Walking Through an Exploded Star: Rendering Supernova Remnant Cassiopeia A into Virtual Reality

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Keywords
Data, virtual reality, science communication, visualisation, augmented reality, narrative

Data on the Cassiopeia A supernova remnant from NASA and other sources have been rendered into a three-dimensional virtual reality (VR) and augmented reality (AR) programme, which is the first of its kind. This data-driven experience of a supernova remnant allows viewers to take a virtual walk inside the leftovers of a massive star that has exploded, select parts of the remnant to engage with and access descriptive texts on what the different materials are. This programme is based on a unique three-dimensional (3D) model of the 340-year old remains of a stellar explosion, made by combining data from NASA's *Chandra X-ray Observatory*, the *Spitzer Space Telescope* and ground-based facilities. A collaboration between the Smithsonian Astrophysical Observatory and Brown University allowed the 3D astronomical data collected on Cassiopeia A to be featured in the VR/AR programme, which is an innovation in digital technologies with public, education and research-based impacts.

Introduction

Overview of Virtual Reality

Virtual reality (VR) is a computer technology that simulates a user's physical presence in a virtual environment. VR's close relative, augmented reality (AR), adds elements such as text, overlays and audio to enhance that experience with sensory input and is briefly discussed on page 19. VR has existed in some form since the 1980s (Faisal, 2017). Though it has faced many ups and downs (Stein, 2015), including the unrealised promise of a Virtual Reality Markup Language in the late 1990s, it has become more commonplace in the consumer market since about 2010 (Faisal, 2017)[1]. Given its potential for improving the gaming industry, media and even adult entertainment, there are major commercial driving forces behind the technology's development (Oracle, 2016; CNET, 2016).

The increased commercial prominence of these technologies, including the availability of less expensive yet good quality and more user-friendly technologies, presents new opportunities for their use in science (Ferrand et al., 2016). There is a potential for VR to revolutionise how experts — from molecular modelling to environmental conservation — visualise and analyse their data and how that data is then communicated to non-experts (Isenberg, 2013).

In medicine alone, VR is a unique tool for data visualisation and comprehension as well as for continuing education and user experiences. Uses of VR programmes that are in development and implementation range from improving health workers' understanding of brain damage (Hung et al., 2014) to implementing virtual surgery training for medical students (Murphy, 2018) and applying VR and AR techniques in an accessible way in the treatment of Alzheimer's disease (Garcia-Betances et al., 2015). VR has been shown to improve upon the traditional tangible model of using dummies to enhance medical students' preparation for assisting patients in high-risk real-life scenarios. It can allow physicians and other health professionals to work with specific cases to practice the applicable caregiving skills (Murphy, 2018).

Beyond the universe of the body and out into the Universe at large, astronomical data sets often provide high-resolution, multi-wavelength and multi-dimensional (lately, even multi-messenger) information. The process of converting photons, or packets of energy, into 2D images has been documented and studied (Rector et al., 2017; Arcand et al., 2013; DePasquale et al., 2015; Rector et al., 2007) but the translation of that information into 3D forms that use human perspective, cognition and stereoscopic vision, less so (Ferrand et al., 2016). Since the Universe is multidimensional itself, as Fluke and Barnes (2016) ask: "Are we making the best use of the astronomer's (and a non-expert's) personal visual processing system to discover knowledge?"

Astronomical VR experiences include exploring exoplanets (planets outside our Solar System) through science-informed 3D artists' impressions converted into

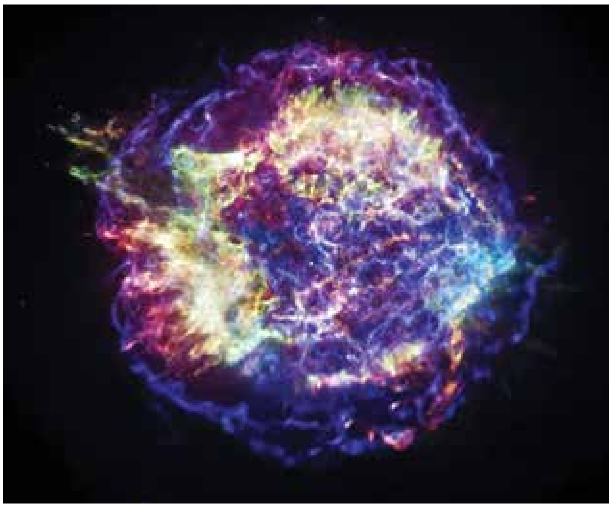

Figure 1. *Cassiopeia A (Cas A) is a supernova remnant located about 10 000 light years from Earth. This 2D visual representation of Cas A has been processed to show with clarity the appearance of Cas A in different bands of X-rays. This will aid astronomers in their efforts to reconstruct details of the supernova process such as the size of the star, its chemical make-up and the explosion mechanism. The colour scheme used in this image is the following: low-energy X-rays are red, medium-energy ones are green and the highest-energy X-rays detected by* Chandra *are coloured blue. The image is 8.91 arcmin across (or about 29 light years). Credit: NASA/CXC/SAO*

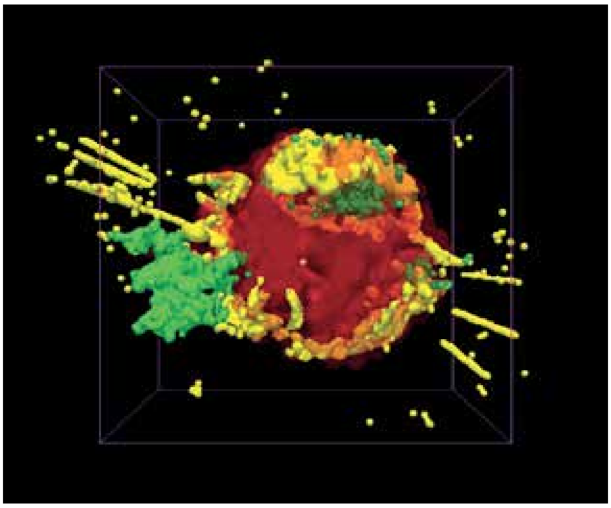

Figure 2. *By combining data from* Chandra, the Spitzer Space Telescope *and ground-based optical observations, astronomers were able to construct the first 3D fly-through of a supernova remnant. This 3D visualisation (shown here as a still image) was made possible by importing the data into a medical imaging programme that has been adapted for astronomical use. Commercial software was then used to create the 3D version of the data. The green region shown in the image is mostly iron observed in X-rays; the yellow region is mostly argon and silicon seen in X-rays, optical and infrared, and the red region is cooler debris seen in the infrared. The positions of these points in three-dimensional space were found by using the Doppler effect and simple assumptions about the supernova explosion. Credit: NASA/CXC/MIT/T.Delaney et al.*

VR[2]; experiencing a NASA mission spacecraft in VR such as the *James Webb Space Telescope*[3]; walking across the surface of Mars[4]; exploring dozens of massive stars from the perspective of the supermassive black hole at the centre of our Galaxy[5] (Russell, 2018); and viewing radio data cubes of a spiral galaxy (Ferrand et al., 2016).

Data Path for Cassiopeia A: From 2D to VR

Supernova explosions are among the most violent events in the Universe. When the nuclear power source at the centre of a massive star is exhausted, the core collapses and in less than a second, a neutron star typically forms. This process releases an enormous amount of energy, which reverses the implosion, blows material outwards and produces a brilliant visual outburst. The resulting debris field is referred to as a supernova remnant.

Cassiopeia A (Cas A) is a supernova remnant from an explosion that occurred approximately 340 years ago in the Earth's timeframe (Figure 1). A multi-wavelength three-dimensional (3D) reconstruction of this remnant was created using X-ray data from *Chandra*, infrared data from *Spitzer* and optical data from ground-based telescopes. In Figure 1, the green regions are mostly iron, the yellow regions include a combination of argon and silicon, the red regions are cooler explosion debris and the blue regions show the outer blast wave.

When elements created inside a supernova are heated, they emit light at specific wavelengths. Because of the Doppler effect, elements moving towards the observer will have shorter wavelengths and elements moving away will produce longer wavelengths. Since the extent of the wavelength shift is related to the speed of motion, the velocity of the debris can be determined by analysing the light. By combining this Doppler information with the expectation that the stellar debris expands radially outwards from the explosion centre, Delaney et al. (2010) used simple geometry to construct a 3D model of Cas A (Figure 2). A programme called 3D Slicer — modified for astronomical use by the Astronomical Medicine Project at Harvard — was used to display and manipulate the 3D model[6].

The visualisation shows that there are two main components to Cas A: a spherical component in the outer parts of the remnant containing light elements like helium and carbon from the outer layer of the exploded star and a flattened (disc-like) component in the inner region containing heavier elements like argon and iron from the inner layers of the star[7]. The blue filaments indicating the blast wave show a different type of radiation that does not emit light at discrete wavelengths, and, therefore, have not been included in the 3D model.

High-velocity jets of heavy material shoot out from the explosion in the plane of the disc-like component mentioned above. Jets of silicon appear in the upper left and lower right regions, while plumes of iron are seen in the lower left and northern regions. These had been studied before the 3D model was made, but their orientation and position with respect to the rest of the debris field had not been mapped before.

The insight into the structure of Cas A gained from this 3D visualisation is important for astronomers who build models of supernova explosions. They have learned that the outer layers of the star come off spherically, but the inner layers come out more disc-like with high-velocity jets in

Figure 3. *A 3D virtual reality (VR) with augmented reality (AR) version of the 3D data of Cas A allows the user to walk inside the debris from a massive stellar explosion, select the parts of the supernova remnant to engage with and access short captions on what the materials are. This photo was taken of the first author inside the Brown University YURT, or VR CAVE, during testing of the Oculus Rift hardware and application. Credit: NASA/CXC/SAO/E.Jiang.*

multiple directions (Delaney et al., 2010). Since the Delaney et al. (2010) study, two other groups have constructed 3D models of Cas A (Milisavljevic & Fesen, 2015; Orlando et al., 2016), demonstrating the rich scientific value of such visualisations for astronomers.

This 3D visualisation was initially created as an interactive for desktop viewing[8]. To move beyond the small screen, it was later translated into a 3D printable format (Arcand et al., 2017), which is particularly conducive for exploration by blind and visually impaired populations[9] (Grice et al., 2015; Christian et al., 2015).

The authors considered VR (Figure 3) as the next step in the translation process, an additional experience beyond the 2D visual and 3D tactile (Eriksson, 2014).

Augmented Reality in Astronomy

As mentioned above, AR adds text, image, sound-based elements or other effects to deliver an enhanced user experience with additional sensory input, typically by merging the real or "live" with virtual information.

AR has become popular because of the number of smartphones, wearable computing devices and other smart gadgets being pushed in the consumer market (Vogt & Shingles, 2013; Amer & Peralez, 2014). From computational interfaces popularised by Pokémon Go (Sicart, 2017) to AR leopards that visitors can interact with to help promote conservation[10], AR is only expected to grow in popularity[11].

The use of AR to explain topics in astronomy is neither a completely new nor a completely unexpected idea. Vogt and Shingles (2013), for example, make note of AR-based designs in astronomy developed for education purposes, including 3D displays of our Solar System, 3D demonstrations of the Sun–Earth interaction and a NASA application that allows users to get up close and personal with a NASA spacecraft[12, 13]. Vogt and Shingles also discuss the use of AR for astronomy research, citing their own interactive AR model of the supernova remnant N132d.

VR Translation and Technical Specifications

Currently, VR software has not been standardised to the point where we can use data as direct input into a VR programme. While software exists to allow visualisations to be displayed across different platforms (Brown Center for Computation and Visualization (CAVE)[14], Viscon Virtual Reality VR PowerWall[15], 3D televisions[16], head-mounted displays[17]) using a variety of input devices (6-degree-of-freedom trackers[18], multi-touch input devices (Marzo et al., 2014), haptic devices[19]), we have yet to design a system that can support raw data without any external software. Therefore, with each new type of data set, effort must be made to build the bridge between raw data and VR software in order to produce the visualisation.

This format of Cas A uses volumetric data (where volume, or the data inside an object, is rendered — as in an MRI or CT scan in medicine) and polygonal data (where only the surface, or the outside data, is rendered) of the supernova remnant Cassiopeia A collected by *Chandra*, *Spitzer* and ground-based optical observatories. It therefore employs volume and surface rendering techniques of the Visualisation Toolkit (VTK)[20] to create a MinVR-enabled programme[21].

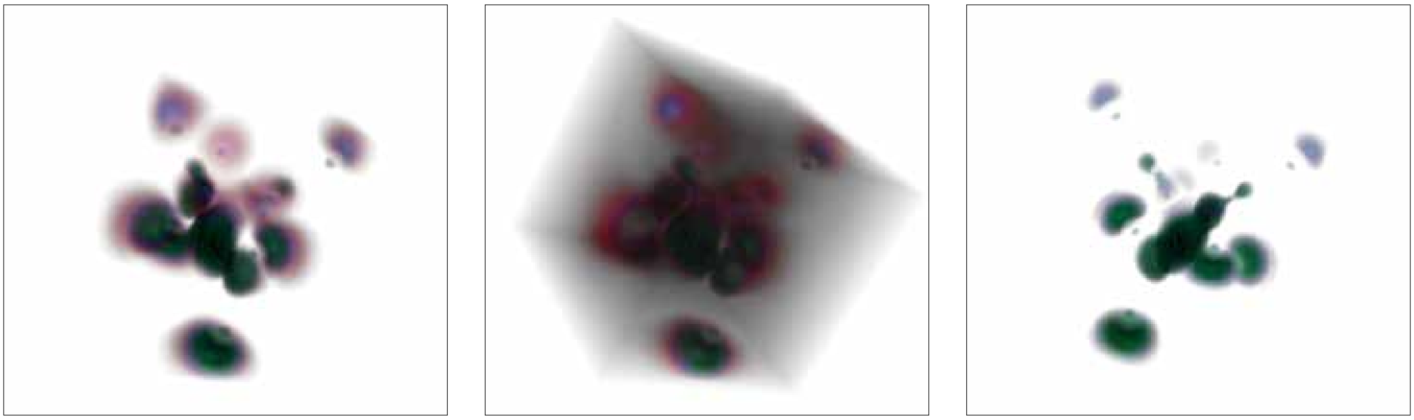

Figure 4. a) b) c) *(Left to right) Volume rendering. Credit: CXC & Brown University.*

Methods

Volume and Surface Rendering

To render the supernova both volumetrically and polygonally, we used VTK, an open-source, freely available software system for 3D computer graphics, image processing and visualisation. VTK supports a wide variety of visualisation algorithms including scalar, vector, tensor, texture and volumetric methods as well as advanced modelling techniques such as implicit modelling, polygon reduction, mesh smoothing and contouring[20] (Kitware, 2010). VTK has a suite of 3D interaction widgets.

With VTK, we were able to read the supernova data sets and use its built-in filters and mappers to render the remnant's volume and surface. The remnant is composed of seven different parts, and each part is represented by a different colour in the surface model.

Integrating with MinVR

MinVR is an open-source project, developed and maintained collectively by the University of Minnesota, Brown University and Malcalester College. It aims to support data visualisation and VR research projects by providing a cross-platform VR toolkit that can be used in many different VR displays, including Brown University's YURT (Yurt Ultimate Reality Theatre, or CAVE[14]).

A technical challenge with this project was integrating the VTK programme with MinVR. Since both programmes had their own render function, we had to use VTK's external module to allow the VTK programme to accept an external render window and render loop. As has been the case when working with our 3D/VR projects thus far, multiple bridges needed to be built between technologies in order to create something new. We worked with VTK to improve the external camera capacity. In the end, we were able to complete the integration and display the supernova models in YURT.

Progress & Results: Volume and Surface Rendering

Figure 4(a) shows a sample volume rendering demo that uses iron density data to simulate what a supernova would look like given its volumetric data.

Figure 4(b) shows that when the opacity level is low enough, one can observe an outer cube that encompasses the iron density data, illustrating the importance of adjusting opacity levels in volume rendering.

On the other hand, when the opacity level is too high, we cannot see enough of the data to observe the differing measurements of density. Figure 4(c) shows that

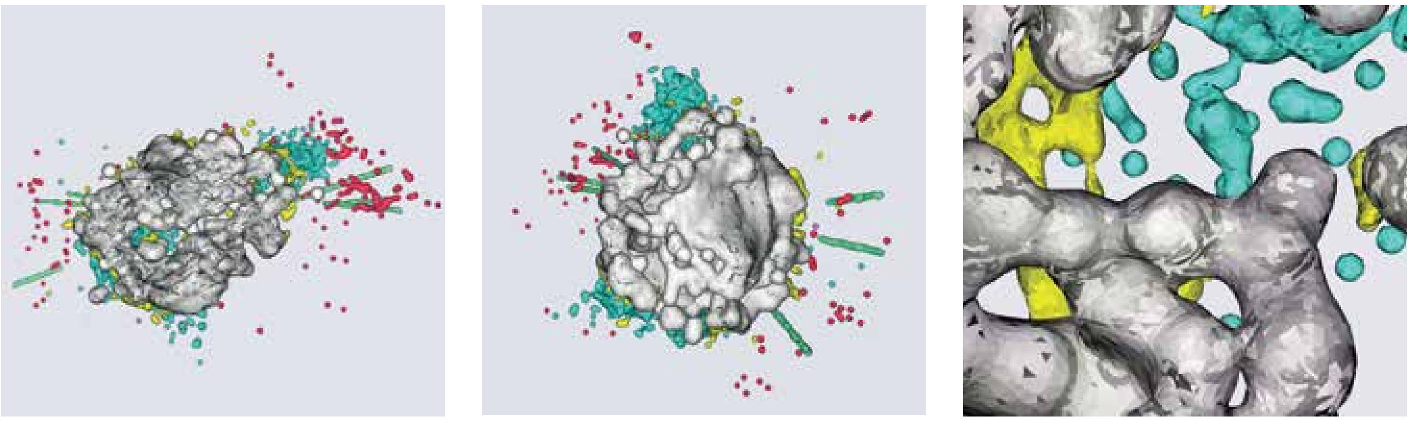

Figure 5.a) b) c) *(Left to right) Surface rendering. Credit: NASA/CXC & Brown University.*

we must work to find an optimal opacity level and an intuitive colour scale.

The model in Figure 5(a) is a surface rendering of Cas A, made up of seven different parts, shown in different colours. Each part is a separate ASCII data file consisting of polygon data and triangular strips.

The seven parts shown in Figure 5(b) include a spherical component (purple), a tilted thick disc (grey), and multiple ejecta jets/pistons (green) and optical fast-moving knots (red, yellow, blue, pink) all populating the thick disc plane.

Figure 5(c) shows the view from inside the spherical structure of the supernova. Here, it is possible to see that the rendering is a mesh of triangles that shape the surface.

Augmented Reality: Narrative Additions

For the Cas A VR experience, adding interactive text over the VR object was an important narrative component of the overall experience because of the complexity of the science model. Providing contextual information has been shown to improve the user's understanding and enjoyment of 2D and 3D astronomy images both among experts and non-experts and across technological platforms (Smith et al., 2017a, 2017b, 2014, 2010). Therefore, the addition of contextual information to VR data sets seemed ideal for users of all kinds.

Our enhanced VR Cas A model includes annotations for each part of the supernova remnant (for example, the neutron star, the iron and silicon debris, etc.) that describe both its components and its overall structure. Users can select a specific part of the supernova remnant by using their input device or wand (such as the Oculus Touch, a device that brings the user's hands or gestures into the virtual environment) to access the annotations and bring them up in their VR environment. They can cycle through each notation to discover more information about Cas A. These additional interactive narrative features may help educators to more effectively tell the life story of a star and provide resources to researchers observing changes in the size, density and shape of stars.

Figure 6(a) shows the addition of narrative text, where the user can select a part of Cas A to focus on and access captions. In this case, the user has chosen to focus on the Neutron Star at the centre of the remnant.

Figure 6(b) captures the screen of a user highlighting the reverse shock sphere that demonstrates wave expansion. Note how the caption superimposed over the image uses analogy to help increase understanding (Smith et al., 2017 (b)).

Discussion

The VR Cas A experience was created for 3D immersive environments such as CAVES and the Oculus Rift (Clark, 2014). Cell phone adaptations that can be viewed with pop-up personal VR viewers such as Google Cardboard and even those that can be used in a browser without any VR viewers have been created to allow additional entry points for viewers who do not have access to more expensive equipment[22].

The Cas A 3D VR model has the potential to be a useful tool that engages experts and non-experts in the data of astronomy and applications of computer science. For non-experts, specifically, astronomy data in general are popular as a science topic, as evidenced by the ubiquitous placement of astronomical images throughout popular culture everywhere from bed linens to computer wallpaper[23].

By linking the data and images of Cas A with unique computer tools in a project such as this, new connections can be made. Astronomy models in virtual reality can provide an unexpected visual and perceptual palette for the modern viewer. Such applications may be able to assist participants in establishing a sense of presence with data that is otherwise difficult to relate to because of the nature of the distance from Earth, sheer scale and other factors. This data can be shown at a monumental scale with VR. There are difficulties with VR technologies to consider, however, such as motion sickness caused by the visual disconnect, the need to incorporate an illusion of boundless movement, accessibility (both for underserved socioeconomic areas and also for physical accessibility by people who are visually impaired[24]), as well as struggles in establishing touch-responsive features (Steinicke, 2016; Amer & Peralez, 2014).

Just as in video games and educational software, VR-enabled science requires narrative integration whether for expert or non-expert users (Gottschalk, 2016). The key to making such a project more than just a toy is to provide meaningful information and content that is clearly embedded in the virtual experience. Projects such as

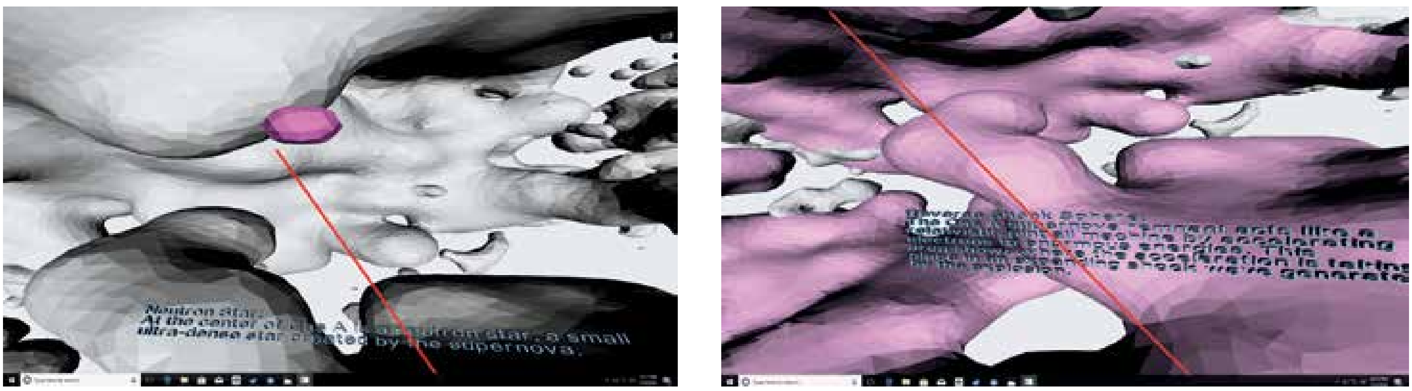

Figure 6.a) b) *(Left to right) Augmented Reality labeling. Credit: NASA/CXC & Brown University.*

this Cas A 3D VR/AR model could be used as a launch point for opportunities in a host of topics in astrophysics, chemistry, computer science and more.

With the current market trends in equipment and adaptations of content and technologies for VR experiences (including multimodal access points for those with physical disabilities), it is a critical time to create quality astronomy-based materials for experienced VR users as well as those new to VR. In education specifically, helping students maximise the potential of VR could be done partially through output adaptations to platforms such as YouTube, which can host 360-degree versions of many VR videos where they can act as a canvas for individualised VR experiences tailored to the needs of different learners (Cotabish, 2017). This aspect of the viewer-driven experience in VR (Chen et al., 2014) could potentially have a positive impact on users with different learning styles, viewers with autism (Lahiri et al., 2015), participants with different physical abilities or other special needs (Tyler-Wood et al., 2015).

Next Steps

Expansion of Astrophysics VR Library

While our current results have provided an immersive and interactive rendering of the supernova remnant Cassiopeia A, we plan to expand our astrophysics VR data sets to build additional 3D visualisations that help illustrate more fully the life cycle of stars, from birth to death, with further interactivity included for the user. We are investigating the application of additional 3D data-driven models that can be imported into the VR pipeline described in previous sections. Future models include volumetric data files of supernovae and younger star systems that might also lead to more comprehensive models.

We are also working to make the existing VR application ADA/Section 508 compliant for accessibility[25].

Beyond Supernovae and Supernovae Remnants

Through rendering 3D models of Cas A, this project has in addition implemented a generic programme with examples of how to create similar programmes to read in and display such data. In the future, the authors hope to demonstrate new models of another famous supernova, SN 1987A, an explosion on the surface of a white dwarf, V745 Sco, and other astrophysical density data. The goal is to generate these models with less effort than that for Cas A. Our intent is that this generic programme could act as a skeleton and tutorial for future data sets in biomedical, physical or other fields[26].

Conclusion

We are excited about both the current abilities and the future potential of opportunities for using VR/AR in astronomy. There is a potential for unique educational experiences that marry the popularity of a visual science like astronomy with the technological advances that continue to evolve in VR/AR. Making "real world" examples like Cas A part of the cadre of VR/AR could spur creative ideas of how to infuse science into a realm that might typically include more content from science fiction. We look forward to making deeper connections with the subject matter we are most familiar with, to see how we can expand its content into the virtual third dimension and beyond.

Acknowledgements

Many special thanks to the Virtual Reality Lab at the Center for Computation and Visualisation at Brown University without which this project could not have been done. The Cassiopeia A digital 3D model was originally developed with Dr Tracey Delaney of West Virginia Wesleyan College (formerly of MIT), with the Chandra X-ray Center at the Smithsonian Astrophysical Observatory, in Cambridge, MA, with funding by NASA under contract NAS8-03060.

Notes

1 Virtual Reality Markup Language: www.cnn.com/TECH/9710/14/3.d.reality.lat/index.html

2 Science-informed 3D artists' impressions converted into VR: www.space.com/38749-visit-six-real-exoplanets-with-virtual-reality.html

3 Experiencing NASA mission spacecraft in VR: connect.unity.com/p/vr-experience-james-webb-space-telescope

4 Walking on Mars: www.jpl.nasa.gov/news/news.php?feature=6978

5 Exploring dozens of massive stars from the perspective of the supermassive black hole at the centre of our Galaxy: chandra.si.edu/photo/2018/gcenter360/

6 3D Slicer (since archived, Initiative in Innovative Computing): am.iic.harvard.edu

7 Cas A 3D Model video: chandra.si.edu/photo/2009/casa2/

8 Smithsonian 3D model: 3d.si.edu/explorer?mid=45

9 Printable Cas A 3D Model: chandra.si.edu/3dprint

10 See for example www.smithsonianmag.com/travel/how-augmented-reality-helping-raise-awareness-about-one-armenias-most-endangered-species-1-180967670/

11 See for example www.thenational.ae/business/peter-nowak-why-augmented-reality-will-be-a-big-trend-in-2017-1.32774; venturebeat.com/2018/02/08/the-nyt-is-boarding-the-ar-train-heres-what-that-means-for-storytelling/

12 The Vogt and Shingles (2013) paper can be downloaded as an augmented article, illustrating the utility of the technology promoted in the paper. The authors argue for collaboration between science researchers and publishing platforms to create more stable, as well as backwards compatible, content for AR.

13 AR-based design in astronomy for education purposes examples from NASA: www.nasa.gov/mission_pages/msl/news/app20120711.html

14 Brown Center for Computation and Visualization (CAVE) software: web1.ccv.brown.edu/viz-cave

15 Viscon Virtual Reality VR PowerWall Software: viscon.de/en/vr-2/vr-powerwall/

16 LG provides a striking example of a 3DTV: www.lg.com/us/tvs/lg-OLED55E6P-oled-4k-tv; Reasonably priced glasses for the 3DTV are available at Kmart: www.kmart.com/edimensional-ed-4-pack-cinema-3d-glasses-for/p-SPM8624650802

17 A very affordable version of the head mounted display is available at: www.amazon.com/dp/B01LZA1EKZ/; See for a more costly option: www.amazon.com/dp/B00VF0IXEY

18 6-degrees-of-freedom trackers: www.roadtovr.com/introduction-positional-tracking-degrees-freedom-dof/

[19] Explanation of haptic devices: www.youtube.com/watch?v=ABeAAHF6k1k

[20] Visualisation Toolkit: www.vtk.org/

[21] MinVR/MinVR". GitHub: github.com/MinVR/MinVR

[22] Online demonstration see: chandra.si.edu/vr/casa

[23] Space and Astronomy section of Geek Wrapped for an assortment of products decorated with astronomical images: www.geekwrapped.com/astronomy

[24] The ADA National Network explains What is the Americans with Disabilities Act?, adata.org/learn-about-ada

[25] United States Access Board (2000) sets out the Section 508 Standards for Electronic and Information Technology.

[26] The CXC does not endorse any specific commercial product, including the virtual reality technologies referenced throughout this paper.

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