3D Data Visualization in Astrophysics

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Abstract. We present unique methods for rendering astronomical data - 3D galaxy catalogs, planetary maps, data cubes, and simulations. Using tools and languages including Blender, Python, and Google Spatial Media, a user can render their own science results, allowing for further analysis of their data phase space. We aim to put these tools and methods in the hands of students and researchers so that they can bring their own data visualizations to life on different computing platforms.

https://www.cv.nrao.edu/~bkent/blender/

1. Introduction

Data visualization is a critical component of astronomical research. Large and complex data need innovative methods for display and analysis. Databases contain catalog surveys with hundreds of parameters creating large phase spaces to be explored. In addition, astronomical data provides some of the most inspiring and visually stunning images and simulations that the scientific community has to offer. Research tools for both scientists and broader impact to the intrigued public requires useful software tools to facilitate visualizing data. Tools are built by innovators within the astronomical community, others are adapted from software in other fields. The cross-disciplinary research creates beneficial resource and knowledge sharing between astronomy, 3D graphics, and data sciences (Kent 2017a).

Visualization using different methods can give insight into astronomical data. It is this data exploration that can shed new light on and lead to new discoveries with imaging, maps, catalogs and multidimensional data cubes. With the the increase in archival data products, research can benefit from *re-visualizing* prior epochs of data in new ways (Berriman & Groom 2011). Figure 1 shows the increase in archive, survey, and project volume vs. time. Visualization techniques and tools have become critical elements of astronomical research in the era of large surveys and high data rates.

Phase spaces of data sets with N > 2 require either a reduction in the number of dimensions to a two-dimensional plot or 3D rendering. With 3D graphics, one can see more information about a given set of data in one view, move in, around, and through a visualization. If there is a time series associated with an observation or simulation, it can be animated and rendered from multiple camera viewpoints. Immersive data experiences (virtual reality/augmented reality/cave wall) allow a user to explore data with devices they always have on their person - namely a mobile phone or tablet. The accelerometer hardware present in said devices can put a user *inside* the data and allow

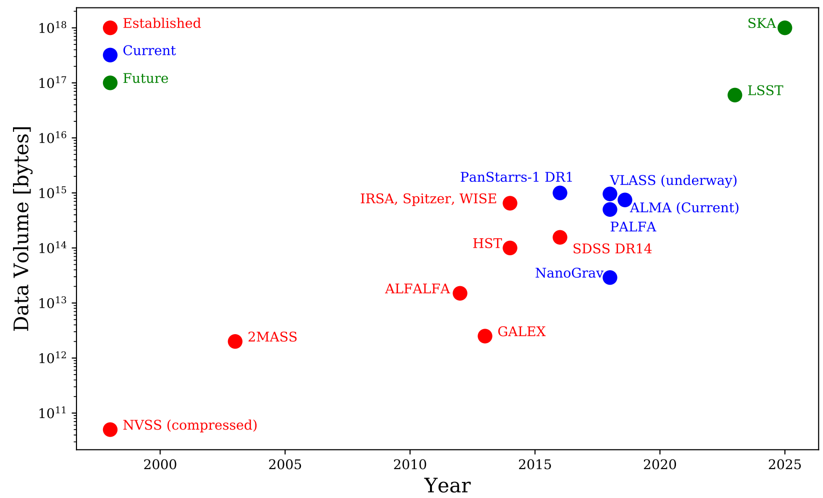

Figure 1. Increasing data volumes from established, current, and future astronomical surveys and observatories. References for these data points are as follows.
NVSS: `https://www.cv.nrao.edu/nvss/`
2MASS: `https://old.ipac.caltech.edu/2mass/overview/`
ALFALFA: Haynes et al. (2018)
GALEX: Bianchi (2014)
HST: `https://registry.opendata.aws/hst/`
IRSA, Spitzer, WISE: Berriman & Groom (2011)
SDSS: `https://www.sdss.org/dr14/data_access/`
PanStarrs: `https://panstarrs.stsci.edu/`
VLASS: Myers et al. (2015)
NanoGrav and PALFA: Demorest & Brazier (2018)
ALMA: Lacy & Halstead (2015)
LSST: `https://www.lsst.org/about/dm`
SKA: `https://www.skatelescope.org/`

visual data inspection and discovery (Kent 2017b). Whatever the application or goal, a 3D rendering can often enhance a data visualization scenario.

In these proceedings we specifically review a brief history of 3D data visualization, tools and types of methods in astronomy, software in the 3D graphics industry, Blender, a Python-API based 3D rendering software package, and Blender's usage in astronomy and astrophysics.

2. History

From a certain point of view, science has always relied on some form of data presentation or visualization to convey the results of an observation or experiment. Astronomy has a long history dating to antiquity of charting the heavens, and tabulating and graphing their temporal motions. Imaging ranging from plates and film to digital allowed astronomers to record and preserve what was detected at a particular time and vantage point. Radio receivers and high energy detectors expand our EM view of the Universe and push the boundaries of time-domain astronomy and the speed at which we can respond to target-of-opportunity events.

Two-dimensional plots act as a standard display to identify trends among data variable. Higher-dimensional data sets must either reduce the number of dimensions, use a 3D display, color with transparency accordingly, or use a combination of all three. Exploratory analysis and visualization can give insight into N-dimensional data with linked views – allowing a scientist to visually mine their data and any statistical properties (Goodman 2012). The availability of a wide variety of data and metadata parameters leads to science-driven development (Fitzpatrick et al. 2016; Graham et al. 2016).

Data visualization has now extended beyond the pages of journals and our desktop screens to virtual and augmented reality (VR/AR) and the mobile devices and tablets ever present in our hands (Vogt & Shingles 2013). These immersive data applications can put the user *in* their data space - while they have a certain aesthetic appeal and definite education and public outreach applications, they also can be used for research. Applications include collaborative visual analytics (Vohl et al. 2017b), multi-screen *CAVE* viewing (Vohl et al. 2017a), 3D printing (Madura 2017), and interactive applications (Punzo et al. 2015; Vogt et al. 2017).

3. Modules, tools, and libraries for 3D rendering

Defining software tools for data visualization can be a bit amorphous. A tool can be a full-featured astro-specific package, an ancillary library of classes and functions, or software from another technical area of research that can be adapted for use in astronomy. Tutorials written with code in a rich-text format or markup, or narrated video tutorials can train students and users on how to import and manipulate their data in new packages.

Astronomy packages like AstroPy (Astropy Collaboration et al. 2013), Kapteyn (Terlouw & Vogelaar 2016), and Montage (Berriman et al. 2007; Jacob et al. 2010) are used in conjunction with 3D graphics software, allowing a user to manipulate data in a Python environment before rendering. The flexibility of using modules makes 3D rendering packages versatile in manipulating different types of astronomical data.

Commercial packages used in the graphics industry are not traditional pieces of software used in the astronomical community. Maya[1], 3D Studio Max[2], and Lightwave[3] are full featured software packages that can be used to render 3D data. The Pixar package Renderman[4] can act as a backend renderer for several modeling GUIs. Others, like Houdini[5], have been successfully adapted for use in astronomy (Naiman et al. 2017).

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[1] `https://www.autodesk.com/products/maya`

[2] `https://www.autodesk.com/products/3ds-max`

[3] `https://www.lightwave3d.com/`

[4] `https://renderman.pixar.com/`

[5] `https://www.sidefx.com/`

4. Blender for Astronomy

Blender is an extremely versatile 3D graphics rendering package[6]. Its Python scripting capabilities and extensive graphical user interface make it a natural fit for astronomical data reduction [Kent 2013]. The utility of the package includes 3D modeling, 2D and 3D texturing, 3D voxel rendering, animation, lighting, camera control, and node compositing. Each of these features can be used alone or in concert for various forms of astronomical data visualization (Kent 2013, 2015).

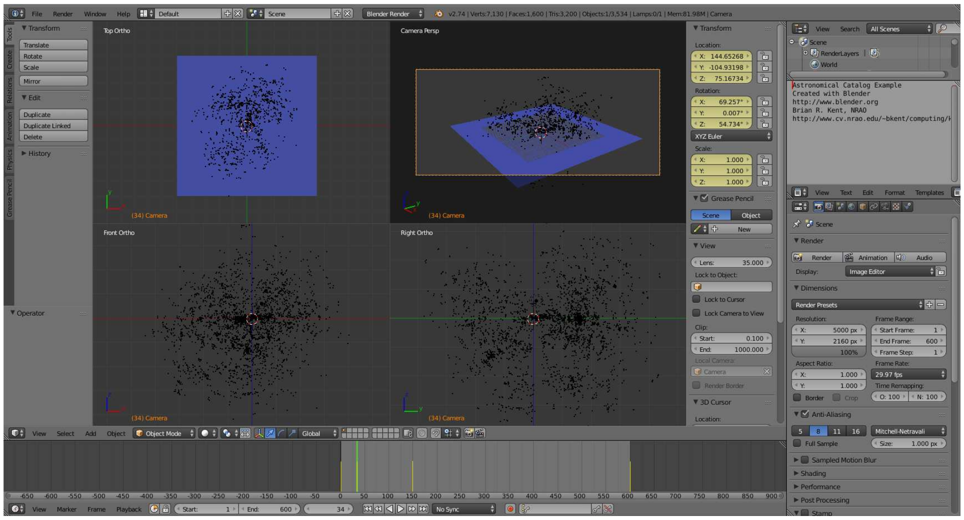

Figure 2. Interface of Blender showing a 3D data visualization of galaxies from multiple angles. The bottom interface shows markers for animation and camera key frames. This particular rendering will be used for spherical panoramic video for use on mobile and tablet devices.

- **Meshes.** Blender objects are built upon meshes - collections of vertex points, connecting lines, and faces. Meshes can be rendered as wire frames (useful for an extragalactic distance grid), as shaded polygons (useful for representative models or simulations), voxel containers (transparent data cubes), or textured 3D surfaces (planetary maps).
- **Cameras.** Rendering in Blender occurs from the view point of a Camera object. Focal length, detector size and resolution, field of view, and projection are all properties of a Blender camera object.
- **Lighting.** Lighting is accomplished via both emission and reflection mechanisms, usually with solid polygon surfaces. Wire meshes can be *self-illuminating* irregardless of where lighting elements are placed in a visualization scene.
- **Animation.** All meshes, lighting elements, and cameras can be animated. Animation involves translation, rotation, and scaling and the associated rates of those elements.

[6] `https://www.blender.org/`

Blender also has plug-ins for nVidia CUDA and OpenCL for GPU hardware acceleration in the rendering process. Depending on the application, this can greatly decrease the rendering time needed for visualization.

The Blender workflow for 3D astronomical rendering first requires the investigator to identify what kind of visualization they wish to make. Is it a single frame or animation? What platform will users view the rendering (video, mobile device/tablet)? Is it a physical model or does a 3D mesh object act as a container for a data cube? What are the requirements for the final rendering output? Is transparency or ray tracing needed? What camera angles are needed to show unique aspects of the data set for review and analysis?

4.1. Data visualization Examples

Astronomers have used Blender in a variety of ways in their work - developing code, tutorials, and examples for the community to build upon.

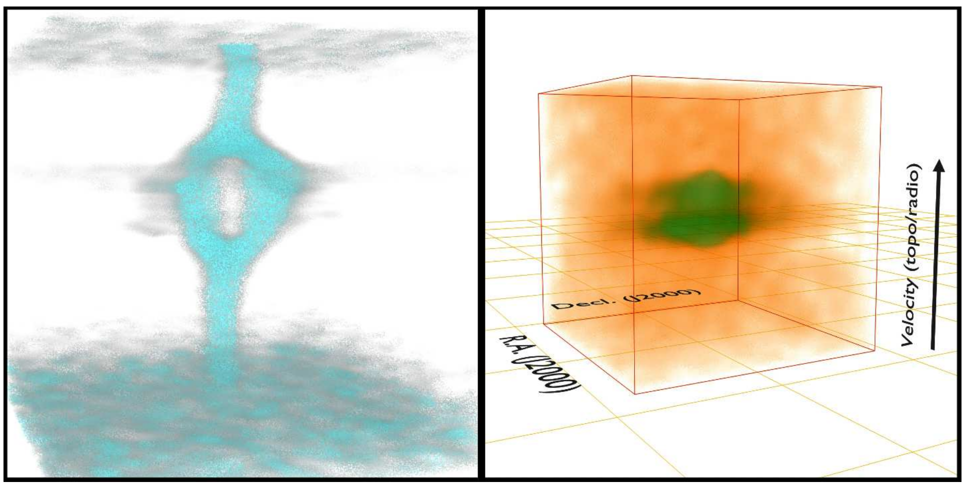

Figure 3. Data cubes with data from ALMA featuring *Left:* a protoplanetary gap (Casassus et al. 2013) and *Right:* HCN in the inner coma of comet C/2012 F6 Lemmon (Cordiner et al. 2014).

Examples are as follows:

- **Data cubes.** The voxel data structure in Blender allows a user to render data cubes transparently. FRELLED (Taylor 2015, 2017) has successfully demonstrated the concept with neutral hydrogen surveys. Gárate (2017) has used Blender to render magneto-hydrodynamic simulations. ALMA data have been successfully rendered using techniques involving Blender (Figure 3).

- **Simulations.** Figure 4 shows a snapshot from a galaxy collision simulation using data from GADGET-2 (Springel 2005). AstroBlend[7], an open-source Python library combines Blender with *yt* (Turk et al. 2011; Naiman 2016).

[7]`http://www.astroblend.com/`

- **Catalogs.** Figure 5 shows a 3D galaxy catalog rendering generated from the Extragalactic Distance Database, EDD (Tully et al. 2009).

- **Surface maps.** Figure 6 shows a displacement map of Martian shield volcano Olympus Mons with data from Christensen et al. (2001). Florinsky et al. (2018) have created morphometric globes for Mars and the Moon using Blender with a web interface.

- **EPO.** Diemer & Facio (2017) has used 3D printing and textile interfaces to create museum displays of cosmological large scale structure.

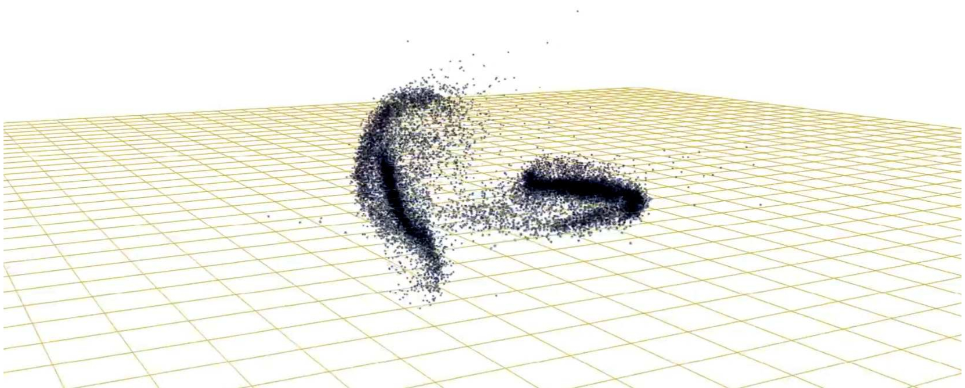

Figure 4. N-body simulation

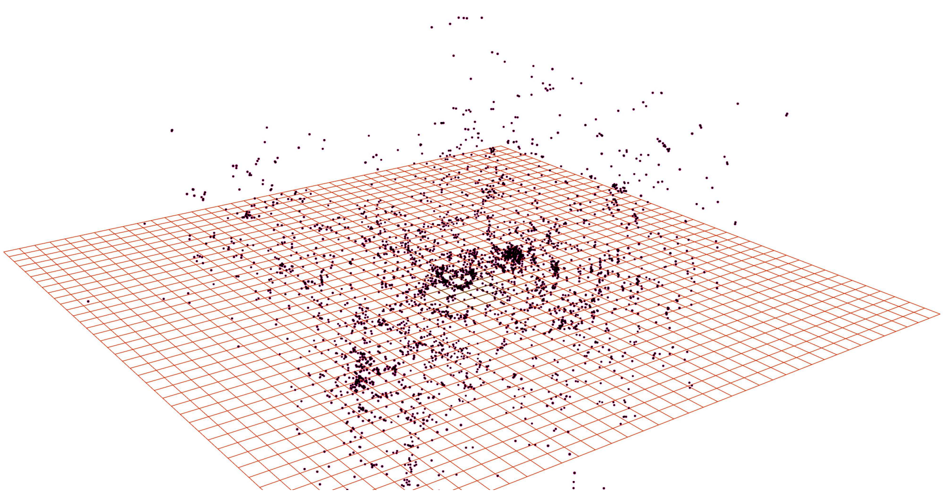

Figure 5. Extragalactic catalog rendering using data from Tully et al. (2009)

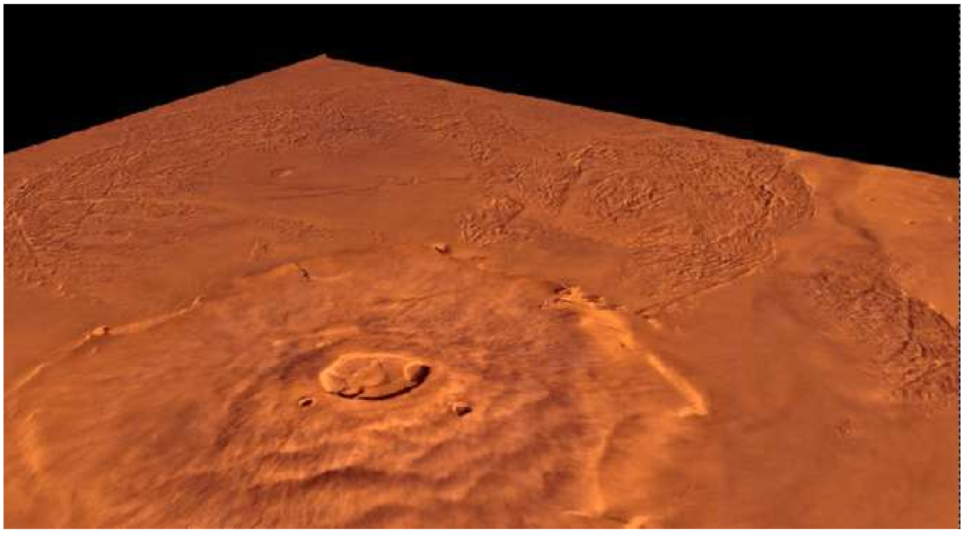

Figure 6. 3D surface rendering of Olympus Mons on Mars.

5. Mobile devices and interactivity

One of the best interactive data viewers is carried in our hands all the time. Mobile phones and tablets have high resolution displays and accelerometers that can allow a user to interactively view data - 3D models, all sky maps, or catalogs. Kent (2017b) and Fluke & Barnes (2018) detail how to do this using two different methods (Figure 7). Google's Spatial Media module[8], available as a standalone program or in Python, can take a spherical 360 degree video, inject metadata into the video header, and then have it be ready for injection in to the video sharing website YouTube. [9]

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[8]`https://github.com/google/spatial-media`

[9]Examples can be found on the author's channel *Visualize Astronomy*:
`https://www.youtube.com/user/VisualizeAstronomy/`

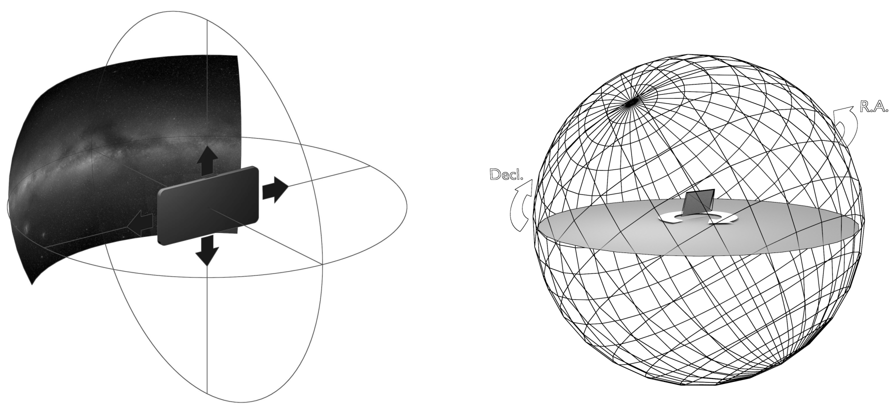

Figure 7. *Left:* A mobile phone or tablet can be used to view an all sky map. *Right:* An all sky map projection.

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