US Magnetosphere Model. The outputs include time-dependent values of pressure, density, velocity, magnetic field, and electric current data [Com18].

A 2D visualization of a BATS-R-US model by Bridgman et al. [BHD+14] depicting a CME impact including magnetic reconnection can be seen in Figure 5.2. For our visualization, the field lines are most important again. The pressure could be precomputed or displayed via an animated texture on a cutting plane. Optionally, particle geometry could follow a precomputed flow in the velocity field.

5.5 Scene 4: Impact on Technology

As explained in Section 4.2.4 and shown in Figure 4.1, the fourth scene contains the affected technology as well as the earth geometry from the previous scene. The disabling of the devices is simulated by shading effects. The models are taken from the abundance of online available 3D models from platforms like Turbosquid [Tur00], Sketchfab [Ske12] and CGTrader [CGT11].

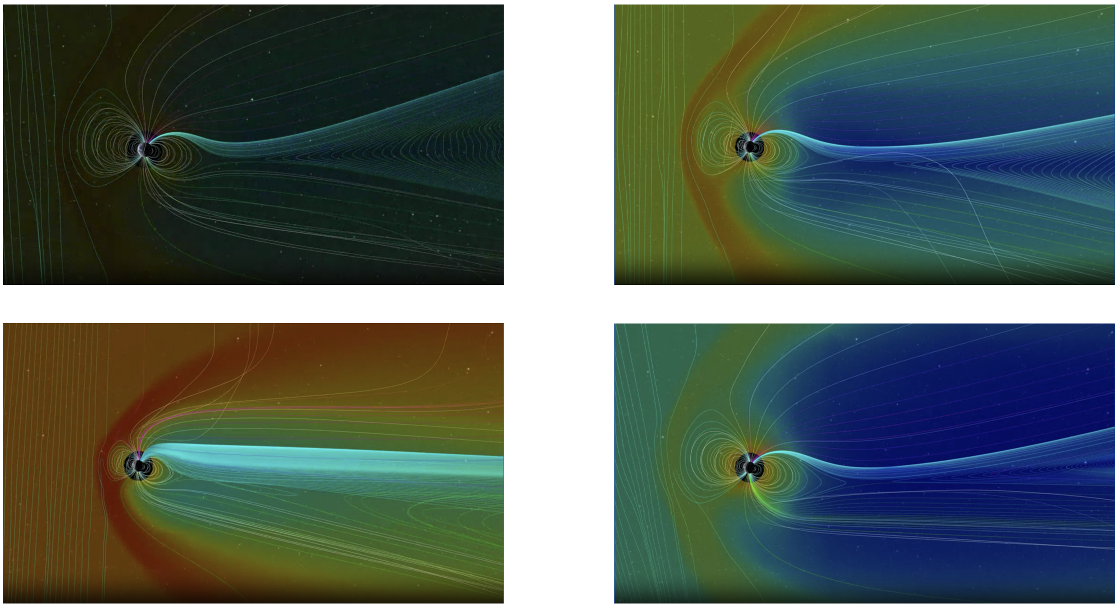


Figure 5.2: Example of the BATS-R-US model depicting a CME [BHD+14].

5.6 Scene 5: Control Room

The control room scene's purpose is to provide the opportunity for simpler, possibly live visualizations. A big screen is positioned in the middle, surrounded by multiple smaller ones. The visualizations on the screens aim to create a look similar to a dashboard. For reference, ESA's space weather dashboard can be seen in Figure 5.3. For the exploration mode, the user can select and interact with the visualization on the big screen. For the educational prototype, the visualization of interest will be displayed on the big screen.

The ideal case is to create a realistic scene of online available 3D models. However, adding interactive 2D screens would also be sufficient. In this case, the screens could be embedded in Scene 6 too.

5.7 Scene 6: Epilogue – Auroras

To wrap up the educational prototype, the final scene will be simply the night sky with auroras. There are 360-degree videos available, examples include William Briscoe Photography [Wil17], as seen in Figure 5.4. As the scene is not focused on conveying new information, it acts as a space for credits, references, and possibly links to further information.

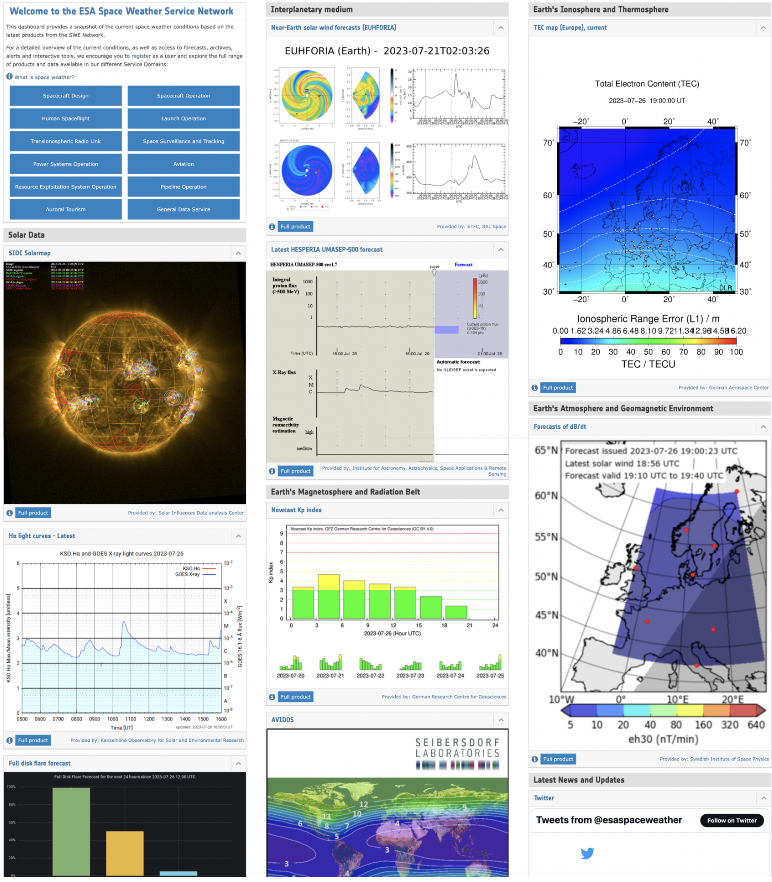


Figure 5.3: Control room visualization examples [SWE].

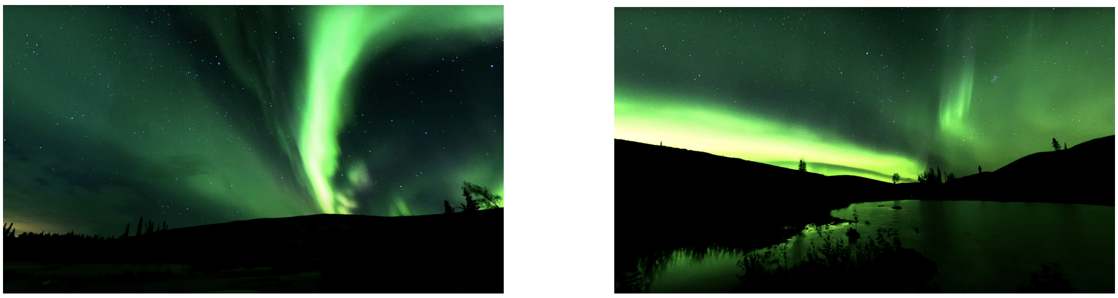


Figure 5.4: Aurora scene examples [Wil17].

CHAPTER 6

Used Technology

This chapter summarizes the implementation plan for the prototypes. The technology choices were already given by the project proposal or the VRVis.

6.1 VR

The application is VR based. Augmented Reality was suggested a well, but as we want to explore full scenes instead of single objects, VR is more feasible. There is a possibility to include AR in the future. VR is by definition immersive, and supports various ways of interaction, making it a suitable tool for this project. Markowitz and Bailenson [MB21] believe that "if you build it, they will download" (in the context of VR and climate change experiences), as long as the application is free, public, connects with users, provides new information, and is scalable across platforms. This aligns with the established goals and further emphasizes the need for making the prototype available for as many types of VR devices as possible, especially lower-budget devices.

6.2 Development

The application is implemented using Unity [Uni04]. The development platform supports development for VR and works cross-platform, ensuring compatibility with the majority of VR operating systems. The models are modified using Blender [Ble94], and can then be imported into Unity directly.

6.3 Prototypes

There are three prototypes planned for this project. Each one is built on the same scenes, but the storyline and interaction differ.

The most important one is the educational prototype. Therefore this concept is specified in most detail. The visualization of the magnetosphere is a core element that needs to be implemented as a priority. The application targets a runtime below 10 minutes, the narration itself is around 6 minutes long.

The exploration prototype consists of the same scenes, however, instead of being guided by the narration, the users can explore the scenes on their own. The transition from sun to earth would most likely be omitted, and manual navigation between scenes can be added. While the concept so far includes suggestions for interactions, they are very dependent on the actual implementation, which is again dependent on budget and time constraints. The inclusion of details on demand can be implemented easily in all scenes except for the journey-to-earth transition scene. If needed, details about the phenomena traveling through space can also be included when they originate at the sun directly.

A third prototype was suggested, which would provide an "executive summary". It is a short version of the educational application. It targets a runtime below three minutes. It is to be implemented after the first application is finished. Its realization is dependent on how fast the educational and exploration prototype can be finished.

CHAPTER 7

Results

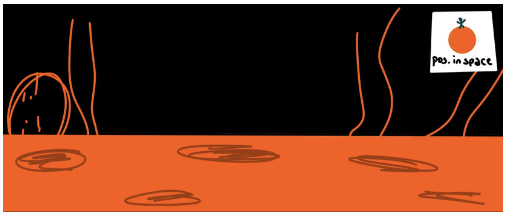
The finished concept is a 6-minute narrated storyboard, which was implemented afterwards. The research that has been done to prepare for the topic, the creation of scenes, and the creation of the story, is summarized in this thesis. During the work on the project, multiple artifacts have been produced, such as earlier drafts and proposals, and state-of-the-art reports. In terms of the space weather research field, this thesis only contains only the selected parts, that were chosen to be referenced in the educational prototype.

The following pages present the mockup. The scene panels are captioned with the corresponding lines in the narration. Some screens are based on gifs and actual images, as they represent the imagery better than the custom sketches. The video version can be found here [Irg23].

Figure 7.1d is taken from NASA's Solar Dynamics Observatory [NAS15b]. Figure 7.1f is based on NASA's Goddard Space Flight Center [NAS15a]. Figure 7.1g is taken from Predictive Science Inc. [DAH+17].

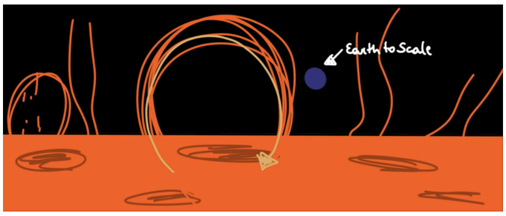
Figure 7.2c is based on Muzhevskyi [Muz]. Figure 7.2d is taken from NASA/Goddard/Conceptual Image Lab [NGC15]. Figure 7.2e is taken from NASA Video [NAS13b]. Figure 7.2f is taken from NASA Goddard's Conceptual Image Lab and Kim [NK].

Figures 7.3a, 7.3b, 7.3c and 7.3d are based on Figure 4.1 [ESA18]. Figure 7.3f includes graphics from BATS-R-US [BHD+14], Mendel [Men], Church [Chu65], Nightman1965 [Nig], Ahluwalia [Ahl08], and Scheiner [Sch11]. Figure 7.3g is based on Hoiberg [Hoi].

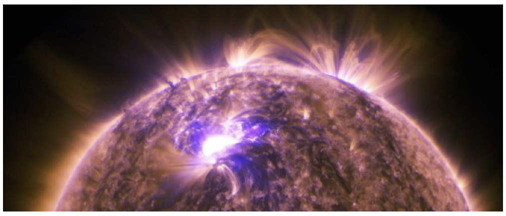


(a) Welcome to the sun, the yellow star in the center of our solar system. Here, we are visiting the origin of the majority of space weather that we have observed today. It originates deep down in the solar core, where hydrogen atoms are fused into helium, generating massive amounts of energy.

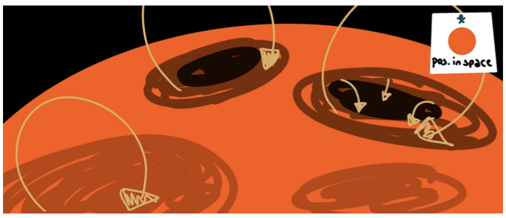
(b) This produces intense magnetic fields, which extend outside of the sun into its atmosphere. We cannot see these fields, however, a mix of ions, free electrons, and neutral atoms, which we call plasma, moves along these fields, making them visible and explorable for us.



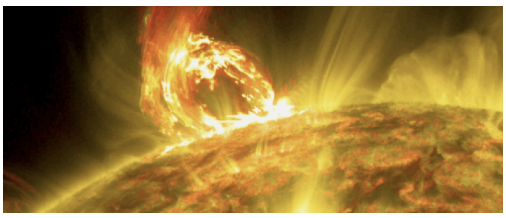
(c) When magnetic fields extend out of the surface we can observe these magnetic loops.



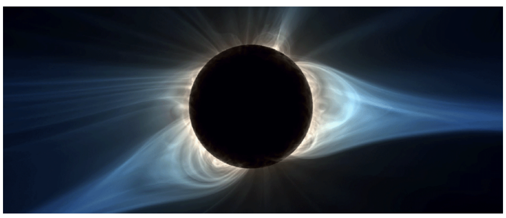
(d) When two loops touch they short circuit, causing the plasma to "spew" away into the atmosphere, traveling through space. We call this a solar flare.



(e) On regions of the sun, where intense magnetic activity happens, convection is inhibited. This causes the photosphere — the layer of the sun that is visible to us — to cool and appear dark. This phenomenon is called a sunspot and has been observed by astronomers as early as 1610. The number of sunspots fluctuates along an 11-year cycle, the next solar maximum is predicted for 2025. In times of a solar maximum, there is an increase in solar flares as well as coronal mass ejections.

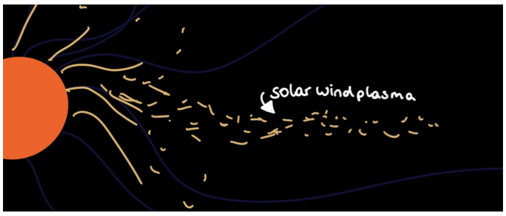


(f) If the magnetic field is closed over sunspot groups, the atmosphere that is confined below can violently release bursts of gas and magnetic fields called coronal mass ejections. Coronal mass ejections send massive particle clouds into space.

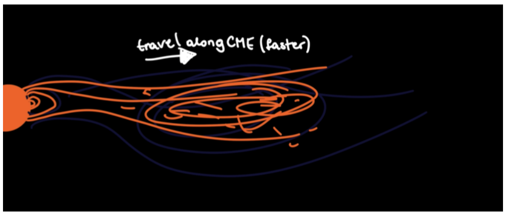


(g) Through the high temperatures in the corona, the sun's outermost layer, charged particles constantly escape the sun's gravity. The plasma streams away from the sun along outwards–extending magnetic field lines.

Figure 7.1: Panels 1 – 7 of the storyboard mockup with the corresponding narration.

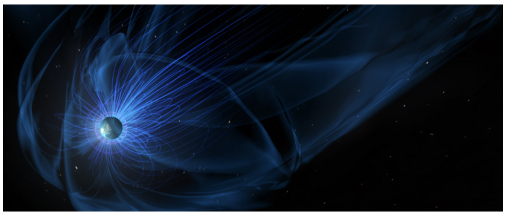


(a) Solar wind plasma consists of electrons, protons, and alpha particles mixed with heavy ions and atomic nuclei. The particles move along the interplanetary magnetic field. They make up the slowest form of space weather, taking between two and four days to reach us.

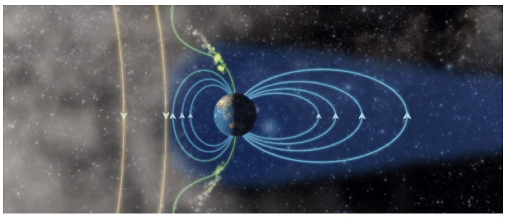


(b) Now we are following the plasma released by a coronal mass ejection. It carries an embedded magnetic field, stronger than the interplanetary magnetic field that the solar wind moves along. The fastest coronal mass ejections take between 15 and 18 hours to arrive on earth. As they travel through space, they expand, taking up the space of up to a quarter of the distance between earth and the sun by the time they reach us.

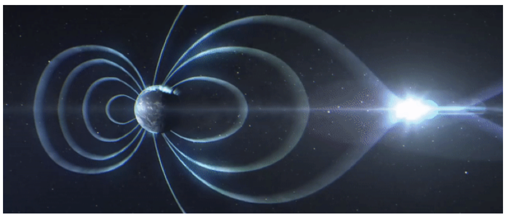
(c) The fastest traveling phenomena connected to space weather are solar flares. They are made up of X-rays and extreme ultraviolet radiation and move at the speed of light. They, therefore, impact us from the moment we can observe them. It takes them eight minutes and 18 seconds to reach earth.



(d) This is the earth's magnetosphere. It is formed by the interaction between solar wind and the earth's magnetic field. Therefore we can see that it is compressed on the daylight side of the earth.



(e) If there is a significant amount of plasma hitting the earth as a variation from solar wind, we call it a solar storm. The magnetosphere hereby acts as an invisible shield. It couples together with the electromagnetic field from the impacting particles and funnels the particles down on the daylight side of the earth's poles.

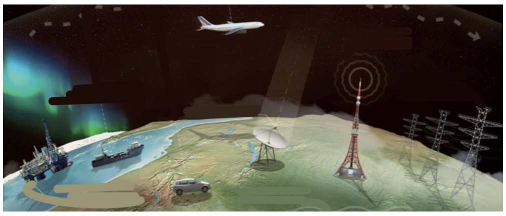


(f) The magnetic lines then stretch further back, coupling again on the tail side of the magnetic field. This releases another stream of gas back to the earth's poles, this time causing the nighttime auroras.

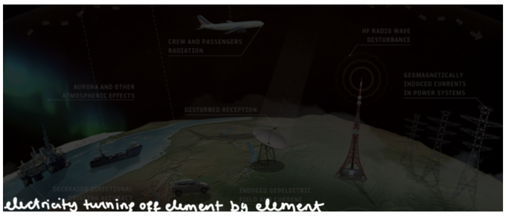
Figure 7.2: Panels 8 — 13 of the storyboard mockup with the corresponding narration.

(a) These are phenomena, we observe regularly. But what would happen if an unusually huge coronal mass ejection was to hit earth? Statistically, at first, a solar flare would hit us. The radiation would ionize the upper parts of our atmosphere causing radio blackouts and GPS failures. GPS failures would lead to planes, ships and cars losing guidance.

(b) Between minutes and hours later electrons and protons would arrive. Satellites would get electrified and damaged, disturbing satellite communication in space and on the ground.

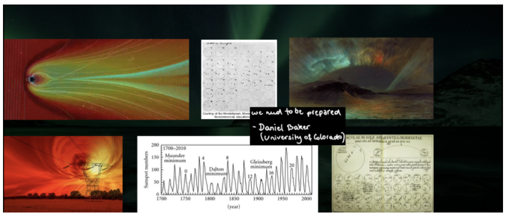


(c) Finally, approximately a day later coronal mass ejections would hit earth. Billions of tons of magnetized plasma would cause all kinds of electricity on earth to disfunction.



(d) Power distribution networks and pipelines would fail. Modern communication channels would malfunction.

(e) Essentially the world would go into a blackout. Reparations would take years.



(f) The probability of such a storm hitting earth within the next 10 years is estimated to be up to 12 %. While we can not prevent these events from happening, we can minimize the long-term effects they have on us. But for that "we need to be prepared".

(g) [*epilogue and credits*]

Figure 7.3: Panels 14 — 20 of the storyboard mockup with the corresponding narration.

CHAPTER 8

Conclusion

8.1 Challenges

The main challenges are handling the data and creating the application within the budgeted time. While there is data available, as mentioned in Section 5, preprocessing the data for VR headsets will be challenging. This will greatly determine, how much actual data will end up in the final prototype. Acquisition of specific textures and models might also become an issue, an example would be acquiring the license for a 360-degree aurora video.

Through the use of Unity, platform compatibility is increased greatly. Depending on specific use cases, challenges could still arise, especially with the differing computing powers of different headsets. A one-fits-all solution might be challenging.

The potential for motion sickness, especially concerning users not familiar with VR, is dependent on the implementation, but can also be a risk factor. The concern could be omitted by forgoing the seamless transitions, or movement in general. This would defeat the established continuity between scenes and phenomena.

The biggest challenge is estimated to be the implementation load under budget constraints. Even though the concept has undergone multiple iterations of scaling down the scenes, the implementation is still more ambitious than easy. Multiple uncertainty factors such as quality of data, availability of assets, and computing load could greatly determine the feasibility.

8.2 Future Work

The next step after the creation of this concept is the implementation of the prototypes, starting with the educational and continuing with the exploration application. There are multiple ways to extend these prototypes.

The number of visualizations could be increased. Additional visualizations can be the ionosphere, a detailed interplanetary magnetic field, and more volume visualizations in general. The data can also be taken from live measured data. However, the acquisition of high-quality live data is challenging. There could be the option to watch different major events unfold.

For the exploration prototype, it is already suggested, but additional information could be included. Engaging with elements would unveil new information and would let the users explore what they are interested in most.

Haptic feedback could be introduced. This would be applicable for any kind of volume data or the magnetic field in general — more dense regions or a stronger magnetic field corresponding to stronger haptic feedback.

A version of the prototype could be optimized for a short film or even an interactive web application, which would greatly increase the number of potential users.

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