

Incorporating interactive 3-dimensional graphics in astronomy research papers[^]

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Abstract

Most research data collections created or used by astronomers are intrinsically multi-dimensional. In contrast, all visual representations of data presented within research papers are exclusively 2-dimensional. We present a resolution of this dichotomy that uses a novel technique for embedding 3-dimensional (3-d) visualisations of astronomy data sets in electronic-format research papers. Our technique uses the latest Adobe Portable Document Format extensions together with a new version of the S2PLOT programming library. The 3-d models can be easily rotated and explored by the reader and, in some cases, modified. We demonstrate example applications of this technique including: 3-d figures exhibiting subtle structure in redshift catalogues, colour-magnitude diagrams and halo merger trees; 3-d isosurface and volume renderings of cosmological simulations; and 3-d models of instructional diagrams and instrument designs.

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1 Introduction

1.1 Visualisation in astronomy

Astrophysical data collections (datasets) are predominantly large and multi-dimensional. Accordingly, the principle approach to studying and compar-

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[^] This is the Acrobat 8 version of this paper, which includes interactive, 3-dimensional graphics.
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ing datasets is to calculate statistical measures such as the moments (mean, skewness, etc.) and correlation functions. Even substantial techniques such as Fourier analysis and principal components analysis rely heavily on basic statistical measures. These methods provide valuable information on the ensemble properties of the datasets. What they are less well-suited to is identifying anomalies or special cases within the data: are there features that we cannot understand or explain based on purely statistical approaches? Usually, there is a great deal of information that can be obtained simply by *looking* at the data. This is called scientific visualisation, hereafter simply “visualisation”.

Broadly speaking, visualisation methods can be classified as being qualitative (direct visual inspection), quantitative (including selection of regions of interest and computation of statistical properties), or comparative (including comparisons between objects with secondary observational catalogues, side-by-side comparisons between datasets, or overlays such as isodensity surfaces).

Visualisation in various forms has played a role in astronomy since early times. The Ancient Egyptians mapped the locations of prominent stars in their tomb decorations, Greek constellations are seen inscribed on the Farnese globe (c. 2nd century CE) and Chinese star maps have been found dating back to 940 CE. The 14th and 15th centuries saw the development of star atlases of increasing accuracy and beauty - truly works of “cognitive art” (Tufte, 1990) in their own right. Beniger and Robyn (1978) and the extremely comprehensive web-site of Friendly & Denis¹ cover the historical development of graphic representations (with passing references to their use in astronomy), including tables, coordinate systems and maps, and the derived forms: line graphs, histograms, scatter plots and so on.

The advent of computer graphics revolutionised visualisation in astronomy. It enabled dynamic presentation, and more importantly, real-time exploration of astrophysical datasets. In general, an interactive digital representation allows the user to actively rotate, zoom, and pan multi-dimensional datasets in order to find a viewpoint that provides more information and understanding. This is *visualisation-led knowledge discovery* and is now a standard and necessary tool in all of the physical sciences.

The first computerised astrophysical visualisation systems were expensive to operate and difficult to use. For example, the 3-dimensional representations of the Centre for Astrophysics (CfA) galaxy surveys, which helped reveal the “Great Wall” and other major filamentary features (e.g. Geller and Huchra, 1989), required custom processors. Image sequences were generated by outputting individual frames that were then printed to 16 mm film for viewing! Real-time interactive motion was merely “a fond hope” (Geller et al., 1992).

¹ Milestones in the History of Thematic Cartography, Statistical Graphics, and Data Visualization: <http://www.math.yorku.ca/SCS/Gallery/milestone>

Today, an entry-level laptop or workstation provides an extraordinary level of graphics performance. In fact, in many modern desktop computers, the graphics processing unit is actually more powerful than the central processing unit. Consequently, there is now a wide selection of commercial and free software applications, programming libraries and data processing environments that provide varying levels of 3-dimensional graphics capabilities to scientists. It is fair to say that astronomers now can, and increasingly *do*, make use of advanced 3-dimensional visualisation in their quest for knowledge discovery.

1.2 *Publishing in astronomy*

The growth of the World Wide Web (Berners-Lee et al., 1994) as a global information repository and communication tool has profoundly affected the way science is performed and reported. In particular, there has been a dramatic change in how research articles are published, with a steady trend away from physical, paper-based journals to fully online digital publications. The way was paved in the early 1990s, as the *Astrophysical Journal* (ApJ) introduced video tapes for “illustrations that are not well suited to single frames or figures” (Abt, 1992) and CD-ROMS of datasets, both of which were distributed with the paper editions. The first online edition of ApJ appeared in September 1995 (Abt, 2002). During the same period, the ADS Abstract Service began its service, providing astronomers with new capabilities to search for and obtain abstracts (Murray et al., 1992; Kurtz et al., 2000), followed soon after with the provision of scanned articles (Eichhorn et al., 1994).

Today, the standard graphics cards that ship with new computers are immensely powerful. They are perfectly suited to running the advanced, 3-d visualisation programs that are becoming necessary for the rapid comprehension of large and complex data collections. Yet despite the nearly complete migration to an electronic workflow in research publishing, published visualisations remain almost exclusively *two-dimensional*² and *static*. The former embodies a graphical communication challenge, as the majority of research data collections in astronomy are multi-dimensional and can in many cases be communicated better with 3-d presentation. The latter limits the presentation of time-evolving data to “cartoon strips” of individual frames. While the major journal publishers have allowed *ex situ* supplementary material to be linked from published papers, the *in situ* publication of 3-dimensional, interactive figures remains largely unexplored.

² Stereoscopic images can be printed, usually to be viewed with coloured anaglyph or chromastereoscopic glasses, but their use in research publications has been limited.

1.3 *This paper*

The latest extensions to the Adobe Portable Document Format (PDF) create an exciting opportunity to bring together the interactivity of a real-time, 3-dimensional visualisation system with the requirements for standardised academic publication (within an electronic document context). In this paper, we describe a relatively straightforward technique for developing and embedding interactive, 3-dimensional science visualisations as figures in PDF files that can be viewed with the freely downloadable Adobe Reader application. We use the S2PLOT library (Barnes et al., 2006) and Adobe Acrobat 3D Version 8.1 software, although other approaches are possible (Goodman et al., *priv. comm.*).

In Section 2 we introduce Adobe’s 3-d extensions to PDF that our technique exploits and motivate the use of 3-dimensional PDF for science reporting. In Section 3 we review S2PLOT as a tool for generating 3-dimensional, scientific models, and describe how these models can be saved and imported for embedding in existing or new PDF files. Advanced, interactive features possible with JavaScript are discussed in Section 4, and alternative uses of 3-d PDF are described in Section 5. Examples are given throughout the paper. We conclude the paper in Section 6 with some brief commentary on the technique we present, and a few remarks on future applications of 3-d figures in astronomy papers.

2 3-dimensional PDF

2.1 *Portable Document Format*

Portable Document Format (PDF) is an open document standard developed by Adobe Systems Incorporated.³ First released in the early 1990s, PDF has become the preferred standard for printable and electronically-distributed documents, supplanting its predecessor PostScript – Adobe’s first document standard. PDF files may contain text, vector graphics and bitmap graphics, and can be produced by most commercial desktop publishing software systems, and by many free applications such as the L^AT_EX typesetting system.

Uptake of PDF by journal publishers is virtually complete in the sense that nearly all publishers have adopted PDF as a standard target file type, for both pre-press operations and electronic distribution. Astronomy has been no

³ Adobe Systems Inc.: <http://www.adobe.com>

exception, with the major journals using PDF for most parts of the paper publication and distribution workflow since the late 1990s. The ability of \LaTeX to produce PDF files, initially via conversion from PostScript and then directly, was pivotal in the embracing of PDF by the physical sciences research community.

2.2 Acrobat 3D and Adobe Reader

In May 2007, Adobe announced the availability of “Adobe Acrobat 3D Version 8” software.⁴ This product builds on extensions to PDF which allow the inclusion of 3-dimensional objects described in the Universal 3D (U3D) format. Acrobat Reader has been able to interactively display U3D objects in PDF files since version 7. However, the release of Acrobat 3D Version 8 and the free Acrobat Reader Version 8 have standardised and dramatically simplified the creation and viewing of 3-d PDF files.

Acrobat 3D Version 8 (hereafter “Acrobat 3D”) is directed at Computer Aided Design (CAD) and Computer Aided Modelling (CAM) professionals. It can import 3-d models from more than 50 third-party file formats. Roughly two-thirds of the supported formats are polygonal meshes from CAD/CAM applications, while the remaining formats cover animation packages, game models, and more generic 3-d formats. In some circumstances, Acrobat 3D can also capture 3-d geometry from the hardware graphics pipeline as it is displayed.

Once a 3-d model has been imported to Acrobat 3D, the publisher can set the preferred lighting, shading and viewing for the model. A number of different configurations can be saved as views. The model tree can be exposed, and its various branches (corresponding to particular geometric elements of the scene) can be switched in or out of the visualisation. Options on import allow colouring of different parts of the model, and optimisation of properties such as surface smoothness and detail. It is evident from the example PDF files supplied with Acrobat 3D that Adobe’s focus is firmly on the ability to embed and share 3-d engineering models in PDF files.

Acrobat 3D also supports the addition of JavaScript to a PDF file, which can be used to programmatically control almost every aspect of a 3-d model visualisation. This control can be intrinsic (ie. JavaScript event handlers that respond implicitly to user interaction with the 3-d model), or extrinsic. The latter entails embedding traditional graphical user interface (GUI) elements into the PDF document and modifying the 3-d visualisation in response to explicit user input via those elements.

⁴ Acrobat 3D Version 8 announcement: <http://www.adobe.com/aboutadobe/pressroom/pressreleases/pdfs/200705/053007Acrobat3DShips.pdf>

With Adobe Reader Version 8 (hereafter “Reader”, freely available from Adobe), 3-d models embedded in PDF files are interactively viewable. All properties of the model set in Acrobat 3D are expressed in the Reader, including saved views. Unless explicitly disabled in Acrobat 3D, Reader allows the user to interactively rotate the model, select their own shading and lighting options, and explore the model tree. And importantly, JavaScript control of the embedded 3-d models extends to the Reader.

Acrobat 3D is *not* free software. Astronomers make extensive use of (and contributions to) free software, and accordingly, a free alternative to using Acrobat 3D to produce PDF files with 3-d annotations is highly desirable. The `movie15` style file has recently been extended by its author (A. Grahn, *priv. comm.*) to support the embedding of 3-d annotations in PDF documents produced by the popular and free typesetting package \LaTeX . To use this approach however, the 3-d model needs to be stored in U3D or PRC format; we are presently investigating techniques for generating these file types.

2.3 3-dimensional PDF for astronomy

3-dimensional PDF holds great promise for improving science reporting. We propose the judicious use of 3-d PDF to add 3-dimensional, interactive figures to astronomy journal papers. We contend that there are many circumstances where the use of 3-d figures can be substantially more illustrative of concepts, relationships and properties, than can their 2-d counterparts. While 3-d figures (and more commonly, dynamic content such as movies) *have* been attached to astronomy papers (for some recent examples see Diemand et al., 2007; Okamoto et al., 2007; Price and Bate, 2007) this has until now been achieved using ephemeral web addresses to direct readers to supplementary material. Directly embedding 3-d figures in a standard document format — for which viewers exist on all major desktop platforms — affords a major improvement for both present useability and future compatibility.

Despite Acrobat 3D being openly targeted at the CAD/CAM user community, we show in this paper that 3-d PDF is also suitable for scientific data. Together with software that produces 3-d models, Acrobat 3D can be used to produce publication-quality, scientifically instructive 3-dimensional figures. The basic geometric elements required to produce scientific plots — lines and points — are readily available, together with an extensive set of higher-level objects such as surfaces and textures.

3 S2PLOT and 3-d PDF

We now describe one approach to producing 3-d figures in PDF files, using the S2PLOT programming library and Adobe Acrobat 3D Version 8.1. S2PLOT (Barnes et al., 2006) is an advanced graphics library with a programming interface familiar to users of PGPLOT.⁵ S2PLOT enables the programmatic construction, display and interactive exploration of 3-dimensional scientific plots and diagrams. S2PLOT can be called from C, C++ and FORTRAN code, and is freely available for GNU Linux, Apple OS X and Windows XP systems.⁶ S2PLOT uses the OpenGL graphics standard to exploit hardware-accelerated graphics performance, and supports standard display devices such as desktop monitors and data projectors, and advanced devices such as passive and active stereoscopic systems and digital dome projectors (Fluke et al., 2006).

S2PLOT is ideally-structured to produce 3-d model output that can be imported into Acrobat 3D. Internally, the S2PLOT library maintains a list of all geometry that is used to make up a scene. On each screen redraw, the active geometry is sent to the graphics pipeline with standard OpenGL calls. In S2PLOT version 2.0 the geometry list can be exported to a file in Virtual Reality Modeling Language (VRML) format. As well as being a supported input format for Acrobat 3D, this language has the distinct advantages that it is (i) text-based, enabling easy editing prior to Acrobat 3D import; and (ii) web-based, yielding further possibilities for model and figure sharing and publication. VRML has received occasional attention from the astronomy community (see e.g. Plante et al., 1999; Crutcher et al., 1998), and one of us (Barnes) has previously developed a VRML viewer for Virtual Observatory data (Beeson et al., 2004).

For basic 3-dimensional figures and diagrams, embedding an S2PLOT-based 3-d figure in a PDF paper is accomplished via a standard key press to export S2PLOT geometry into a VRML file, then importing the VRML file into Acrobat 3D. Within Acrobat 3D, the author can place the 3-d figure anywhere within the PDF file, add annotations, and set default rendering, lighting and viewing properties. Where necessary, special views that exhibit particular features of the figure discussed in the text of the paper can be saved and named for the reader to select.

We now give three examples of relatively simple, 3-dimensional figures that are illustrative of common plotting requirements in astronomy: a dark matter

⁵ PGPLOT is written by T.J. Pearson: <http://www.astro.caltech.edu/~tjp/pgplot/>.

⁶ Windows XP support for S2PLOT is provided via the Cygwin system: <http://www.cygwin.com>.

merger tree, a survey catalogue redshift distribution and a colour-magnitude diagram.

3.1 *Example 1: Halo merger trees*

Semi-analytic modelling has been developed as an efficient way to study the hierarchical formation of galaxies (see e.g. White and Frenk, 1991; Cole et al., 2000). The first stage in the process is to generate a merger tree of dark matter halos from direct N -body simulations or Monte Carlo methods. Analytic solutions are applied on top of the dark matter framework to treat the baryonic component, and to model the physical processes required to build a galaxy (initial mass function, star formation history, feedback, etc.). While merger trees are predominantly studied statistically, individual trees feature intricate and exquisite structure that can only be fully appreciated via interactive 3-d visualisations. Conventional, static 2-d projections simply fail to represent this structure.

Figure 1 is a 3-d representation of a merger tree, using data from the Virgo-Millennium Database⁷ (Springel et al., 2005; De Lucia and Blaizot, 2007). Colour indicates the formation redshift for the progenitor haloes that combine through mergers to produce the final galactic halo. By rotating this merger tree, the filamentary LSS within which the progenitors form is clearly visible.

3.2 *Example 2: Redshift catalogues*

The redshift wedge or cone diagram is somewhat peculiar to astronomy. It is typically used to exhibit large-scale structure (LSS) as (right ascension, declination, redshift)-tuples, and can comprise several individual plots to show different slices from a larger volume of the Universe. This is a classic case of the traditional publishing medium (i.e. paper) limiting the communication of genuine 3-dimensional information, and the opportunity for advancement by provision of interactive 3-d figures is clear.

In Figure 2 we present an interactive, 3-dimensional plot of the redshift distribution of the combined HICAT (Meyer et al., 2004) and HICAT+N (Wong et al., 2006) galaxies. Meyer et al. (2004) presented two sky projections of HICAT in its entirety, coloured by redshift, as well as two full-page figures for a multi-layer wedge diagram. Here, for the first time we combine HICAT and HICAT+N into one figure, using the same colour coding as Meyer et al.

⁷ <http://www.g-vo.org/Millennium>

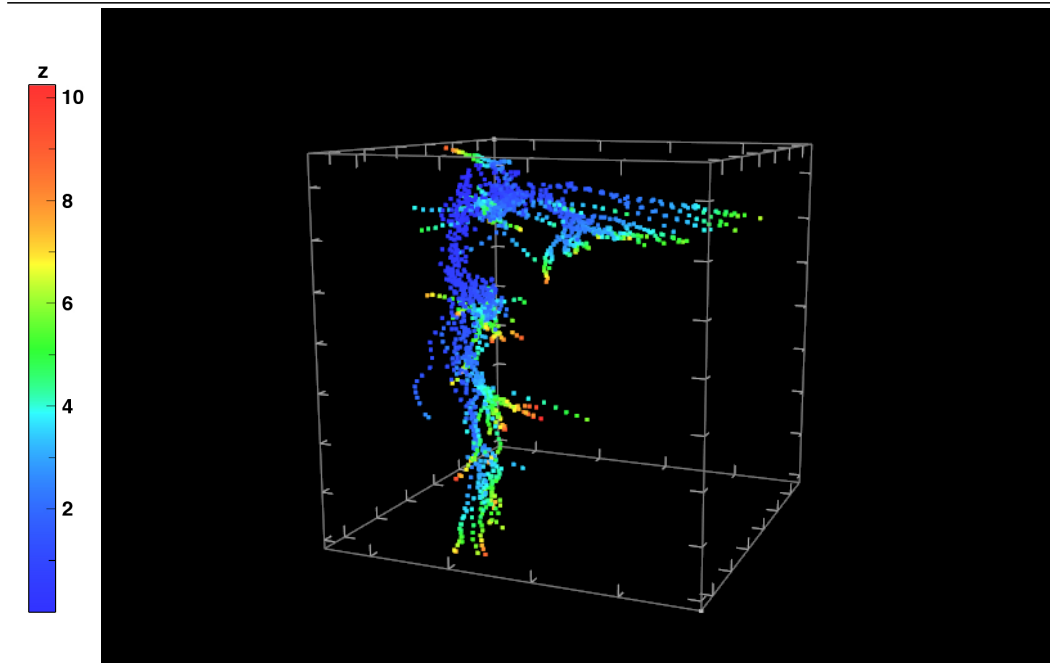


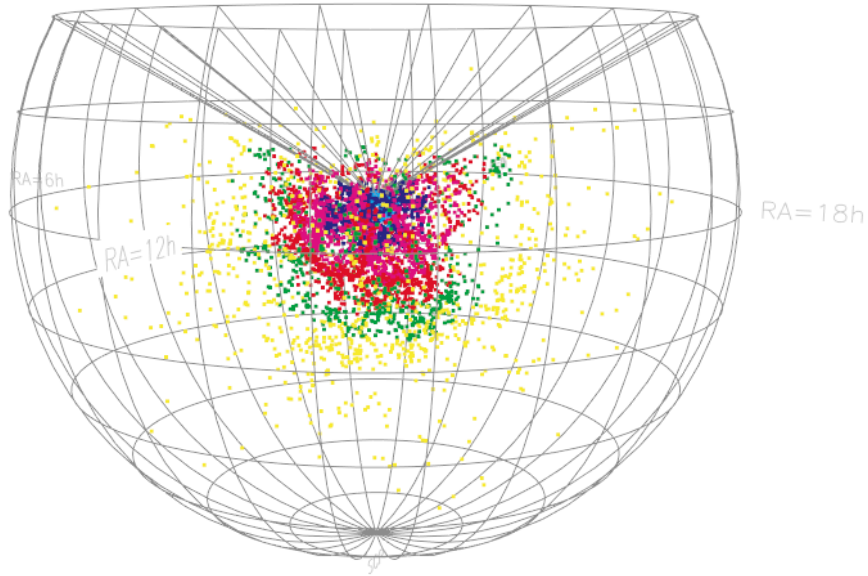
Fig. 1. A merger tree showing the hierarchical formation of a galactic dark matter halo, using data obtained from the Virgo-Millennium Run database. Colour indicates the formation epoch of progenitor haloes.

(2004). The reader is invited to explore the plot by moving the camera around, into and out of the galaxy distribution. The filamentary LSS is much more obvious than in a static figure, and the local void is particularly noticeable from certain orientations. The coordinate grid and labels may be toggled (off) on by expanding the model tree and (de)selecting the `GRID` and `LABELS` nodes.

3.3 Example 3: Colour-magnitude diagrams

Widely-used 2-dimensional plots such as colour-magnitude diagrams (CMDs) can benefit from a 3-dimensional treatment. CMDs are most frequently presented as scatter plots, where each measurement is added to the plot as a dot. The quantitative interpretation of these plots is becoming more difficult as star counts increase with instrument capability. One obvious improvement is to dispense with the scatter plot approach entirely.

In Figure 3 we demonstrate that a simple 2-d histogram is an effective replacement for a conventional CMD. The source data for the figure are 28 568 stellar photometry measurements for the Large Magellanic Cloud globular cluster NGC 1898 made with Hubble WFPC2 (Olsen, 1999). The figure shows the result of binning the $(M_V, V - I)$ pairs onto a grid, and plotting the result as a logarithmic 2-d histogram. In certain orientations, the surface colour



Point colour

- | | | |
|---|---|---|
| • $V_{\text{CMB}} \leq 1000 \text{ km s}^{-1}$ | • $2000 < V_{\text{CMB}} \leq 3000 \text{ km s}^{-1}$ | • $4000 < V_{\text{CMB}} \leq 5000 \text{ km s}^{-1}$ |
| • $1000 < V_{\text{CMB}} \leq 2000 \text{ km s}^{-1}$ | • $3000 < V_{\text{CMB}} \leq 4000 \text{ km s}^{-1}$ | • $5000 < V_{\text{CMB}} \text{ km s}^{-1}$ |

Fig. 2. Interactive, 3-dimensional plot of the distribution of galaxies in the combined HICAT and HICAT+N catalogues.

alone aids the eye in interpreting relative star counts; viewed “side-on” the height of the surface above the base gives a direct and quantitative comparison between different parts of the colour-magnitude plane: something that colour alone cannot accomplish. Some choices of colour scales, such as the standard “rainbow” map, should be avoided for presenting relative data values - grey-scales offer a more intuitive choice (Tuft, 1990).

4 S2PLOT, JavaScript and 3-d PDF

The JavaScript capabilities of 3-d PDF enable us to go well beyond the relatively simple examples shown in Figures 2–1. The S2PLOT graphics model divides the scene into *static* and *dynamic* geometry. The former is drawn once and never changes, while the latter can be redrawn every refresh cycle and enables the construction of visualisations that evolve with time or in response to user input. By embedding small JavaScript components in a PDF file, we can propagate some of S2PLOT’s dynamic features into 3-d PDF figures.

There are two basic reasons for using JavaScript in a PDF file: (i) to offer the user *explicit* control of the 3-d figure(s) in the file, and (ii) to *implicitly* modify the 3-d figure(s) in response to internal events or user actions. Adobe

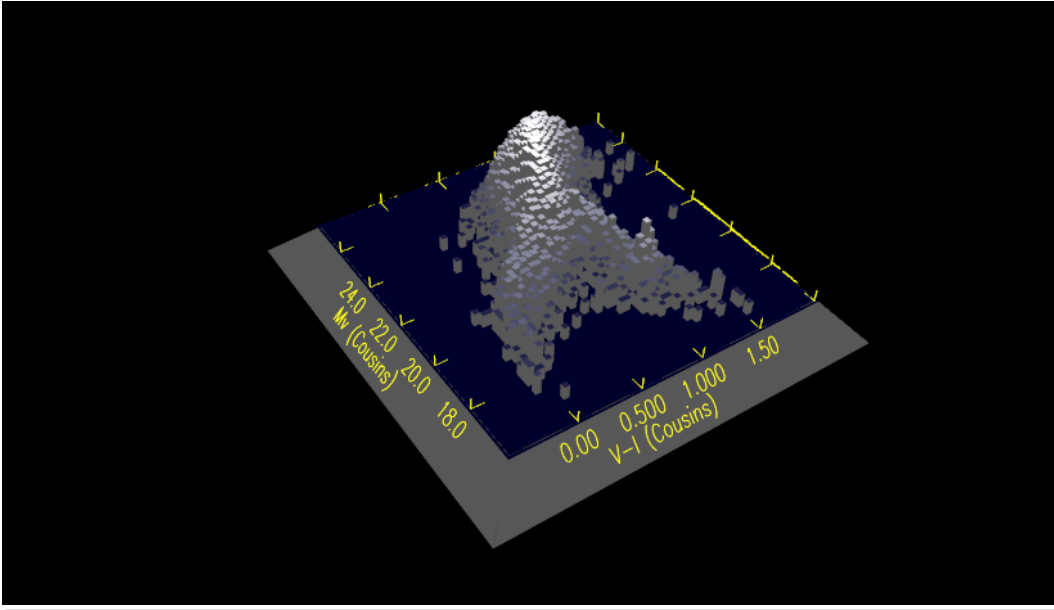


Fig. 3. 2-dimensional colour-magnitude histogram of the stellar population of NGC 1898.

JavaScript for Acrobat 3D is sufficiently complete that it is reasonable to expect to see genuine, fully-fledged visualisation applications as components of PDF files before long. In the meantime, we describe two examples that demonstrate how explicit and implicit JavaScript control can be used to immediately enhance the use of 3-d figures in astronomy.

4.1 Example 4: Large scale structure isosurfaces

In this era of $N \sim 10^6$ galaxy surveys (Adelman-McCarthy et al., 2007) and $N \sim 10^{10}$ particle simulations (Springel et al., 2005), scatter plot wedge diagrams quickly become overcrowded, and the large scale structures we aim to understand are lost in a sea of points. An alternative approach is to draw isodensity contours (usually calculated on a regular mesh) over the point distributions. These help to highlight connected structures, and isolate the regions of highest (or lowest) density.

In Figure 4, isodensity surfaces are overlaid on a dark-matter only cosmological simulation ($\Omega_M = 0.24, \Omega_\Lambda = 0.76, h = 0.73$, where cosmological parameters have their usual meaning, and the simulation box length was $50 h^{-1}$ Mpc). While the full simulation had 256^3 million particles, we only plot 5 000 of these. Particles are smoothed onto a 32^3 mesh using a triangular shaped cloud kernel (Efstathiou et al., 1985), and the 40% and 60% isodensity levels are generated. By clicking on the NEXT button, it is possible to move between these levels, demonstrating explicit JavaScript control. The other buttons toggle the

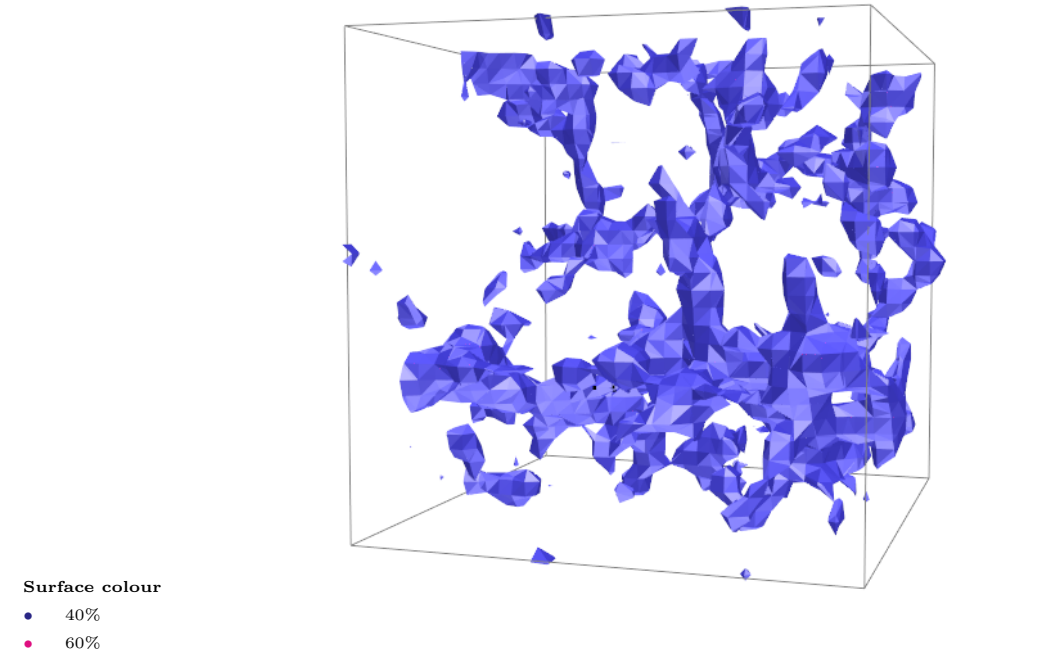


Fig. 4. 40% and 60% isodensity levels from a dark matter-only cosmological simulation. Clicking the **NEXT** button toggles between the two isodensity levels, demonstrating explicit JavaScript control within a 3-d PDF figure.

display of the particle distribution and the bounding box.

4.2 Example 5: Substructure in a dark matter halo

The Cold Dark Matter (CDM) model, and its variants, has been very successful at explaining a number of observational properties of galaxies and galaxy clustering, particularly on large scales. However, on small scales and/or in high density regions, contradictions between CDM model predictions and observations exist. One such example is the “missing satellite” problem (Bardeen et al., 1996; Kauffmann et al., 1993; Klypin et al., 1999; Moore et al., 1999; Kamionkowski and Liddle, 2000): high resolution CDM simulations of Milky Way-type dark matter haloes produce many more bound sub-structures than there are observed satellites. Visualisation techniques are extremely valuable for studying individual haloes, in order to better understand the role and spatial distribution of sub-structures.

Figure 5 shows a 3-d model of a dark matter halo identified from within a CDM simulation using a friends-of-friends algorithm. The visualisation chosen is a direct volume rendering, which in this case highlights regions of higher density. In S2PLOT, real-time volume rendering is achieved by creating three



Fig. 5. Volume rendering enhances the visibility of sub-structures in a dark matter halo, compared to only plotting locations of points. By querying the location of the camera relative to the model, implicit JavaScript control determines which of the three sets of volume rendered textures should be displayed.

orthogonal sets of slices (textures) through the data volume, then for every redraw choosing and transparently layering the set that is most orthogonal to the camera view direction. While the transitions between different texture sets are occasionally visible, this is a very effective method for real-time inspection of a gridded volume. When writing VRML, the three texture sets are exported and stored in uniquely-named parts of the VRML model tree. A simple JavaScript attached to the 3-d figure in the PDF file is then used to determine which texture set to display on every redraw cycle. This JavaScript runs “behind the scenes” to add implicit control over the rendering in the 3-d PDF file.

5 Other approaches

While the preceding examples have highlighted the data visualisation advantages of 3-d PDF, there are other aspects of academic publication where the CAD/CAM functionality can be used. Two such cases are in instrument design and the presentation of instructional models (3-d cartoons), which we now demonstrate.

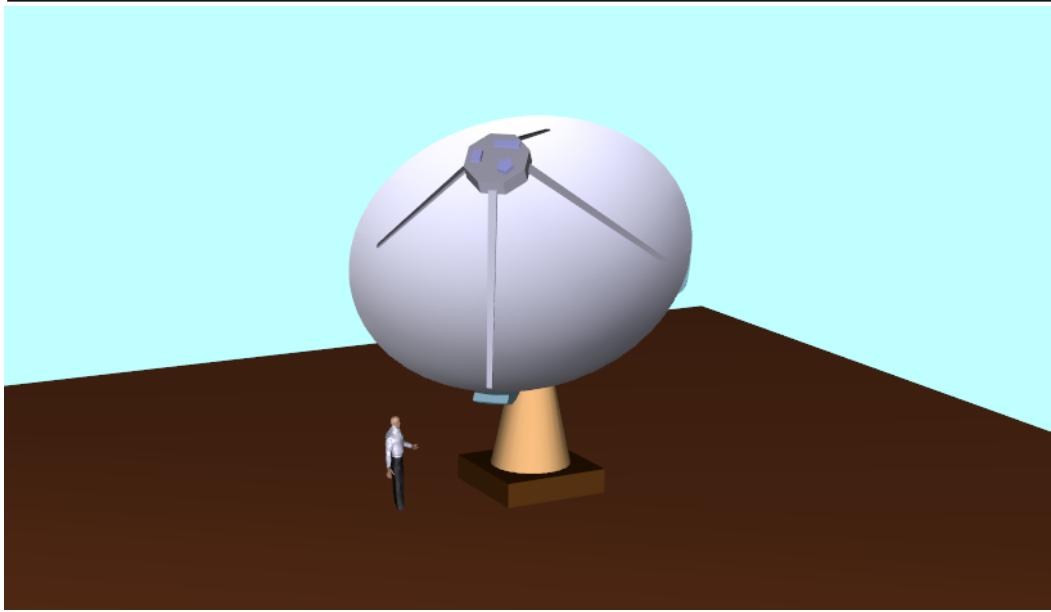


Fig. 6. A model radiotelescope constructed as a part of a promotional campaign for the Australian SKA Pathfinder. By opening the model tree, individual components of the model may be (de)selected.

5.1 Example 6: Instrument design

Advances in astronomy are intimately linked to technological developments, particularly through new instrument designs which enhance the capability of existing facilities. CAD/CAM packages are a natural source of engineering models for astronomy instrumentation, but a range of polygon modelling packages exist, many developed and used within the computer animation industry.

As a means of promoting design concepts for the Square Kilometer Array (SKA) and Australian SKA Pathfinder (ASKAP), one of us (Fluke) worked with engineers from the CSIRO Australian National Telescope Facility to create a series of 3-d radiotelescope models.⁸ Based loosely on engineering drawings, the telescopes were built using NewTek's Lightwave 3D V8.0,⁹ and exported for Acrobat 3D in 3DS format. This binary format stores geometrical objects as a mesh of 3-vertex polygons with associated materials (i.e. colours). The 3DS format can be imported without further conversion to Acrobat 3D, and the model tree allows selection of individual components based on the material. The result is shown in Figure 6.

⁸ 3DS human model from <http://www.klicker.de>

⁹ <http://www.newtek.com>

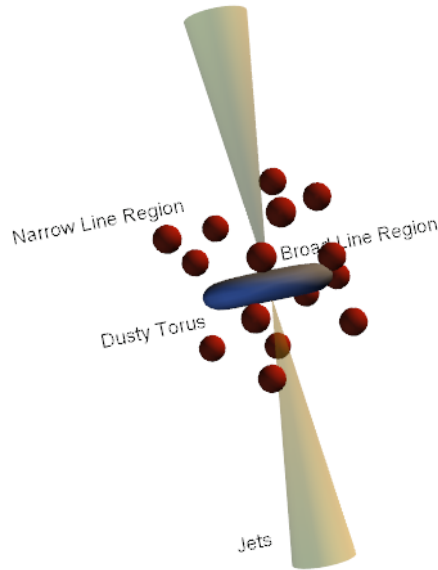


Fig. 7. The unified model of Active Galactic Nuclei presented in interactive form (components are not strictly to scale). The viewing angle determines the visibility of the broad line region-emitting “clouds” surrounding the central engine, and the orientation of the jets. Presented in this form, the view-dependent classification of AGN type may for some people be more instructional than in a series of static 2-d images.

5.2 Example 7: Instructional diagrams

An important component of many research articles and textbooks is the instructional diagram, often presented in a simplified cartoon format. These diagrams usually show spatial and/or other relationships between the elements of a model. In many cases only a single orientation of a model is presented yet, as with astronomical datasets, these models are often inherently three-dimensional. 3-d PDF makes possible the inclusion of simple but interactive, 3-d diagrams in electronic articles, with applications in teaching, pedagogy and outreach.

One particular instructional diagram common in astronomy is the unified model for Active Galactic Nuclei (AGN) and quasars (e.g. Antonucci, 1993). Classification of an AGN as either Type 1, Type 2 or Blazar depends on the orientation of the dusty molecular torus to the observer’s line-of-sight. The viewing angle determines the presence or absence of broad and narrow line emission, and beamed radiation from jets. In Figure 7 we present an interactive 3-d AGN (components of the model are not to scale). By rotating the model, the reader is able to “observe” the AGN from arbitrary viewpoints, and see for example the obscuration of the broad line region and central engine by the torus.

6 Closing Remarks

We have demonstrated that the new 3-d extensions to the PDF standard can be used to publish instructive and interactive 3-d figures in astronomy research papers. Our approach uses the S2PLOT programming library and VRML as an intermediary 3-d model description format. It is sufficiently easy to create and embed 3-d figures in PDF articles that we believe it can become a standard technique in the publication of scientific research results, particularly in the fields of astronomy and astrophysics. 3-d PDF files are portable, relatively compact and viewable on many desktop platforms today.¹⁰ Small changes to the publishing workflow are required, but we contend they are insignificant in the context of the major advantages 3-dimensional figures and diagrams will bring to inter- and intra-domain science communication.

There is one major caution to be made on the use of 3-d PDF in science. Scientists traditionally use large collections of *points* to representing instances in parameter spaces, while the CAD/CAM community works primarily with *surfaces*. Like their CAD/CAM and animation software counterparts, Acrobat 3D and Reader show a clear preference for mesh (surface) data over point data. We found that the 3-d PDF reader client (Acrobat Reader) — and to a lesser extent the content creation tool (Acrobat 3D) — did not perform well when more than $\sim 10\text{--}20\,000$ points were used in a single 3-d figure. Gridding point data and then rendering isosurfaces and/or volumes is one effective work-around. Some improvement in the underlying software is required before 3-d figures of eg. redshift catalogues containing 10^5 to 10^8 galaxies can be published, although doing so would have an obvious impact on the file size of the article.

In this paper we have only touched on the possibilities of 3-d PDF for astronomy and astrophysics. We envisage many further applications of the technology, but specifically we are interested in further enhancing the interaction the user can have with the figure. For example, it is possible with JavaScript to capture mouse clicks on individual elements of the 3-d scene; this could be used to directly select a galaxy (or galaxies) in a redshift catalogue visualisation and report their names to the user. In principle, object names gathered this way could then be used in JavaScript queries to remote data sources such as virtual observatory services. Additional proposals include developing uses for the Reader's measuring tool, and if possible, calculating and reporting statistics on regions selected by the user.

Finally, the opportunity to improve the science community's capacity to convey advances in our disciplines to the wider public should not be ignored. PDF

¹⁰ Adobe Reader 8 is available for Microsoft Windows, Apple Mac OS X and Linux systems.

is the most widely-used, self-contained electronic document format. Our funding agencies, governments and public can now easily interact with instructive, 3-dimensional graphical representations of our work — all we have to do is create and publish them.

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