# Bringing Cosmic Objects Down to Earth: An Overview of 3D Modelling and Printing in Astronomy and Astronomy Communication

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Three-dimensional (3D) modelling is more than just good fun, it offers a new vehicle to represent and understand scientific data and gives experts and non-experts alike the ability to manipulate models and gain new perspectives on data. This article explores the use of 3D modelling and printing in astronomy and astronomy communication and looks at some of the practical challenges, and solutions, to using 3D modelling, visualisation and printing in this way.

## Introduction

Over the past decade, three-dimensional (3D) modelling in science has become more accessible. From models of chemical compounds and molecules to anatomical representations and geographic models of Earth, 3D data representations can offer scientists and the public cognitive tools for scientific inquiry (Saleh, 2011).

While interacting with 3D data on a computer screen can be powerful, the ability to create a physical manifestation of the model — through 3D printing — can take things a step further. One of the most popular methods of 3D printing involves what is known as additive manufacturing on demand, whereby a material of some sort — from sugar to plastic to titanium — is continually added in layers to create the object. This makes the production of scientific tools possible wherever a viable 3D printer can be found (Clements, Sato & Portela Fonseca, 2016). The process of additive manufacturing on demand is known as fused deposition modelling (FDM) and has become increasingly more accessible and affordable to consumers over the past five years.

Although 3D printing is still relatively young, its possibilities are varied and intriguing. From planning a possible sustainable lunar base from Moon dust (Klettner, 2013), to medical printing of skin or embryonic stem cells (Everett-Green, 2013), there are endless possibilities for 3D printing applications in science.

In astronomy, data and the images that astronomical data produce are often only two-dimensional (2D). From our vantage point on Earth and from nearby orbiting telescopes, the Universe appears as a flat projection on the sky. While some surveys will contain information about the distances to objects, it is rare to have three-dimensional information about the sources themselves. Therefore, those astronomical objects that have been explored to date in 3D represent only a small fraction of what astronomers observe overall.

The ability to study astronomical sources from every side gives scientists a better understanding of how cosmic objects are structured and their underlying physics. Astrophysicists, computer scientists, engineers, technicians, and developers are creating new techniques to push astronomy visualisation beyond 2D images and expand into this important third dimension of space. This enables scientists and the general public to view objects from any angle and in some cases to virtually travel through them. A push is also being made towards 3D data representation that includes other information, such as time and velocity.

The field of astronomy, despite the challenges associated with obtaining 3D data, has developed innovative ways to obtain such information about distant sources. Astronomy has already benefited from advances in 3D modelling and printing, and it will continue to do so in this era of big-data astronomy. In this paper, we include examples of successful astronomical projects and discuss best practice that we have developed or experimented with to date.

## Astronomical medicine and 3D models of molecular clouds

Arguably one of the most innovative milestones in the recent development of 3D imaging in astronomy has been the Astronomical Medicine project (archived as of 2011). This effort combined the talents of a group of scientists at the Harvard-Smithsonian Center for Astrophysics and the Initiative in Innovative Computing with a program led by Alyssa Goodman[1]. Astronomical Medicine adapted existing 3D software and brain-imaging techniques from Boston-area medical personnel for use in astronomical data visualisation. The Astronomical Medicine project enabled

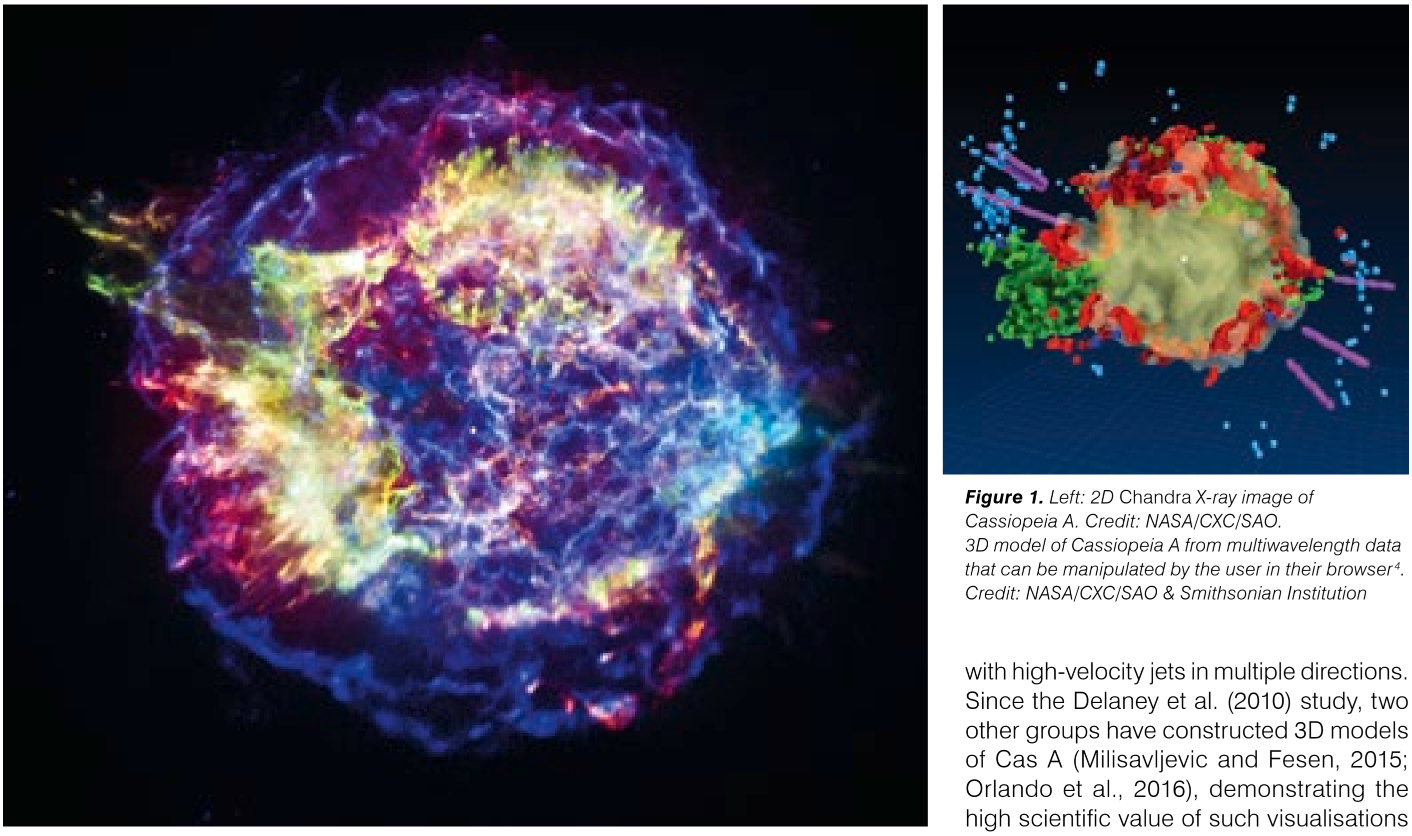

***Figure 1.*** *Left: 2D* Chandra *X-ray image of Cassiopeia A. Credit: NASA/CXC/SAO.*
*3D model of Cassiopeia A from multiwavelength data that can be manipulated by the user in their browser*[4]*.*
*Credit: NASA/CXC/SAO & Smithsonian Institution*

researchers to generate 3D images of molecular clouds, which could then be interactively included in digital editions of journals such as *Nature*, allowing readers to manipulate the 3D model directly in the enhanced PDF (Goodman et al., 2009)[2].

## Cassiopeia A: 3D visualisation to 3D print

Shortly after Goodman et al. began disseminating their results from the Astronomical Medicine project, technologists at the Chandra X-ray Center (CXC) began to apply it to another object type, supernova remnants. Cassiopeia A (Cas A) is the result of the catastrophic explosion of a star about 15–20 times the mass of our Sun (Orlando et al., 2016). The stellar debris of Cas A is known to be expanding radially outwards from the explosion centre.

Using simple geometry and Doppler effect data from *Chandra*, the *Spitzer Space Telescope*, and ground-based optical telescopes, Tracey Delaney, then at the Massachusetts Institute of Technology, collaborated with developers from the Astronomical Medicine project and CXC to create a 3D model of the supernova remnant with software such as 3D Slicer (Delaney et al. 2010). In partnership with the Smithsonian, a version of the 3D supernova remnant was produced (Figure 1) that could be manipulated in a browser by changing the viewing angle and selecting which data to show. This allowed the user to, for example, select data with different X-ray or infrared energies, allowing emission from different elements to be isolated, such as certain types of neon from *Spitzer*, or iron from *Chandra*. The CXC also created a fly-through, more transparent version adapted from the data into the commercial 3D software Autodesk Maya so that textures and colours more reminiscent of astronomical imaging and a star field could be applied. This Cas A 3D project was the first time astronomers could see above, below, around and through an exploded star based on observational data[3].

The insight into the structure of Cas A gained from this 3D visualisation is important for astronomers who build models of supernova explosions. The 3D visualisations tell them that the outer layers of the star come off spherically, but the inner layers come out in a more disc-like manner with high-velocity jets in multiple directions. Since the Delaney et al. (2010) study, two other groups have constructed 3D models of Cas A (Milisavljevic and Fesen, 2015; Orlando et al., 2016), demonstrating the high scientific value of such visualisations for astronomers.

While data-based 3D visualisations can be beneficial to expert populations, it is also recognised that there is much potential for non-experts to work with 3D models. The Cas A project is an excellent example of this and shows what can happen when “next steps” are taken. In the case of Cas A, it stands out as the first supernova remnant to be prepared and generated in a 3D printing.

***Figure 2.*** *3D print of Cassiopeia A. Credit: NASA/CXC/SAO*

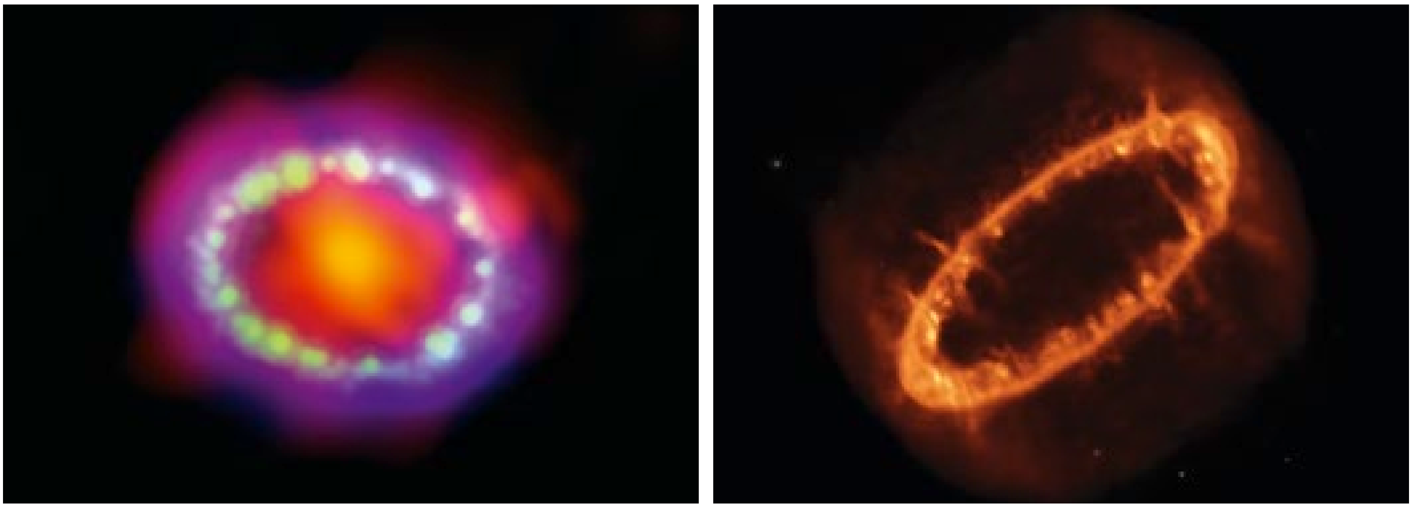

***Figure 3.** Left: Multiwavelength 2D view of supernova SN1987A. Credit: NASA/CXC/SAO/PSU/K. Frank et al. (X-Ray); NASA/STScI (Optical); ESO/NAOJ/NRAO/ALMA (Millimetre). Right: This visualisation is based on a 3D simulation published by Salvatore Orlando and collaborators that incorporates the physics of SN 1987A, based on* Chandra *X-ray data. The simulations show how the shape of the X-ray structure and the amount of X-rays observed at different wavelengths evolve with time[7]. Simulation Credit: Salvatore Orlando (INAF – Osservatorio Astronomico di Palermo). Visualisation Credit: NASA, ESA, & F. Summers, G. Bacon (STScI)*

Collaborating with Smithsonian specialists in 3D scanning and printing[4], CXC generated the first ever 3D print of a supernova remnant (Figure 2) in 2013. Today, Cas A in 3D is freely available as a 3D print-ready model with supports (600 k triangle OBJ file at 27 MB)[5] and in volumetric data form (ASCII VTK files created from telescope data at 3.94 MB) for use with any 3D printer and proprietary software.

Research groups have shown that non-expert populations can benefit from such 3D-printed models, including students (Rennie, 2014) and populations with visual impairments (Grice et al., 2015 & Christian et al., 2015). To date, the Cas A 3D model has been printed and shared directly by CXC with numerous schools in the USA, libraries, Maker Spaces, STEM programmes such as Girls Who Code and Girls Get Math, groups of blind and visually impaired persons, members of the Smithsonian Astrophysical Observatory Advisory Board, the secretary of the Smithsonian, and politicians such as U.S. Senators Harry Reid and Jack Reed, among many others.

## 30 years of Supernova 1987A

In 2017, the CXC released another 3D model to help commemorate the 30th anniversary of the discovery of supernova SN 1987A. This model is primarily made from simulation data, but is constrained by X-ray observations and was also successfully 3D printed (Figure 4). The visualisation — the static image of the final epoch shown in Figure 3 — depicts SN 1987A and the evolution of the resulting supernova remnant up to the present day, beginning by showing the progenitor star surrounded by a ring of gas produced late in the life of the star. A flash of light depicts the supernova explosion, and is followed by expansion of the subsequent blast wave. The blast wave then collides with the ring of gas, causing high-density knots of material to become hotter and brighter, and lower-density gas to be blown outward. One frame is shown per year and the visualisation steps between them at four years per second. Upon reaching the present day (February 2017), the time development is halted, and the camera circles around the ring to show its structure[6]. With the skewed perspective we have of this system from our vantage point on Earth, understanding SN 1987A's inner structure is much more difficult without such a 3D representation.

To print the 3D representation, CXC created three STL files for this object: the Ring Debris 2017 (the final epoch from the visualisation); the Ring 2017; and a file that combines both objects. For the silver 3D

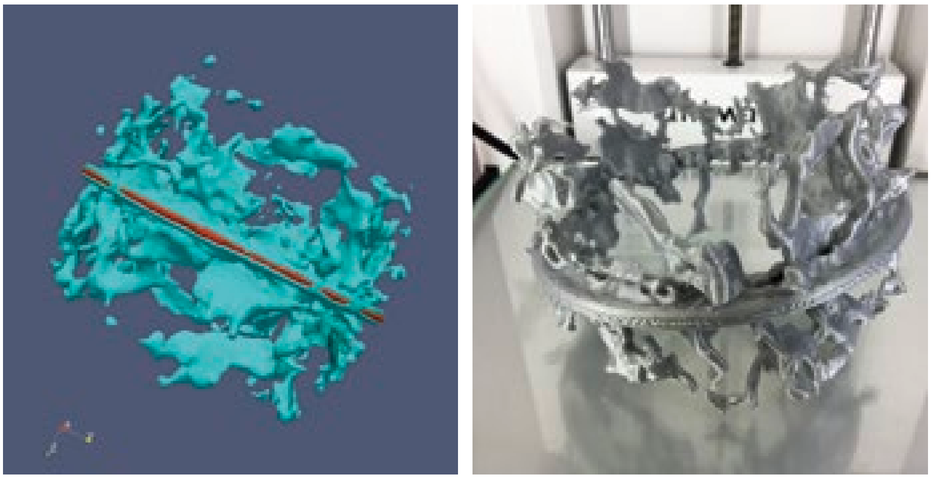

***Figure 4.** This 3D file (shown in two colours on the left) was translated into a 3D print (shown in one colour on the right), depicting the SN 1987A supernova remnant at its current observed age of 30 years based on 3D simulations by Orlando et al., and constrained by X-ray observations. Simulation Credit: Salvatore Orlando (INAF – Observatorio Astronomico di Palermo). 3D print Credit: NASA/CXC/A. Jubett et al.*

print version (Figure 4, right), dissolvable support structures were used, and the photo shows the model after the support structures were dissolved. Using the Ultimaker 3 printer with dissolvable supports at 0.1 mm resolution this model took about forty hours to print. Figure 4 (left) shows the 3D model of SN 1987A. Small blobs of gas, visible on the left, that were disconnected from other blobs or from the ring (floating free in space) were removed before production using 3D animation software for ease of printing, and noted accordingly on the website. Figure 4 shows two different colours for the ring versus the debris which can also be printed in a two-colour format on 3D printers such as the Ultimaker 3 that have dual extruders — the nozzles in the printer through which the material is deposited to create the print.

## Eta Carinae & Pillars of Creation: shaping our view

We have found so far that one size does not fit all when it comes to creating 3D models and 3D prints of astronomical phenomena. We therefore briefly touch upon 3D prints of other object types using different techniques and data sets to help present a more balanced perspective of 3D printing in astronomy.

Researchers working with *Hubble Space Telescope* data have developed models of areas of stellar birth (the Eagle Nebula, or “Pillars of Creation”) (Figure 5) and stellar aging (Eta Carinae and the Homunculus Nebula) (Figure 6). In both cases, scientists combined high-resolution spectroscopic data from the European Southern Observatory’s (ESO) Very Large Telescope (VLT) with *Hubble’s* views to reach a deeper understanding of the 3D environment of these objects.

Astronomers have found that the famous Pillars of Creation (Figure 5) are separated from each other in space — the tip of the largest pillar is pointing toward us, while the other pillars are pointing away from us (McLeod et al., 2015). Owing to this orientation, and the intense bombardment from nearby young stars, the tip of the tallest pillar appears brighter. The 3D plot (Figure 5, lower) shows the separation and orientation of the pillars, further adding to and expanding upon the information quotient of the 2D image.

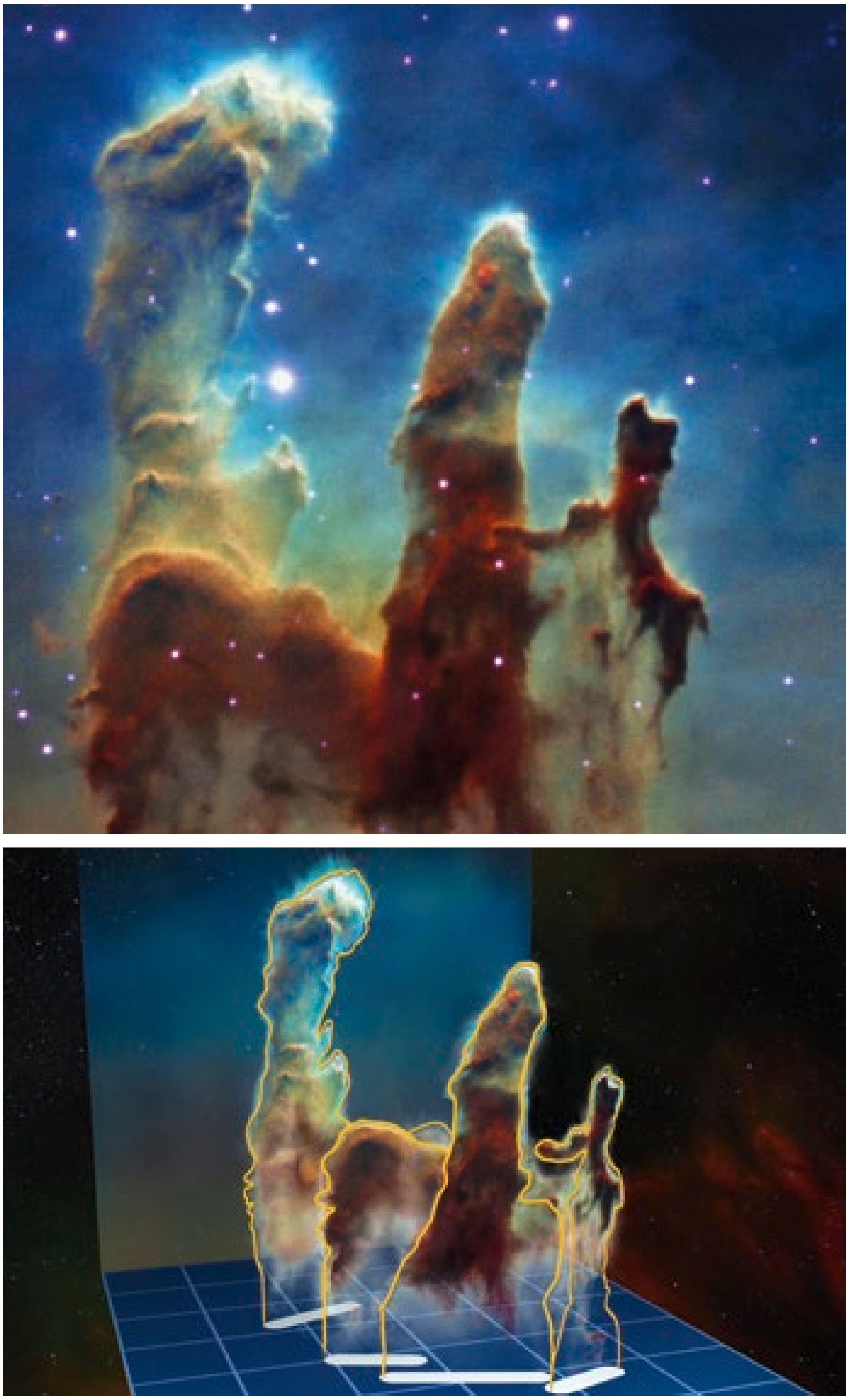

***Figure 5.*** *Upper: 2D Optical image of Eagle Nebula/Pillars of Creation from the Very Large Telescope. Lower: The Pillars plotted in 3D. Credit: ESO*

In the case of Eta Carinae, scientists mapped the shape of the bipolar bubble, known as the Homunculus nebula, surrounding the star (Figure 6). Using 3D modelling software designed for astronomy called SHAPE[8], researchers built a printable 3D model of the Homunculus nebula (Steffen et al., 2014). Additionally, further 3D modelling of the Eta Carinae system has been done on much smaller

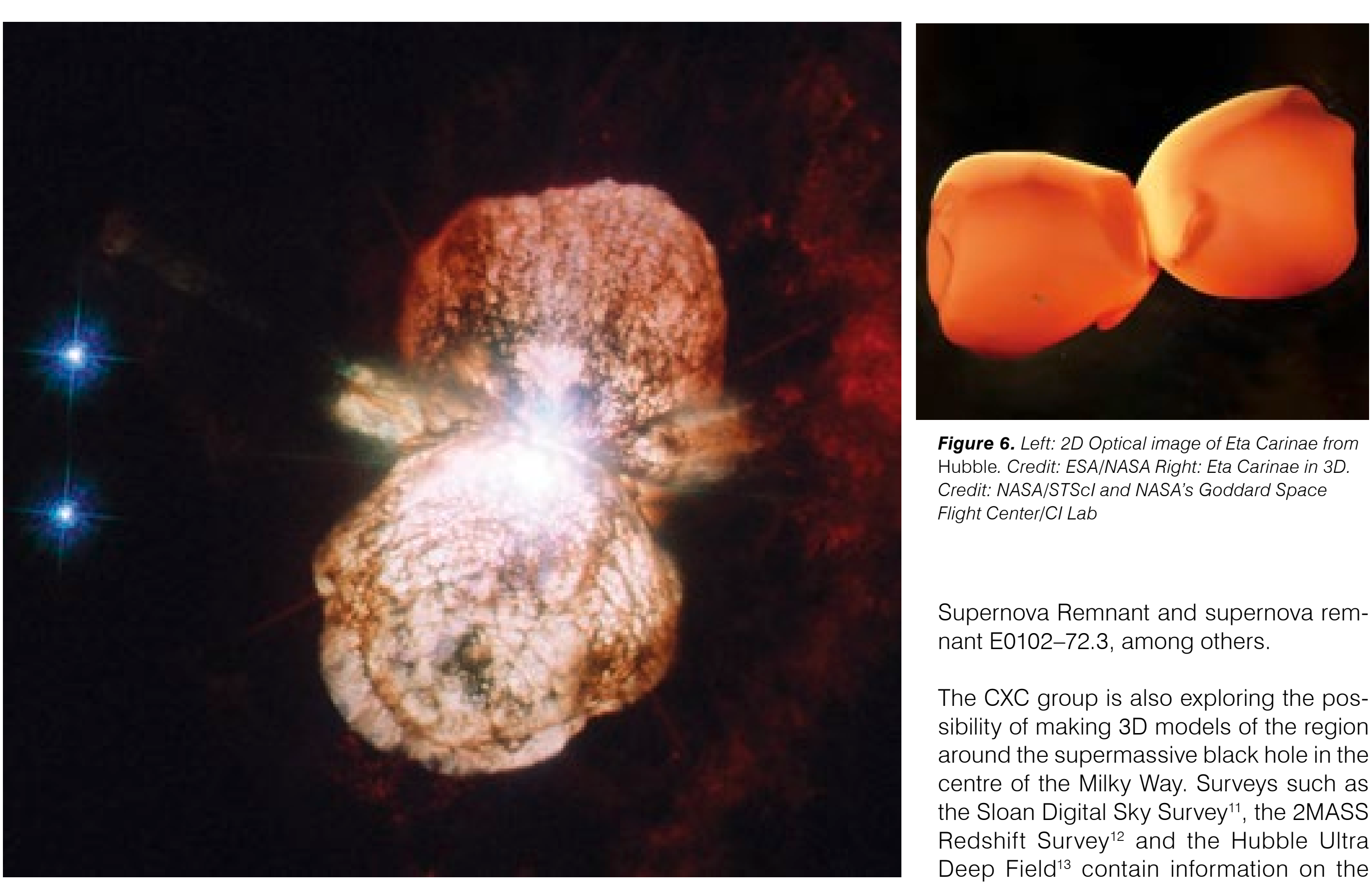

**Figure 6.** *Left: 2D Optical image of Eta Carinae from* Hubble*. Credit: ESA/NASA Right: Eta Carinae in 3D. Credit: NASA/STScI and NASA's Goddard Space Flight Center/CI Lab*

scales, close to the binary in the central region[9]. Such modelling helps to better show the multiple dimensions of this system, something that 2D images cannot individually do, particularly when the object's perspective in relation to observatories on or around Earth is so skewed.

## Cosmic microwave background: touching temperature

A recent paper (Clements, Sato & Portela Fonseca, 2016) describing a 3D model of the Cosmic Microwave Background (CMB) demonstrates astronomical 3D printing on perhaps the grandest scale, as people can now hold the observable Universe (in a much scaled-down size, of course) in their hands. While the CMB is typically shown in a 2D projection map, astronomers have struggled to visualise it effectively in three dimensions. Projecting this map onto a sphere and mapping the temperature fluctuations to bumps and dips within the sphere proved to be effective in creating a model of the CMB that can be printed and explored through touch (Figure 7).

## Next steps for 3D printing astronomical data

Though the amount of astronomical data extended to the third dimension remains limited, the collection is growing. NASA's 3D resource website[10] maintains a database of more local 3D objects such as the Moon and Mars (as well as many spacecraft models).

Certain types of celestial objects may lend themselves more naturally to obtaining, visualising and printing 3D data than others. For example, astronomers may be able to gather velocity data on supernova remnants other than Cas A using *Chandra* and other high-resolution telescopes, as well as data on other types of novae. Supernova remnants that are well studied often have the benefit of being relatively close by (in the Milky Way or a nearby satellite galaxy), and/or have been highly studied by many telescopes, so there is a larger source of multiwavelength data to work from. The CXC team and other researchers are currently investigating some of these sources, including Tycho's Supernova Remnant and supernova remnant E0102–72.3, among others.

The CXC group is also exploring the possibility of making 3D models of the region around the supermassive black hole in the centre of the Milky Way. Surveys such as the Sloan Digital Sky Survey[11], the 2MASS Redshift Survey[12] and the Hubble Ultra Deep Field[13] contain information on the distance to objects, so astronomers can generate maps of galaxies and larger-scale structures in three dimensions. We are not aware of any 3D printing of objects from these surveys yet.

## Practical tips and challenges of 3D printing cosmic objects

### File formats

When delving into the world of 3D printing, one will encounter a handful of file formats, which might seem inconsistent. Most 3D printers can print directly from OBJ and STL files, and each printer has its own unique set of acceptable formats. Some OBJ files can be stubborn, depending on the number of polygons in the model and other factors. OBJ is a bit more versatile, however, being commonly accepted to import into/export from multiple 3D software packages such as the Autodesk 3D design programmes Maya[14], 3D Studio Max[15] and AutoCAD[16], as well as OpenSource programs like MeshLab[17] and Paraview[18]. There are several software packages that can convert other file formats into STL or OBJ. MeshLab can handle several differ-

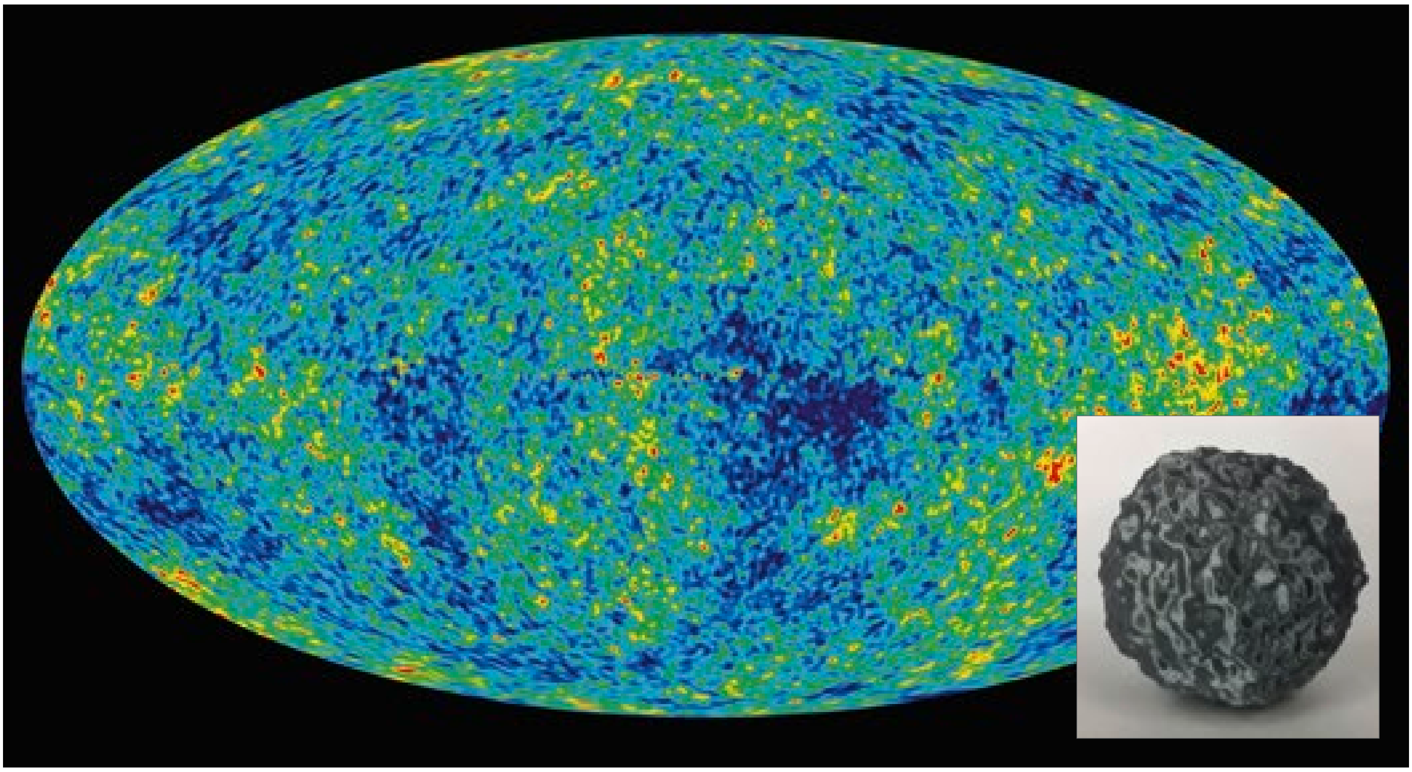

***Figure 7.*** *A typical Mollewide projection of the CMB. Inset: A 3D print of the data mapped to a sphere. Credit: NASA/WMAP Science Team*

ent formats, including COLLADA (or DAE) files and PLY files derived from 3D scanners. Using Paraview, one can readily import VTK data files, which are commonly used by astronomers visualising data sets. With a bit of a learning curve and a few filters, one can visualise these data sets in Paraview as mesh objects and save the data as STL.

There are also some proprietary file extensions, including X3G and THING files, which are used by Makerbot software and printers. FBX is owned by Autodesk and can be converted by several Autodesk programs. Other Autodesk proprietary extensions are 3DS (3D Studio Max) and MB or MA (Maya Binary or ASCII files). Various CAD (computer aided design) programmes use DWG or DXF, which can typically be converted to other formats accepted by most 3D printers. PLY and DAE files often need to be converted in a 3D design programme as well. Conversions between format extensions can take a bit of research depending on the available software and the make and model of printer being used. Fortunately, there is a wealth of information available, and as 3D printer technology evolves, more of the once-obscure file formats are becoming more mainstream.

Some printers and 3D printing services can also accept colour data as WRL or VRML files. These provide colour information for the models which can be handled by some printers or when outsourcing to 3D printing services. A current goal for the Cas A 3D model, for example, is to 3D print a version with the separate elements (silicon, iron, etc.) marked by colour, as seen in the original 3D visualisation in Figure 1.

## Structures

As with any new technology, there are unique challenges and limitations associated with creating successful 3D prints. This is especially apparent with the often complicated structures of astronomical objects. When using the FDM method of 3D printing, great care must be taken in creating the 3D model to ensure that all parts of the model are connected in ways that will be self-supporting in printed form. For example, a nebula with many interconnected and free floating knots of gas may fall apart when printed. Where applicable, the model might need to be simplified to allow for printing.

Additionally, one must be aware of large overhangs where additional support structures will be required for the print to be successful (Figure 8). These structures, though useful and often necessary, cause longer print times and use up more filament than simpler models. The supports must be carefully removed with needlenose pliers and other similar finishing tools in post-processing of the print.

Alternatively, next-generation, dual-extrusion 3D printers are now capable of printing complicated objects with a dissolvable, water-soluble support structure which eliminates the need for time-consuming and potentially damaging removal of supports. Using newer, possibly more expensive, printers could result in limited dissemination of 3D-printed objects, however, and more difficulty for the end user. Many schools and libraries, for example, are likely printing on basic FDM models from Makerbot or similar companies, which offer affordable access to 3D printing technology but might have difficulty printing more complicated models. Care should be taken to know your audience and the type of equipment that they might have access to when creating and disseminating the 3D files.

***Figure 8.*** *3D print of Cassiopeia A before support removal. Credit: NASA/CXC/SAO*

## Conclusion

Astronomy communicators are in a strong position to take advantage of the recent and ongoing advancements in 3D modelling and printing, as well as immersive 3D environments such as Virtual Reality Modelling Language labs. As the costs of such efforts go down, the possibilities increase. In addition to enabling expert populations to have new views and therefore a new understanding of their data sets, non-expert populations can also benefit from 3D models and prints, including students and visually impaired participants. By taking astronomical images from two into three dimensions and placing 3D models and prints directly in the hands of both experts and non-experts, we can expand information access to a whole new medium, and sense.

## Notes

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[2] The Astronomical Medicine project: https://www.cfa.harvard.edu/~agoodman/newweb/3dpdfNews.html

[3] Cas A 3D Model: http://chandra.si.edu/photo/2009/casa2/

[4] Smithsonian 3D model: https://legacy.3d.si.edu/explorer?modelid=45

[5] Printable Cas A 3D Model: http://chandra.si.edu/3dprint

[6] SN1987a animation: http://chandra.si.edu/photo/2017/sn1987a/animations.html

[7] Visualisation and simulation of SN 1987A https://arxiv.org/abs/1508.02275 & http://chandra.si.edu/deadstar/sn1987a.html

[8] SHAPE: http://www.astrosen.unam.mx/shape/v4/whyshape.html

[9] Eta Carinae in 3D: https://www.nasa.gov/content/goddard/astronomers-bring-the-third-dimension-to-a-doomed-stars-outburst and https://www.nasa.gov/content/goddard/nasa-observatories-take-an-unprecedented-look-into-superstar-eta-carinae

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[11] Sloan Digital Sky Survey: http://www.sdss.org/science/

[12] 2MASS Redshift Survey: https://www.cfa.harvard.edu/~dfabricant/huchra/2mass/

[13] Hubble Ultra Deep Field: https://www.youtube.com/watch?v=oAVjF_7ensg

[14] Autodesk 3D design programme Maya: https://www.autodesk.co.uk/products/maya/overview

[15] Autodesk 3D design programme 3D Studio Max: https://www.autodesk.co.uk/products/3ds-max/overview

[16] Autodesk 3D design programme AutoCAD: https://www.autodesk.com/solutions/3d-cad-software

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