



ADVANCED DATA VISUALIZATION IN ASTROPHYSICS: THE X3D PATHWAY

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ABSTRACT

Most modern astrophysical data sets are multi-dimensional; a characteristic that can nowadays generally be conserved and exploited scientifically during the data reduction/simulation and analysis cascades. However, the same multi-dimensional data sets are systematically cropped, sliced, and/or projected to printable two-dimensional diagrams at the publication stage. In this article, we introduce the concept of the “X3D pathway” as a mean of simplifying and easing the access to data visualization and publication via three-dimensional (3D) diagrams. The X3D pathway exploits the facts that (1) the X3D 3D file format lies at the center of a product tree that includes interactive HTML documents, 3D printing, and high-end animations, and (2) all high-impact-factor and peer-reviewed journals in astrophysics are now published (some exclusively) online. We argue that the X3D standard is an ideal vector for sharing multi-dimensional data sets because it provides direct access to a range of different data visualization techniques, is fully open source, and is a well-defined standard from the International Organization for Standardization. Unlike other earlier propositions to publish multi-dimensional data sets via 3D diagrams, the X3D pathway is not tied to specific software (prone to rapid and unexpected evolution), but instead is compatible with a range of open-source software already in use by our community. The interactive HTML branch of the X3D pathway is also actively supported by leading peer-reviewed journals in the field of astrophysics. Finally, this article provides interested readers with a detailed set of practical astrophysical examples designed to act as a stepping stone toward the implementation of the X3D pathway for any other data set.

Key words: methods: data analysis – publications, bibliography – standards – techniques: miscellaneous

Supporting material: interactive figures

1. INTRODUCTION

A large majority of data sets in modern astrophysics, whether observational or theoretical, are multi-dimensional with a number of dimensions $n > 2$. The multi-dimensionality of a data set can be intrinsic: for example, the (reduced) three-dimensional (3D) data cubes acquired by integral field spectrographs. Alternatively, the multi-dimensionality of a data set can be the result of the combination of several subsets of data, for example, when looking at the fundamental plane formed by elliptical galaxies (Springob et al. 2012). Understanding and characterizing the structure and content of these complex data sets across all of their dimensions holds the key to improving our understanding of the physics at play in the universe.

The computing power nowadays accessible to astronomers usually allows multi-dimensional data sets to be handled as such throughout the entire data reduction/simulation and analysis cascades. At the result publication stage, however, multi-dimensional data sets are systematically sliced, compressed, and/or projected: a “habit” largely driven by historical reasons. As dedicated scientific journals were physically printed on papers, it was a *physical requirement* for scientific diagrams (used as a mean of illustrating the content of complex data sets) to be printable.

Forcing a multi-dimensional data set on a two-dimensional (2D) diagram usually implies a loss of information. Such a loss of information is certainly not always detrimental, as it can help emphasize certain elements of interest in the data. In a growing number of cases, however, the need to understand the full multi-dimensional structure of the data—and our ability as scientists to share such structures with the community—is

directly and evidently affected by the current lack of suitable alternatives to the classical 2D *printable diagrams*.

The exploration of alternative techniques for data visualization is not only warranted by the existing difficulties associated with sharing multi-dimensional data sets in a clear, concise, and meaningful way, but also by the data “deluge” triggered by the most recent or forthcoming astronomy facilities. For example, data products from the *Low-frequency Array for Radio Astronomy* or the *Square Kilometre Array (SKA)* by 2020 cannot be easily handled with current computing power and technologies. Visualizing and sharing such complex (and large) data sets with the community will inevitably require innovative solutions.

All major scientific journals dedicated to astrophysical sciences are now published online. Some, like the *American Astronomical Society journals*⁴ (AAS journals), have in fact abandoned the physically printed form altogether. It has also become usual for articles submitted to peer-reviewed publications to be uploaded to the *arXiv* online pre-print server. The emergence of *supplementary online material*, such as extensive data tables, is possibly the prime example of the benefits that have resulted (so far) from the implementation of electronic journals. New initiatives such as that of *Research Objects*⁵ aim at further exploiting online technologies to group more strongly scientific articles with their associated data sets, tools, workflows, and methodologies (e.g., Hettne et al. 2012, 2013) in

⁴ The AAS journals include (at the time of submission of this article) the *Astrophysical Journal* (ApJ), the *Astrophysical Journal Letters* (ApJL), the *Astrophysical Journal Supplement* (ApJS), and the *Astronomical Journal* (AJ) <http://www.researchobject.org>

order to improve their identification, legacy, and re-usability (see also Goodman et al. 2015).

Given a largely electronic publishing landscape, one may wonder why no well-established alternative(s) to the classical 2D printable diagrams exist at this time. The problem of sharing and publishing multi-dimensional data sets has of course been identified in the past. Besides movies and animations, several alternative solutions have been discussed in recent years in the field of astrophysics, including interactive PDF documents (Barnes & Fluke 2008), stereo pairs (Vogt & Wagner 2012), augmented reality (Vogt & Shingles 2013), 3D printing (Steffen et al. 2014; Vogt et al. 2014; Madura et al. 2015) and interactive HTML documents (Vogt et al. 2014). However, most of these propositions suffer from two distinct and equally severe flaws that hinder their expansion in the field of astrophysics.

First, these techniques have been largely associated with specific software, some of which are not open-source. In the case of the interactive PDF approach, Barnes & Fluke (2008) suggested the `s2plot` software (Barnes et al. 2006) for generating 3D models, and relied on the commercial ADOBE ACROBAT PROFESSIONAL software for the conversation of the model to the U3D file format: the only 3D file format suitable for the inclusion of interactive 3D models in PDF documents. Relying on specific software restricts the *freedom of choice* of the user, and often impedes one’s ability to experiment with these new techniques. Software is also subject to very rapid changes and evolution, so that specific tools can become obsolete unexpectedly rapidly. In the case of interactive PDFs for example, ADOBE ACROBAT PROFESSIONAL stopped supporting the inclusion of U3D files in interactive documents in v10; a task that was then relegated to third party software.

Second, the degree to which these different methods are supported by the principal scientific journals in the field of astrophysics varies widely, and no technique is currently “actively” supported and encouraged by all journals. The different visualization techniques mentioned above are therefore often regarded as *experimental*. The need for specific software to implement these different solutions certainly also reinforces this impression.

The present article introduces the concept of the “X3D pathway” as a new approach to visualizing, sharing, and publishing multi-dimensional data sets that solves the above mentioned issues. Specifically, the X3D pathway suggests the utilization of the X3D file format as a centralized mean of implementing advanced visualization solutions via 3D diagrams for astrophysical multi-dimensional data sets.

The primary goals of this article are (1) to further demystify the use of advanced visualization techniques in the field of astrophysics, (2) to introduce the X3D pathway as a viable and polyvalent approach to advanced multi-dimensional data visualization, and (3) to provide a full set of dedicated astrophysical examples (including complete scripts, data sets, and step-by-step instructions) to enable interested readers to familiarize themselves and implement the X3D pathway rapidly and easily with their own data sets.

This article is structured as follows. The notion of the X3D pathway is introduced in Section 2 and example implementations are presented in Section 3. The demonstration data sets are described in Section 3.1. Each branch of the X3D pathway is then discussed individually, including the creation of X3D models in Section 3.2, the creation of interactive HTML

documents in Section 3.3, the connection of X3D to 3D printing in Section 3.4, and the creation of high quality movies and animations in Section 3.5. We present our conclusions in Section 4. All uniform resource locators provided in this article are valid as of the date of submission. Wherever available, digital object identifiers (DOI) are quoted instead.

2. THE X3D PATHWAY

The X3D (Extensible 3D) file format is an International Organization for Standardization (ISO) ratified standard developed and maintained by the Web3D Consortium.⁶ A detailed description of this file format is provided by Daly & Brutzman (2007), to which we refer the interested reader for further information. Repeating verbatim the description provided by the Web3D Consortium, “X3D is a royalty-free open standards file format and run-time architecture to represent and communicate 3D scenes and objects using XML.” The X3D file format has evolved from the Virtual Reality Modeling Language (VRML) format, with the intent to become the standard file format for the publication of 3D graphics on the World Wide Web. While the X3D standard is still evolving, backwards compatibility of the file format is a key objective pursued by the Web3D Consortium (Daly & Brutzman 2007). The Web3D Consortium has also established connection with the World Wide Web Consortium⁷ and other partners⁸ to ensure the compatibility of the X3D file format with the evolving World Wide Web.

The X3D file format uses a rectangular, right-handed coordinate system. It supports (among other elements) polygonal and parametric geometry, with data points and meshes represented via solid shapes and surfaces. The X3D standard also supports the inclusion of 2D text in 3D space, useful for annotating models, as well as lighting elements and materials. Volumetric rendering (with an emphasis on human anatomy representation) is being developed by the *Medical Working Group for X3D*⁹, with dedicated (and still limited) specifications included in *ISO X3D v3.3*. Several quality assurance tools developed alongside the X3D standard itself, for example *X3D-EDIT*¹⁰ or the online *X3D VALIDATOR*,¹¹ allow one to easily inspect X3D files to ensure they contain no syntax errors and follow the X3D file format conventions.

The underlying idea of the X3D pathway is that the X3D file format lies at the core of different visualization solutions for multi-dimensional data sets via 3D diagrams, including interactive HTML documents, 3D printing, and high-end movies and animations. A schematic guide to the implementation of these advanced visualization techniques (via the X3D standard) for multi-dimensional data sets is presented in Figure 1. The links forming the X3D pathway are marked with thick orange connections.

The X3D pathway is not software-dependant. The specific software connecting each node of the pathway are existing and working solutions that we believe are currently the most suitable for astronomers with no prior experience in 3D data

⁶ <http://www.web3d.org>

⁷ W3C; <http://www.w3.org/>

⁸ <http://www.web3d.org/about/liaisons>

⁹ <http://www.web3d.org/working-groups/medical>

¹⁰ <https://savage.nps.edu/X3D-Edit>

¹¹ <https://savage.nps.edu/X3dValidator>

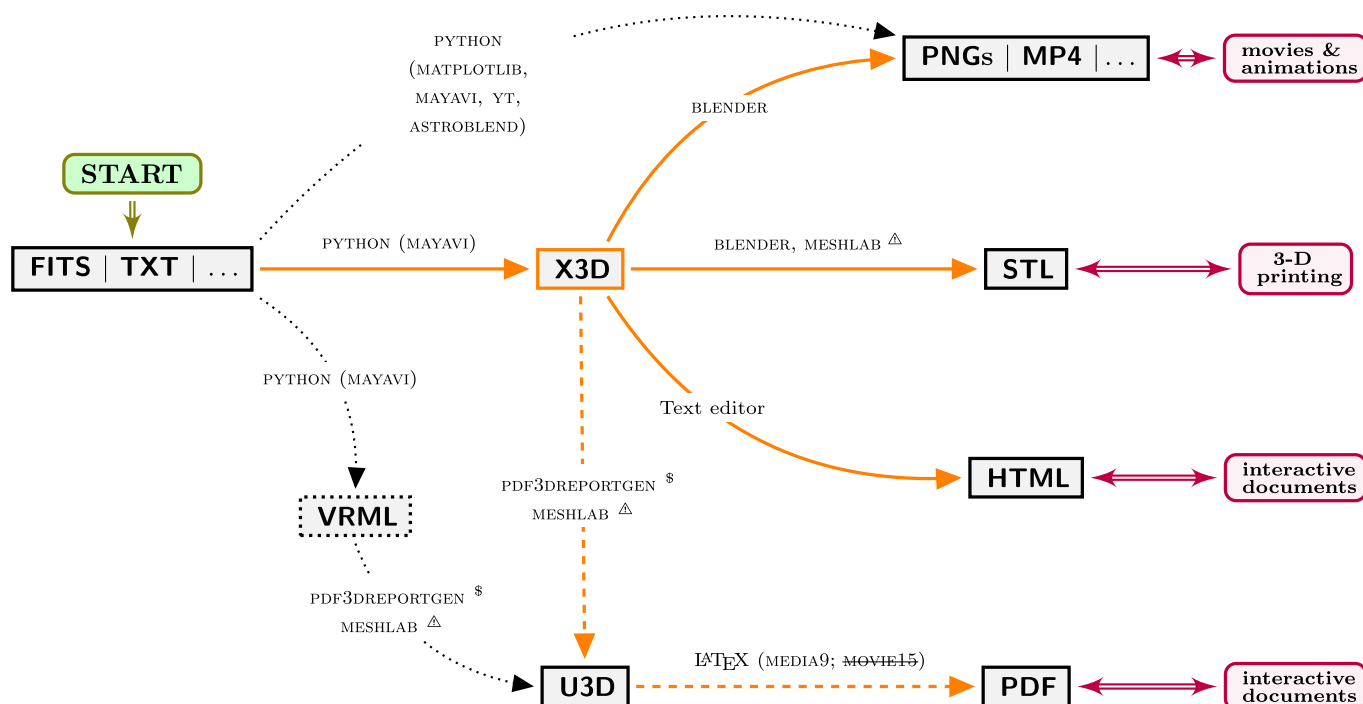


Figure 1. Schematic of the X3D pathway, illustrating the routes leading to the creation of different advanced visualization techniques. The X3D file format forms the core of a product tree (thick orange arrows) that includes (but is not limited to) interactive HTML documents, 3D printing, and high-end animations and movies. The X3D file format can also lead to interactive PDF documents via a conversion to the specific and dedicated U3D file format, which uniquely serves that purpose. This “X3D to PDF” branch is marked with dashed arrows, as it (currently) requires either commercial software (marked with $\$$) or open-source software with significant limitations (marked with Δ). The X3D pathway is based on file formats, and software links in the diagram only list our (current) personal favored solutions discussed in this article. Dotted arrows illustrate the alternative route to the creation of interactive PDF model implemented by Vogt et al. (2015), as well as a more direct (and usual) route to the creation of movies and animations by-passing the X3D file format.

visualization, and for which we provide dedicated examples as supplementary material to this article. However, a wide range of software compatible with the X3D pathway exists, some intrinsically more complex and/or non-open source, but possibly more capable and/or familiar to specific users. Specific alternatives will be mentioned in Sections 3.2–3.5.

Rather than specific software, the X3D pathway is centered on file formats—and, in particular, on the X3D file format. Although file formats are not immune to change and evolution, such changes can be expected to be gradual and slow in comparison to the evolutions of associated software. In fact, relying on file formats rather than specific software not only ensures the long-term stability of the X3D pathway, but also does not restrict the existing (or future) *freedom of choice* of astronomers to implement it. The X3D standard also brings the important features of *re-usability* and *lasting legacy* of the material, as backward compatibility is a key element of the X3D file format set by the Web3D consortium. Finally, the X3D standard is fully open source, a fact which acts as a guarantee that we (as a community) are able to directly influence its evolution to match our needs; for example via the hypothetic creation of a new Web3D working group¹² dedicated to the promotion and development of new X3D specifications for the field of astronomy and astrophysics.

2.1. Interactive PDF and Interactive HTML Documents

Interactive PDF documents are a *reader-friendly* solution to sharing interactive 3D models with the scientific community

because they do not require readers to have access to costly commercial software.¹³ Interactive PDF articles have been used successfully by several authors in recent years in the field of astrophysics (see, e.g., Putman et al. 2012; Springob et al. 2012, 2014; Miki et al. 2014; Steffen et al. 2014; Madura et al. 2015; Vogt et al. 2015). Of course, one of the main advantages of interactive PDF documents (from a scientist’s perspective) is that interactive models can be embedded directly inside the PDF of an article, thereby ensuring their long-term accessibility. The pathway (as implemented by Vogt et al. 2015) leading to the U3D file required for the creation of an interactive PDF document is illustrated in Figure 1.

However, interactive PDF documents also have two distinct drawbacks. First, interactive PDF documents can (at the time of submission of this article) only be opened using ADOBE ACROBAT READER v9.0 or above, as other PDF reading software (such as Apple’s PREVIEW) will only display a still cover image. As such, interactive PDF documents very strongly restrict the freedom of choice of the reader. Second, the U3D file format is not straightforward to generate. For example, Vogt et al. (2015) used the commercial software PDF3DREPORTGEN. MESH LAB¹⁴ is an open-source alternative often cited as the solution to the creation of U3D files. In reality, MESH LAB (v1.3.3) is suitable for creating U3D files only under very specific circumstances because this software currently does not support semi-transparent layers, and is unable to conserve a complex model tree throughout the conversion process.

¹³ Interactive PDF documents can be opened using recent versions of ADOBE ACROBAT READER, freely available online: <https://get.adobe.com/reader/>

¹⁴ <http://meshlab.sourceforge.net/>

¹² <http://www.web3d.org/working-groups>

The idea of interactive HTML documents was recently used by Vogt et al. (2014) to publish an interactive model of a 3D emission line ratio diagram. Unlike interactive PDF documents, interactive HTML documents do not strongly restrict the user's freedom of choice (they are compatible with all major web browsers, see Section 3.3), and most importantly, the X3D file format (at the base of interactive HTML documents) can be freely created using open-source software (e.g., PYTHON). These publishing advantages are clear enough that the AAS journals are now actively supporting and promoting the use of interactive HTML documents to share multi-dimensional data sets, where Figure 1 in Vogt et al. (2014) was used as a proof-of-concept.¹⁵ Interactive 3D graphics are but one of a suite of plans for enhanced graphics and advances in publishing technology currently being discussed by the AAS journals.¹⁶

Although we believe that the intrinsic advantages of interactive HTML documents render them more suitable for the field of astrophysics than interactive PDF documents, we stress that these solutions are not mutually exclusive. Indeed, U3D files can be generated from X3D files (see Figure 1), so that interactive PDF documents in fact represent another branch of the X3D pathway tree. We shall not discuss interactive PDFs in detail in this article, because (1) their creation (using the MEDIA9 or the now obsolete MOVIE15 LATEX packages) and features have already been discussed by Barnes & Fluke (2008) and (2) to the best of our knowledge the creation of U3D files remains a difficult problem to which no real open-source solution currently exists (modulo MESHLAB under specific circumstances).

3. IMPLEMENTING THE X3D PATHWAY

In this section, we implement a practical demonstration of how the X3D pathway can be used to aid in the visualization and publication of complex, multi-dimensional data sets in astrophysics. Although the X3D pathway does not rely on specific software *per se*, software is certainly still required to exploit and implement it. Hence, this section is also intended as a means of providing complete and realistic scripts and step-by-step instructions to the interested reader. All of the scripts are available in a dedicated Github repository¹⁷, and for legacy purposes, a DOI was tied to the release v1.0 of the repository at the date of publication of this article (<http://dx.doi.org/10.5281/zenodo.45079>). We set our focus on two specific tools: the MAYAVI¹⁸ module in PYTHON (Ramachandran & Varoquaux 2011; used for the initial 3D plotting of multi-dimensional data sets and the export to the X3D file format) and BLENDER¹⁹ (for the creation of high-end movies and animations and 3D printable models).

The structure and content of the supplementary material to this article is described in detail in the Appendix. The different scripts and sets of instructions provided are not discussed in detail in the core of this article, as their description is not of direct importance to the concept of the X3D pathway itself. Furthermore, these scripts represent only one (among a few equivalent) ways to implement the X3D pathway, so that

describing specific examples in detail would unjustifiably emphasize specific software.

3.1. Demonstration Data Sets

3.1.1. Green and Red Dice

In order to provide a series of examples of increasing complexity, we first use two basic 3D structures: a green dice and a red dice. These models are designed with incremental complexity leading to the visualization of a datacube from the Very Large Array (VLA; see Section 3.1.2). Screenshots of both the green and red dice examples (as drawn inside the MAYAVI interactive plotting window) are presented in Figure 2.

The green dice is our most simple example. It illustrates the basic, minimal steps required to visualize multi-dimensional data interactively using MAYAVI, publish it using interactive HTML documents, and animate it using BLENDER. The red dice example contains a semi-transparent cube with two inner-spheres (white and yellow), some 3D text and a colorbar. This example was designed to hit some of the current limitations associated with creating X3D files using MAYAVI while keeping the actual 3D structure as simple as possible.

3.1.2. The H I Gas Content of HCG 91

Our realistic astrophysical example is based on the VLA observations of the H I gas distribution and kinematics around the galaxies inside the Hickson Compact Group (HCG) 91. The complexity of this VLA data set makes it a prime example to illustrate how advanced visualization techniques such as interactive HTML documents, 3D printing, and high-end animations (implemented via the X3D pathway) can help in visualizing, understanding, sharing, and publishing the structural content of the data. Visualizing the cold gas distribution in and around galaxies to trace their evolution is also one of the main scientific drivers of the SKA, and 3D diagrams can play an important role in the analysis of these data sets (see, e.g., Punzo et al. 2015).

HCG 91 is a group of four galaxies first cataloged by Hickson (1982) at a distance of ~ 100 Mpc in the constellation of Piscis Austrinus. The H I cold gas distribution and kinematics in this group, which is a prime tracer of ongoing gravitational interactions between its member galaxies and of the overall evolutionary stage of the group (e.g., Verdes-Montenegro et al. 2001), was observed by the VLA in New Mexico (P.I.: L. Verdes-Montenegro, P.Id.: AV0285) on 2005 October 5. This data set was used by Vogt et al. (2015) to characterize the evolutionary stage of the galaxy HCG 91c and will be analyzed in detail in L. Verdes-Montenegro et al. (2016, in preparation) to which we refer the reader for further details on the scientific implications of these observations. Here, we restrict ourselves to a generic description of the data, which is used as a realistic and representative example of multi-dimensional astrophysical data sets.

The datacube is in units of ([X]: arcsec; [Y]: arcsec; [v]: km s^{-1}). A subset of the complete VLA cube, spanning $10 \text{ arcmin} \times 10 \text{ arcmin} \times 972.4 \text{ km s}^{-1}$ and centered on HCG 91, is shown as a top-front-side projection triplet in Figure 3. Three semi-transparent and one opaque iso-contours are used to reveal the complex structure of the H I gas emission in this spatial-kinematic volume, alongside colored markers indicating the location of features of interest. In particular, the cyan line traces a tidal tail wrapping around the main group galaxy

¹⁵ DOI: <http://dx.doi.org/10.1088/0004-637X/793/2/127/data>

¹⁶ <http://aas.org/posts/news/2015/02/changes-ahead-aas-journals>

¹⁷ <https://github.com/fpavogt/x3d-pathway>

¹⁸ Throughout this article, when we refer to MAYAVI, we mean MAYAVI2, the second generation module developed and maintained by Enthought: <http://docs.entthought.com/mayavi/mayavi/>

¹⁹ <http://www.blender.org>

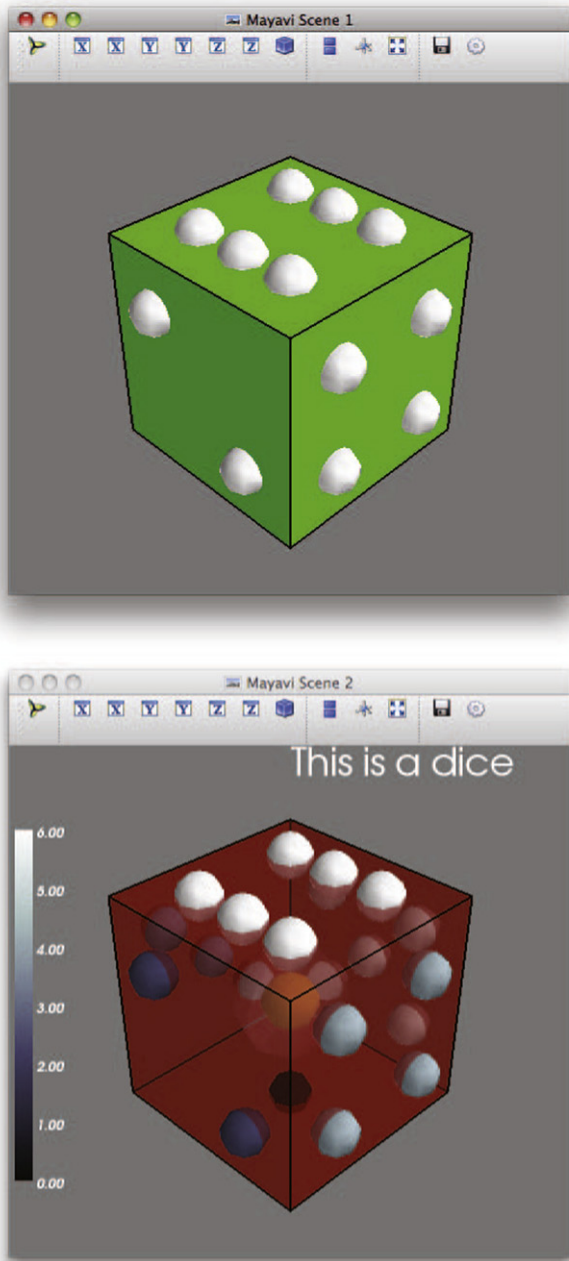


Figure 2. Green (top) and red (bottom) dice used to demonstrate how to implement the X3D pathway. These models complement the more realistic example of the VLA observations of the H I gas inside HCG 91 by providing two additional examples of incremental complexity. An interactive version of these diagrams is accessible online as an interactive HTML document.

HCG 91a (marked by a green sphere) with a velocity extent of $\sim 400 \text{ km s}^{-1}$.

3.2. Creating X3D Files

Many different software solutions exist to create X3D files given the central role that this data format is gaining on the World Wide Web scene for sharing 3D graphics.²⁰ Here, we

²⁰ See, e.g., <http://www.web3d.org/x3d/content/examples/X3dResources.html#Applications>

rely on the MAYAVI module in PYTHON (Ramachandran & Varoquaux 2011) for three reasons.

First, the PYTHON programming language has been steadily growing in popularity within the astrophysical community in recent years. A PYTHON solution to the problem of multi-dimensional data visualization will therefore be best suited to many astronomers. Second, MAYAVI offers a simple and rapid way to generate X3D files for non-experts with no a priori knowledge of the package. In particular, the MAYAVI syntax is extremely reminiscent of the popular MATPLOTLIB package (Hunter 2007) dedicated to the creation of 2D diagrams in PYTHON. Third, MAYAVI intrinsically provides an interactive view of the data set without the need to export it first. In other words, MAYAVI is perfect for allowing individual researchers to rapidly explore the content of a multi-dimensional data set interactively and assess the need for and eventual benefit of additional forms of 3D data visualization (e.g., in the form of interactive HTML documents) without having to implement them first. Detailed examples of the MAYAVI capabilities and associated syntax are accessible online²¹, to which we refer the interested reader for more information.

We do provide as supplementary material to this article the full PYTHON scripts used to generate the 3D models of the green dice, the red dice, and the H I datacube from the VLA (see the Appendix and <http://dx.doi.org/10.5281/zenodo.45079>). Figure 3 was generated using a slightly modified version of the latter script. We note that our examples do not explore the issue of mesh reduction or decimation, which may be required for specific models/structures before generating X3D files.

The ease of use of MAYAVI (and even more so for existing PYTHON users) is counter-balanced by specific drawbacks (e.g., the currently imperfect underlying VISUALIZATION TOOLKIT (VTK) X3D EXPORTER v0.9.1). Both the red dice and HCG 91 examples are specifically designed to hit the existing limitations of MAYAVI (see also Punzo et al. 2015), and offer possible solutions, including the creation of axes with ticks and labels, and/or the addition of a colorbar to the scene. The example scripts are clearly commented regarding these aspects, which we voluntarily do not discuss further in this article.

Punzo et al. (2015) presented a detailed comparison between MAYAVI and other software (PARAVIEW, 3DSLICER, and IMAGEVIS3D) with similar *visualization* capabilities (see also Taylor 2015, regarding FRELLED), but among these, only PARAVIEW²² (Ahrens et al. 2005) is able to export models to the X3D file format. The YT PROJECT (Turk et al. 2011) represents another open-source alternative to MAYAVI to create X3D models.

3.3. From X3D to Interactive HTML Documents

The most straightforward application for X3D files (because of their design driver) is their inclusion in HTML documents on the World Wide Web. This article is not the first time that the use of the X3D file format for that specific purpose has been advocated in the field of astrophysics. Fluke et al. (2009) already suggested the use of the X3D file format, in combination with a dedicated FLASH plugin, for visualizing data products from the S2PLOT software (Barnes et al. 2006). However, the need for a specialized FLASH plugin to access their interactive 3D models on the web, albeit open-source,

²¹ <http://docs.enthought.com/mayavi/mayavi/auto/examples.html>

²² <http://www.paraview.org>

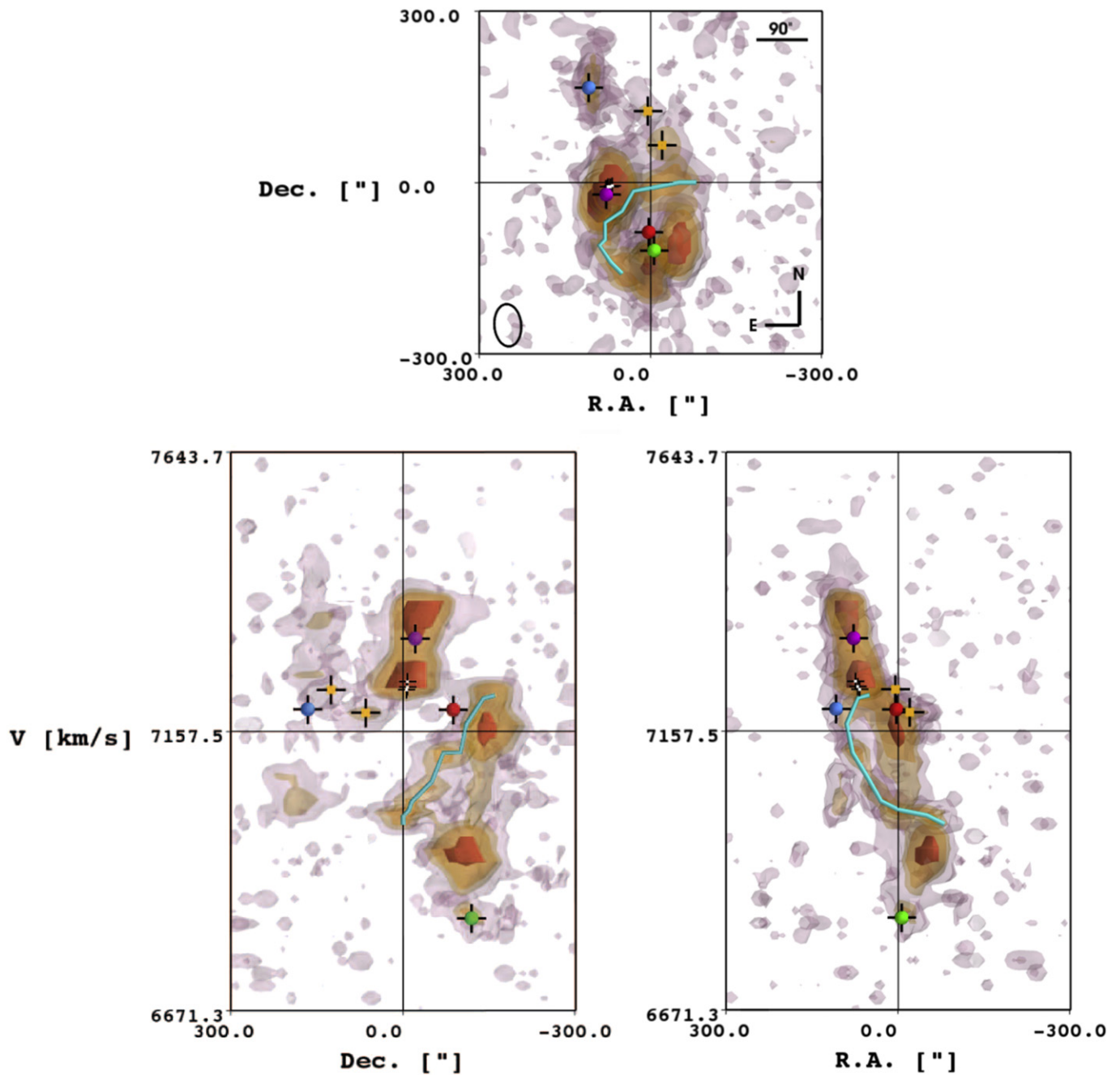


Figure 3. H I gas distribution and kinematics of the compact group of galaxies HCG 91 observed by the VLA. Individual intensity iso-contours at 1.3, 2.5, 3.5, and 6.0 mJy/beam are fitted in 3D inside the datacube before being projected along top-front-side projections. The innermost contour is fully opaque, while the others are set at 80% transparency to enable a *see-through* effect. The galaxies HCG 91a, b, c, and d are marked with green, blue, purple, and red spheres, respectively. A large tidal tail originating to the southeast of HCG 91a is traced inside the 3D cube with a cyan line, and other elements of interest are marked with white and yellow cubes (see Vogt et al. 2015 for details). In the top panel, the black ellipse traces the beam size and orientation associated with the VLA data. An interactive version of this figure is accessible online as an interactive HTML document.

remained a negative factor affecting the expansion of this technology.

Fortunately, as part of the X3D version 4.0, full HTML5 support using the x3DOM approach (Behr et al. 2009, 2010) is being implemented inside the X3D standard. In other words, interactive X3D models ought to be accessible directly (without the need for external plugins) by all web browsers in the near future. At the time of publication of this article, interactive 3D models placed within HTML pages using the x3DOM approach can already be loaded directly (without the need for any

external plugins) with up-to-date versions of the FIREFOX, CHROME, SAFARI, and INTERNET EXPLORER web browsers that are WebGL-enabled.²³

The interactive HTML counterparts to Figures 2 and 3 are available online. Software-wise, the creation of interactive HTML documents only requires a text editor to create the HTML script and a 3D model as an X3D file.

²³ A detailed and up-to-date web browser compatibility list with the x3DOM approach is available online: http://www.x3dom.org/?page_id=9.

We provide as supplementary material to this article a detailed walkthrough leading to the creation of the interactive HTML counterpart of Figures 2 and 3. The example HTML scripts also detail the creation of interaction buttons to set pre-defined views or display/hide specific data sets. Interaction buttons provide authors with an efficient tool to focus the reader’s attention on specific aspects of the interactive model without restricting the reader’s freedom to explore the content of the data set. In the case of the H I gas location and kinematics in HCG 91 for example, the ability to show and/or hide different iso-contours can provide readers with a less obstructed view of the most intense H I emission around each galaxy. We note that our example scripts are applicable for the inclusion of any X3D model inside an HTML document, irrespective of the software used for their creation.

3.4. From X3D to 3D Printing

The concept of 3D printing, formally known as additive manufacturing, has recently been suggested and used as a new way to share multi-dimensional data sets in astrophysics (Steffen et al. 2014; Vogt et al. 2014; Madura et al. 2015). The emergence and increasing availability of reliable 3D printers within universities and research institutes in recent years is facilitating researchers’ access to this technology, easing experimentation, and reducing the associated costs (both financially and time-wise).

Clearly, the concept of 3D printing in astrophysics is still in its infancy, and its future remains uncertain at this stage. The potential of 3D printing at a professional level has been explored and discussed by Madura et al. (2015), who found that the technique can help better understand the structural content of complex numerical simulations. Using the physical model of a 3D emission line ratio diagram created by Vogt et al. (2014), one of us also observed how 3D printed diagrams can promote and facilitate “live” interactions and discussions around a complex data set between researchers (e.g., in-group meetings).

At the time of submission of this article, the most evident use for 3D printing in astrophysics most certainly lies within outreach activities. 3D printed models provide a new pathway for researchers to share complex data sets and concepts with non-experts. Giving members of the general public the possibility of physically handling real astrophysical data sets enables them to use their kinaesthetic sense (and not solely their sight) to “visualize” astrophysical data sets in an unprecedented way. This diversification of senses used to “perceive” a given multi-dimensional data set can lead to an improved understanding of its structure and of its associated parameters. The efforts undertaken at the Space Telescope Science Institute toward sharing *Hubble* images of the universe with blind and vision-impaired members of the general public using 3D printing are also particularly noteworthy (Christian et al. 2014).

Whichever future awaits 3D printing technology in astrophysics, the X3D pathway already provides astronomers with an efficient way to create 3D printable models of 3D diagrams. As a well-supported and well-defined 3D data format, X3D models can be easily exported to specific file formats (e.g., STL) required by 3D printers and associated software. For example, the conversion of an X3D file to an STL file can be achieved easily using the open-source software MESHLAB. Unlike for the creation of U3D files, transparency information and complex model trees are not required to be conserved

inside STL files, so that MESHLAB offers a suitable solution in this case. For complex data sets, BLENDER offers a significantly better way to convert 3D diagrams from X3D to 3D printable models while allowing the addition of support structures to hold free-floating elements.

We have created a 3D printable version of the H I gas distribution and kinematics in the compact group of galaxies HCG 91. Two demonstration prints (with a final model size of [15 cm × 15 cm × 19 cm] and [7.5 cm × 7.5 cm × 9.5 cm], respectively) were performed on the Fortus 400mc printer at the Research School of Astronomy and Astrophysics at the Australian National University. The larger print, after dissolution of the temporary support structures and manual reproduction of the color scheme of the model, is presented in Figure 4. The corresponding STL file (compatible with most 3D printers currently available on the market) is included as supplementary material to this article, as well as the associated BLENDER file used for the X3D to STL conversion process.

3.5. From X3D to High-end Animations

Movies and animations have long been used in astrophysics to share the content of multi-dimensional data sets, where time is being added as an extra-dimension to a given 2D diagram. Generally speaking, movies consist of a series of still frames (e.g., PNGs) that are stacked together into an animation, for example, using the open-source and polyvalent FFMPEG software. Certainly, the creation of PNGs does not require the prior creation of an X3D model, and can be achieved either using 2D or 3D plotting solutions with direct export to still PNGs, as illustrated in Figure 1.

In this section, we specifically explore the possibility of implementing high-end animations of 3D diagrams exported as X3D models using BLENDER. BLENDER is a free, open-source, multi-platform (Windows, Mac, GNU/Linux) 3D graphics and animation software package.²⁴ The reader is referred to Kent (2013, 2015) for a thorough description of the software in the context of astrophysical data visualization.

BLENDER is implemented with a PYTHON 3 application programming interface (API), which includes a built-in terminal and text windows for internal scripting, and the ability to write and execute external scripts without invoking the BLENDER graphical user interface. This PYTHON API contains several major packages by default (e.g., NUMPY) and the ability to install additional external packages. For the large (and growing) fraction of astronomers already familiar with PYTHON, BLENDER can be thought of as a new external visualization package. BLENDER also supports the X3D file format by default.

As a dedicated open-source 3D creation suite software supporting “*modeling, rigging, animation, simulation, rendering, compositing, motion tracking, video editing and game creation*”²⁵, the number of options available for presentation and animation of X3D meshes in BLENDER is extremely large. The many capabilities of this software lie at the core of its steep learning curve, so that using BLENDER for the first time may appear to be a formidable task. To ease the process and facilitate the first-time use of BLENDER, we provide as supplementary material to this article annotated PYTHON scripts, which automatically import X3D files generated using MAYAVI (see Section 3.2) and produce high quality ready-to-render

²⁴ <http://www.blender.org>

²⁵ <http://www.blender.org/about/>

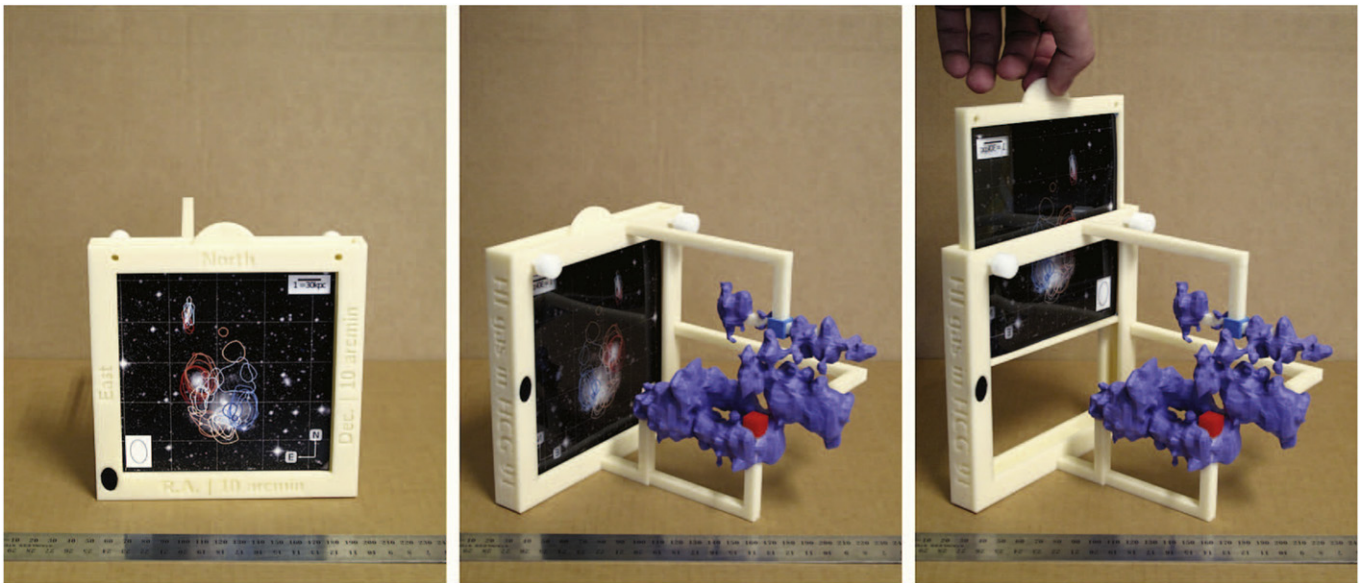


Figure 4. 3D printed model of the H I distribution and kinematics inside HCG 91 (at the 1.3 mJy/beam level). Cubes mark the position of the galaxies in the [X-Y-V] volume, and are colored according to Figure 3. The base plate contains a “sliding-rack” designed to hold an on-sky picture of the galaxy group, and augment the experience of the 3D print in allowing a direct comparison between the 2D projected diagram and the full 3D structure. Additional information (including the size and orientation of the VLA beam, visible as a black ellipse in the images) is also engraved in the base plate directly as part of the 3D printing process. The colors were added manually using acrylic paint, after dissolution of temporary support structures. For reference, the ruler at the bottom of the frames is in centimeters, and the model has a physical size of [15 cm × 15 cm × 19 cm].

animations. One final rendered movie frame is presented in Figure 5 for completeness.

We note that our example scripts only explore a very limited number of features of BLENDER. We include as supplementary material a second animation of the VLA datacube generated using a more complex version of the *HCG91_animation.py* script (available on demand) to illustrate some additional features of BLENDER. For more extensive examples and tutorials on how to use BLENDER with astrophysical data sets (including different ways to import the data and by-passing the X3D file format altogether), we refer the interested reader to the ASTROBLEND project.²⁶

4. CONCLUSIONS

Most data sets in modern astrophysics are multi-dimensional. However, despite a largely electronic publishing landscape, their visualization and publication in dedicated articles remain problematic. Here, we have introduced the concept of the X3D pathway as a new approach to the creation, visualization, and publication of 3D diagrams in scientific articles. The fact that the X3D open-source (and ISO standard) 3D file format lies at the center of an advanced data visualization product tree that includes interactive HTML documents, 3D printing, high-end animations (and possibly interactive PDF documents) forms the core of the X3D pathway.

The X3D pathway is designed to be “file format-dependant” rather than “software-dependant,” so that it is less prone to rapid and un-anticipated changes and evolution. In particular, although the X3D standard is not immune to any evolution, such evolution will always be slower than that of associated software. Backward compatibility is also a core characteristic of the X3D standard. We note that the evolution of the X3D standard can be directly influenced by official working groups. As such, the

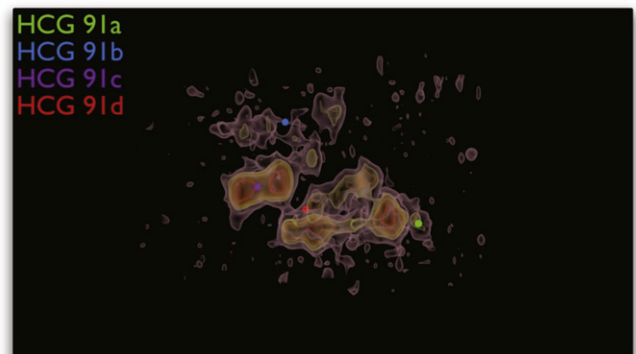


Figure 5. Final BLENDER rendered view of the H I iso-intensity contours in HCG 91 observed by the VLA (first exported to X3D using MAYAVI) generated using the PYTHON script provided as supplementary material to this article. An animation of this figure is available.

hypothetical creation of a dedicated *Astronomy and Astrophysics Web3D working group* to promote and develop new X3D specifications for our field appears to be an enticing idea.

The interactive HTML branch of the X3D pathway is actively supported by leading peer-reviewed journals within the field of astrophysics. From this perspective, we believe that the X3D pathway has already evolved beyond an “experimental” status. The future of the 3D printing branch remains to be defined at this stage, but the possibility of rapidly creating 3D printable models from existing X3D files ought to allow and facilitate additional experimentation with this technology. Finally, the X3D file format also provides “regular” astronomers with the means to implement scientifically accurate and visually compelling movies and animations to communicate the complex, multi-dimensional content of their data sets.

It has become increasingly evident that the large volume of modern multi-dimensional astrophysical data sets—either

²⁶ <http://www.astroblend.com>

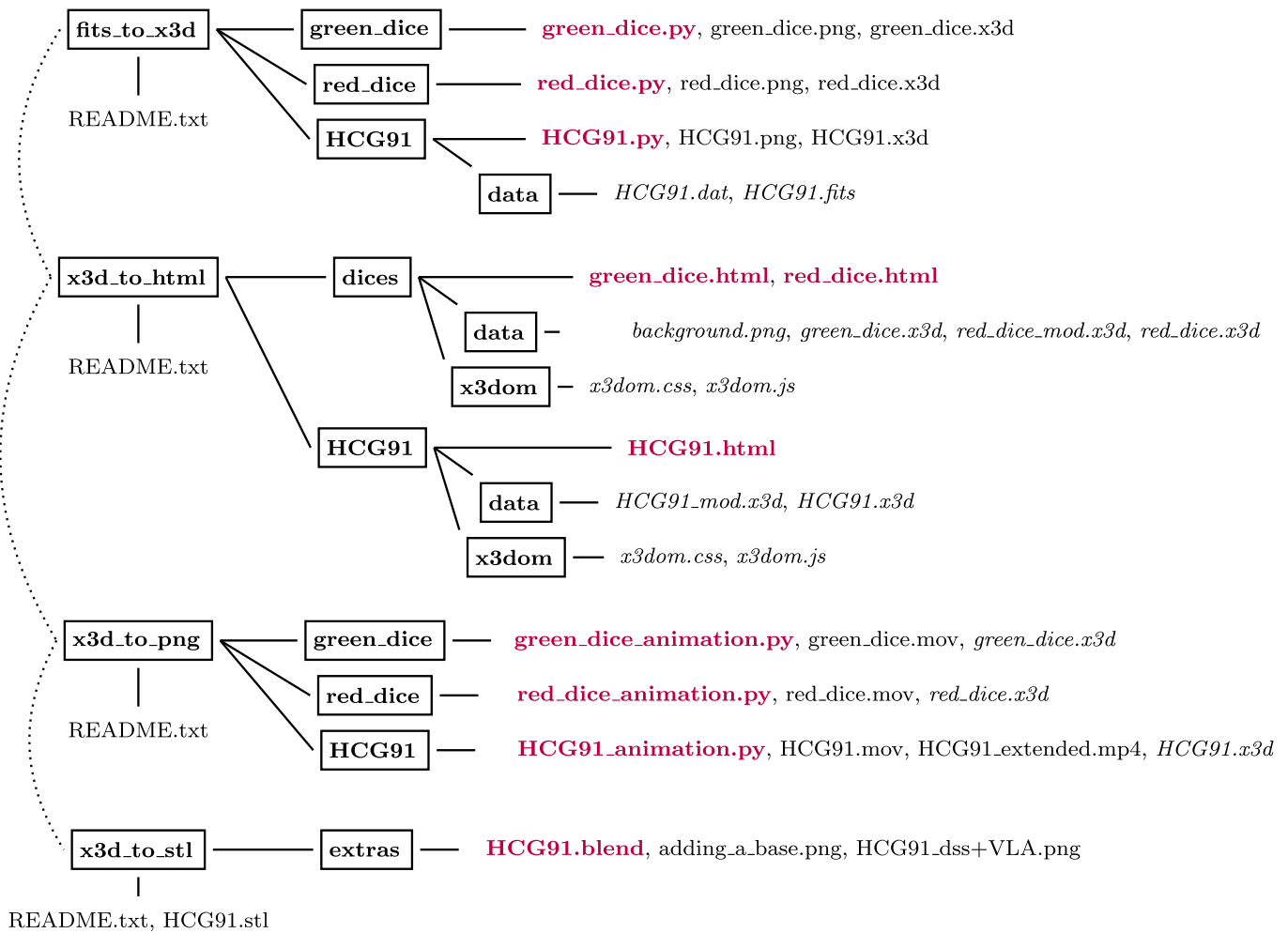


Figure 6. Structure and content of the supplementary material associated with this article. Folders are marked with boxes. Scripts and instruction files are marked in bold purple. Required data input files are in italic. Four dedicated “README” files provide a specific introduction to the different families of examples. This material can be downloaded as free software (under the GNU General Public License version 3) from its dedicated Github repository (<http://dx.doi.org/10.5281/zenodo.45079>).

theoretical simulations or data products from existing/forthcoming observing facilities (e.g., the SKA)—require innovative alternatives to 2D diagrams for their visualization and publication. We strongly believe that tackling this issue requires us to move the focus away from specific software and direct the discussion toward file formats. Here, we propose that the X3D pathway offers a viable framework to develop alternative visualization techniques (such as interactive HTML documents) while providing a single entry point connecting a growing range of advanced data visualization solutions.

The detailed examples provided in this article demonstrate the current possibilities (and existing limitations) offered by the X3D pathway in terms of data visualization, and provide interested readers with the means of testing and implementing the X3D pathway with their own data sets. As a complete and new framework for multi-dimensional data visualization, we believe that the X3D pathway also provides a useful reference and comparison point (in terms of capabilities, limitations, and flexibility) for ongoing efforts and future propositions regarding the visualization and publication of complex multi-dimensional data sets.

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for PYTHON hosted at <http://aplpy.github.com>, and of MONTAGE, funded by the National Aeronautics and Space Administration's Earth Science Technology Office, Computation Technologies Project, under Cooperative Agreement Number NCC5-626 between NASA and the California Institute of Technology.

APPENDIX STRUCTURE AND CONTENT OF THE SUPPLEMENTARY MATERIAL

We include as supplementary material to this article a series of scripts, data files, and instruction sets (released as free software under the GNU General Public License version 3) designed to provide a stepping stone for the reader interested in implementing the X3D pathway. As an example, some of these scripts aided in the creation of the interactive counterpart to Figure 3(c) in Bouché et al. (2015).

A global overview of the structure and content of the supplementary material provided with this article is provided in Figure 6. The supplementary material is divided into four sections dedicated to the creation of X3D files, the creation of interactive HTML documents, the creation of high-end animations and 3D printing. All of the material is located in a dedicated Github repository.²⁷ The scripts described in this article are contained in the release v1.0 associated with the Github directory (<http://dx.doi.org/10.5281/zenodo.45079>). All scripts provided are commented in detail to help in their understanding.

The different examples build on one another: for example, the X3D files created using the PYTHON scripts are used as input material for the HTML visualization scripts. Included are three examples of incremental complexity. The “green dice” examples (*green_dice.py*, *green_dice.html*, and *green_dice_animation.py*) are the most basic. The red dice examples were designed to hit some of the limitations associated with MAYAVI to export X3D files. The third set of examples (*HCG91.py*, *HCG91.html*, and *HCG91_animation.py*) are the most complex, and do not shy away from the additional intricacies

associated with visualizing real astrophysical data sets, including the use of *World Coordinate System* units.

REFERENCES

- Ahrens, J. G., Geveci, B., & Law, C. 2005, in *The Visualization Handbook*, ed. C. D. Hansen, & C. R. Johnson (Amsterdam: Elsevier), 717
- Astropy Collaboration Robitaille, T. P., Tollerud, E. J., et al. 2013, *A&A*, **558**, A33
- Barnes, D. G., & Fluke, C. J. 2008, *NewA*, **13**, 599
- Barnes, D. G., Fluke, C. J., Bourke, P. D., & Parry, O. T. 2006, *PASA*, **23**, 82
- Behr, J., Eschler, P., Jung, Y., & Zöllner, M. 2009, in Proc. 14th Int. Conf. on 3D Web Technology, Web3D '09 (New York: ACM), 127
- Behr, J., Jung, Y., Keil, J., et al. 2010, in Proc. 15th Int. Conf. on Web 3D Technology, Web3D '10 (New York: ACM), 185
- Bouché, N., Carfantan, H., Schroetter, I., Michel-Dansac, L., & Contini, T. 2015, arXiv:1501.06586
- Christian, C. A., Nota, A., Grice, N. A., et al. 2014, in American Astronomical Society Meeting Abstracts, **223**, 24416
- Daly, L., & Brutzman, D. 2007, *ISPM*, **24**, 130
- Fluke, C. J., Barnes, D. G., & Jones, N. T. 2009, *PASA*, **26**, 37
- Hettne, K. M., Dharuri, H., Zhao, J., et al. 2013, arXiv:1311.2789
- Hickson, P. 1982, *ApJ*, **255**, 382
- Hunter, J. D. 2007, *CSE*, **9**, 90
- Kent, B. R. 2013, *PASP*, **125**, 731
- Kent, B. R. 2015, *3D Scientific Visualization with Blender* (Morgan & Claypool Publishers)
- Madura, T. I., Clementel, N., Gull, T. R., Kruij, C. J. H., & Paardekooper, J.-P. 2015, *MNRAS*, **449**, 3780
- Miki, Y., Mori, M., Kawaguchi, T., & Saito, Y. 2014, *ApJ*, **783**, 87
- Punzo, D., van der Hulst, J. M., Roerdink, J. B. T. M., et al. 2015, *A&C*, **12**, 86
- Putman, M. E., Peek, J. E. G., & Joung, M. R. 2012, *ARA&A*, **50**, 491
- Ramachandran, P., & Varoquaux, G. 2011, *CSE*, **13**, 40
- Springob, C. M., Magoulas, C., Colless, M., et al. 2014, *MNRAS*, **445**, 2677
- Springob, C. M., Magoulas, C., Proctor, R., et al. 2012, *MNRAS*, **420**, 2773
- Steffen, W., Teodoro, M., Madura, T. I., et al. 2014, *MNRAS*, **442**, 3316
- Taylor, R. 2015, arXiv:1506.04621
- Turk, M. J., Smith, B. D., Oishi, J. S., et al. 2011, *ApJS*, **192**, 9
- Verdes-Montenegro, L., Yun, M. S., Williams, B. A., et al. 2001, *A&A*, **377**, 812
- Vogt, F., & Wagner, A. Y. 2012, *Ap&SS*, **337**, 79
- Vogt, F. P. A., Dopita, M. A., Borthakur, S., et al. 2015, *MNRAS*, **450**, 2593
- Vogt, F. P. A., Dopita, M. A., Kewley, L. J., et al. 2014, *ApJ*, **793**, 127
- Vogt, F. P. A., & Shingles, L. J. 2013, *Ap&SS*, **347**, 47

²⁷ <https://github.com/fpavogt/x3d-pathway>