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# The Interactive Astronomy Textbook

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## Abstract

We introduce the use of in situ interactive three-dimensional (3-d) figures in digital astronomy textbooks as a means of enhancing student learning. The recent 3-d extensions to the Adobe Portable Document Format (PDF), combined with simple JavaScript, provide new ways to present intrinsically 3-d models, data sets, and instructional diagrams in digital publications. This is an enhancement to the usual method of presenting static, two-dimensional views, or "comic strip" sequences, to indicate changes in viewpoint. Interactive figures provide opportunities for students to undertake active learning while reading a textbook: they are able to explore and uncover the connections between viewpoint, orientation, and the 3-d nature of models and data sets for themselves.

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**This version of the article, created to accompany the standard *AER* versions, contains three-dimensional figures integrated into the document. Adobe Acrobat Reader 8 is required to use the 3-d functionality. The standard *AER* versions may be accessed at http://aer.noao.edu/cgi-bin/article.pl?id=264 (HTML) and http://aer.noao.edu/figures/v07i01/07-01-03-02.pdf (PDF with static figures).**

# 1. INTRODUCTION

"His pattern indicates two-dimensional thinking." Spock (*Star Trek II: The Wrath of Khan*)

There is a long tradition of using textbooks to teach astronomy as alternatives to original scientific works, journal articles, and other academic publications. Gingerich (1990) summarizes a number of the most influential texts of the last 800 years, starting with *Sacrobosco's Sphere* (c. 1220), which appeared in numerous editions over the following centuries. A key component of the majority of these early astronomy texts, particularly those aimed at an introductory or nonscientific audience, was the use of images. In fact, one of the earliest extant *scientific* graphs is in the appendix of an astronomy text, Macrobius's commentary on Cicero's *In Somnium Sciponis* (*Macrobius Boetius in Isagog. Saec. X*), which was transcribed by an unknown monk in the 10th or 11th century CE (Funkhouser 1936 and figures therein). The graph is a diagrammatic representation of the motion of the planets relative to the ecliptic versus time.

While the astronomy content may have changed over time, the reliance on figures to support the text has not; open any modern astronomy textbook, and it is full of photographs, visualizations, and instructional diagrams. Bruning (2007b, see Table 4) provides counts of the number of figures present in a survey of 21 recently published astrophysics textbooks for astronomy majors, showing that figures contributed between 5% and 39% of the total page layout, with an average contribution of 25%.

Prior to the computer-enabled multimedia revolution (especially the development of CD-ROM and, more recently, DVD technologies) and the introduction of the World Wide Web (WWW) (Berners-Lee et al. 1994), astronomy texts were almost exclusively static and two-dimensional (2-d). The main exceptions to this were the elaborate volvelles or rotula that were introduced in the 13th century by English historian Matthew Paris. A volvelle uses a combination of rotatable paper disks and string markers, which were bound into astronomy texts as early interactive displays. Now mainly a historical curiosity, volvelles have evolved into the modern cardboard or plastic planispheres. For discussions of the use of volvelles in astronomy, ranging from textbooks to medical diagnosis via astrology, see Stebbins (1959), Robbins (1970), Gingerich (1990), and Brück & Conway-Pikorski (1998).

In the multimedia/WWW era, there has been a revolution in publication. This has occurred in both the academic world, where digital publication of research journal papers has become standard (the present journal being an exemplar of this), and in education. Rich content, such as animations, movies, and interactive demonstrations, are provided to students on CD-ROMs or as URL links as part of astronomy textbook packages. Of the 23 introductory astronomy textbooks examined by Bruning (2007a), 18 had an ancillary CD-ROM with images and animations, 4 had a supporting Web site, and 3 texts were identified as "e-Books."

To date, these enhanced media have not been fully integrated into a stand-alone textbook format (but see our discussion of Web page presentations in the next section). Instead, the student is required to leave the text that he or she is reading (either paper based or electronic) to insert a CD-ROM, download a movie, or open a Web link. This can generate additional problems, such as compatibility issues between conflicting operating systems and computing platforms (Mac OS X vs. Windows vs. Linux), difficulties in installing specific software, and so on. These activities would all seem to distract from the continuity of an "all-in-one" educational experience—an actual enhanced, interactive textbook. But does such a product exist?

## 2. INTERACTIVE DIGITAL PUBLICATIONS AND 3-d PDF

The Portable Document Format (PDF), developed by Adobe Systems Incorporated as an open document standard, was released in the early 1990s. It has rapidly become the de facto standard for digital publication, replacing Adobe's PostScript. One of the main advantages of PDF is that the resulting documents are platform independent, so documents are easily transferable between different operating systems, and there is some certainty that all readers will see the same content in the same way. PDF files may be produced from a range of commercial desktop publishing packages, along with free applications like LaTeX.

An exciting addition to the PDF standard was announced by Adobe in May 2007: Adobe Acrobat 3D Version 8. This update enables the inclusion of interactive figures within PDF documents, which can be viewed and modified using the freely downloadable Acrobat Reader Version 8. Aimed initially at the engineering market, in which computer-aided design/computer-aided modelling (CAD/CAM) applications produce 3-d models, 3-d PDF can be used for a range of other purposes. This includes the presentation of scientific data (Barnes & Fluke 2008 [hereafter BF]; Goodman et al. 2008), and, as we will describe here, a step toward a self-contained, interactive digital textbook.

In BF, we demonstrate how a variety of scientific data sets may be presented in an interactive form, including point data, iso-density surfaces, and volume rendering. Two of these demonstrations are enhanced through the use of JavaScript, which allows custom controls such as buttons and menu items to be added to the file and linked to the 3-d figures. The interactive presentation of 3-d data sets provides new opportunities for knowledge discovery: published figures are subjected to a higher degree of peer scrutiny, and every reader can have a unique experience by controlling the way data are viewed.

The majority of the examples in BF and in the present article were produced using the S2PLOT programming library (Barnes et al. 2006), which provides a straightforward pathway for creating an interactive model via output in an intermediate data format (VRML). The VRML model is suitable for direct inclusion in PDF using Adobe Acrobat 3D Version 8.0, currently only available for Windows. A range of CAD/CAM and graphics formats produced from standard 3-d modelling packages, including Autodesk's 3ds Max and NewTek's Lightwave 3D, can also be imported.

The general process for including scientific data sets (such as demonstrated in the figures below) is as follows:

1. Prepare a representation of the data in 3-d space. This may require an appropriate conversion from spherical (e.g., right ascension, declination, distance) to Cartesian coordinates, and the creation of text labels and other annotations
2. Describe this data representation in a 3-d format that Adobe Acrobat 3D can import, such as VRML, Universal 3D (U3D), or Adobe's PRC format
3. Save/export the digital text file in PDF with appropriate spaces left for the 3-d figures
4. Open the PDF file in Adobe Acrobat 3D and add the data file as a 3-d annotation
5. Optionally, add JavaScript code to the 3-d figure and form elements in the PDF document to provide model-specific interactive features

We note that alternative pathways exist that do not require the author to use Adobe Acrobat 3D, such as creating U3D format figures that may be imported directly via the LaTeX documentation preparation system. Stand-alone viewers are available for 3-d formats such as VRML, so that the data models can be used within other contexts (including presentation on Web pages), and 3-d figures may be extracted from the PDF file if the end user has access to Adobe Acrobat 3D. There may be advantages in a user community sharing resources for the creation of standard figure components; we envisage making S2PLOT samples available as they are developed.

While elements of the desired integrated interactivity might seem to be available solely through Web page delivery, this approach has a few limitations:

- Cross-platform and cross-browser issues abound: what works with Explorer on Windows machines may not work with Safari on a Mac.
- Formatting and layouts are not strictly adhered to because the user may not have particular fonts installed or may choose to change default font size, etc.
- Web pages are ephemeral: teachers and students who have found a good online astronomy text or figure may not be able to return to it in the future.
- Most important, unless the user downloads the entire Web site in advance, there is a need for the user to be online—a situation that might not be practical for all students.

This last limitation can be reduced somewhat if the Web content is reproduced on a CD-ROM accompanying a textbook, but this requires the added overheads of authoring, burning, and distribution. As a fully self-contained interactive text, a PDF document works across all the main platforms (Windows, Mac, Linux), formatting is preserved, and the PDF file can be downloaded once and read offline.

## 3. INTERACTIVE EXAMPLES FROM ASTRONOMY

There is a clear application for 3-d PDF in teaching a range of scientific and mathematical disciplines (e.g., presenting the 3-d chemical structures of DNA and other biological molecules, investigating the tracks of particles produced in a high-energy physics experiment, or plotting strange attractors and other complex 3-d mathematical entities). In this article, we focus our attention on astronomy.

We believe that there are pedagogical advantages when students are able to interact with 3-d figures directly connected with the accompanying text. In BF, we presented an instructional diagram of the unified active galactic nuclei (AGN) model. Because the AGN model is interactively rotated, the visibility of the jet, dusty torus, and broad and narrow line regions changes, revealing the link between AGN classification and orientation. Building on this idea, the examples that follow demonstrate several standard 3-d problems that an introductory astronomy textbook is likely to cover. Usually, these are presented as 2-d static figures, relying on the choice of viewpoint or using a comic strip sequence of frames to show time dependence or changes in orientation. The relationship between these viewpoints may not be intuitive to students, particularly when they are presented before the student has developed an internal (cognitive) model of the 3-d configurations.

We contend that interactive figures enable the student to discover the connections between orientations and, we hope, improve their conceptual understanding of the 3-d nature of astronomical objects, compared with using static 2-d figures or even prerendered animation sequences (in which the student is again only presented with one viewpoint and cannot interact with the model except by starting and stopping the animation). This interactive approach promotes an active learning experience.

We note that the figures are only interactive in the PDF version of this article, and require Acrobat Reader Version 8.0 or later.

## 3.1 Solar System Orbits: The Inclination of Pluto

If a single example from astronomy is sufficient to justify the use of interactive and 3-d figures, it is the demonstration of the inclination of Pluto's orbit (17.16°). In Figure 1, we show the orbits of the eight planets (blue lines; Earth orbit is cyan line) and Pluto (red line). By clicking on the diagram and then interactively altering the viewing position and direction, the reader can compare the orbits of the major Solar System bodies in their own time and following their own "learning path." They can inspect the orbits from directly above the plane of the Solar System, from edge-on, and from oblique angles. With appropriate context and prompting in the text preceding the figure, most students will easily deduce that Pluto is the odd one out in terms of its orbit. Furthermore, the 3-d presentation of the orbits allows the reader to make the important discovery that the orbits of Pluto and Neptune do not intersect even though Pluto is at times nearer to the Sun than the eighth planet.

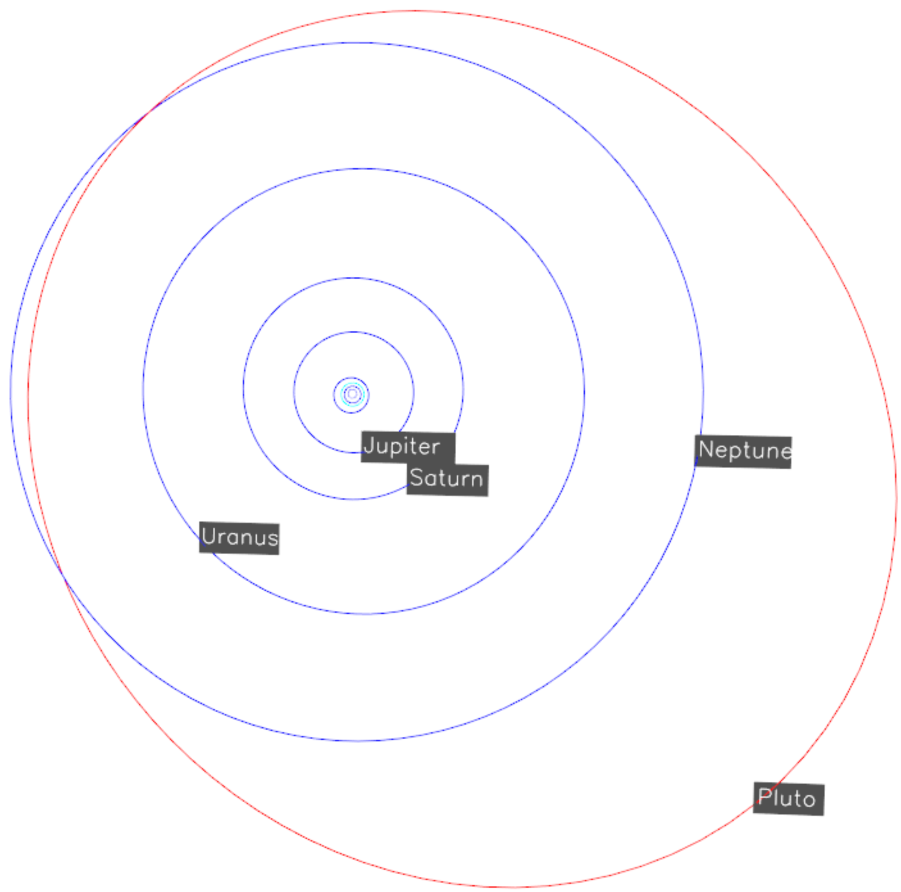


**Figure 1.** The inclination of Pluto's orbit (red) with respect to the plane of the Solar System is clearly apparent. The cyan line indicates Earth's orbit.

## 3.2 The Cause of the Seasons

At an introductory level, one of the most widely held astronomy misconceptions relates to the cause of the Earth's seasons. Although the Earth's elliptical orbit does bring it marginally closer to the Sun in

December than in June, it is the axial tilt that has the dominant effect of producing opposite pairs of seasons between the northern and southern hemispheres. A figure representing this relationship needs to show the Earth's orbit around the Sun and its axial tilt, while maintaining the correct spatial relationships between the two. A view from above the plane of the Earth's orbit is insufficient because the tilt of the Earth is not easily discernible. An oblique view is unsatisfactory because it distorts the Earth's (nearly) circular orbit shape in projection, which might be confused with the orbit's ellipticity. An interactive 3-d representation allows the reader to choose his or her preferred viewpoint so that the fixed direction of the Earth's axis and the (nearly) circular orbit shape are both apparent. The interactive 3-d figure suppresses the (incorrect) perception that the orbit is noncircular because (1) the reader can rotate the viewpoint to a position where the orbit *is* circular, and (2) the more natural perspective projection is used rather than the orthographic projection typical of 2-d figures. This is demonstrated in Figure 2.

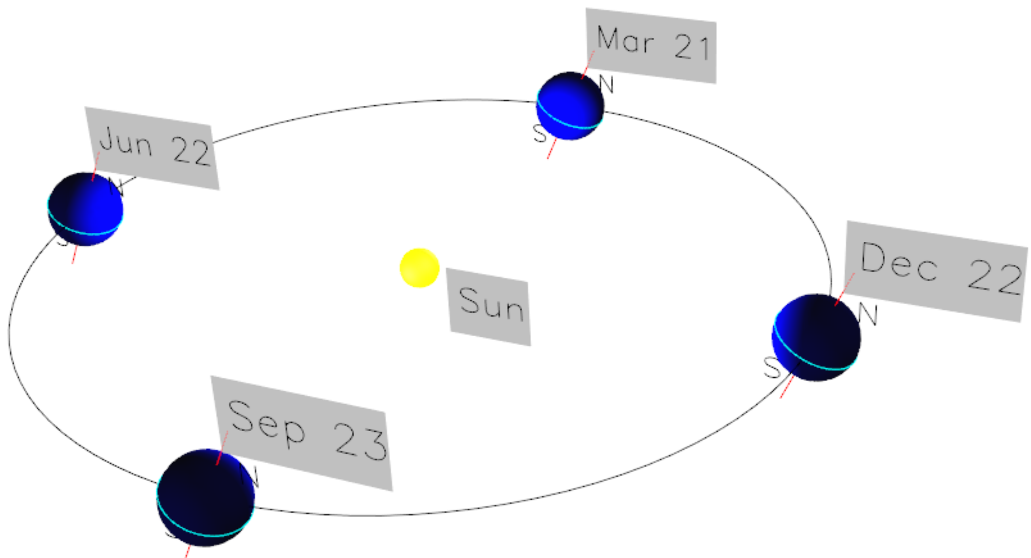


**Figure 2.** The cause of the Earth's seasons is the fixed direction of the axial tilt (red line) as the Earth (blue sphere) orbits the Sun (yellow sphere) in a nearly circular orbit. The cyan line indicates the Earth's equator. The Earth, the Sun, and the Earth's orbit are not drawn to scale.

## 3.3 Radar Mapping of Solar System Bodies

A growing number of Solar System bodies have now been mapped in 3-d. Whereas the Sun and planets are relatively smooth, oblate spheroids, the multitude of asteroids, satellites, and other small Solar System bodies have much more interesting nonspherical shapes. One of the most startling is the dumbbell (or dog bone!) geometry of the M-class asteroid 216 Kleopatra (Ostro et al. 2000), as shown in Figure 3. Three-dimensional interactive figures of unusual shapes and structures are far more instructive—at least qualitatively—than any collection of static 2-d projections. We contend that a figure such as this one enables the reader to construct a more accurate cognitive model of the asteroid's true shape than he or she would from 2-d figures, and in less time.

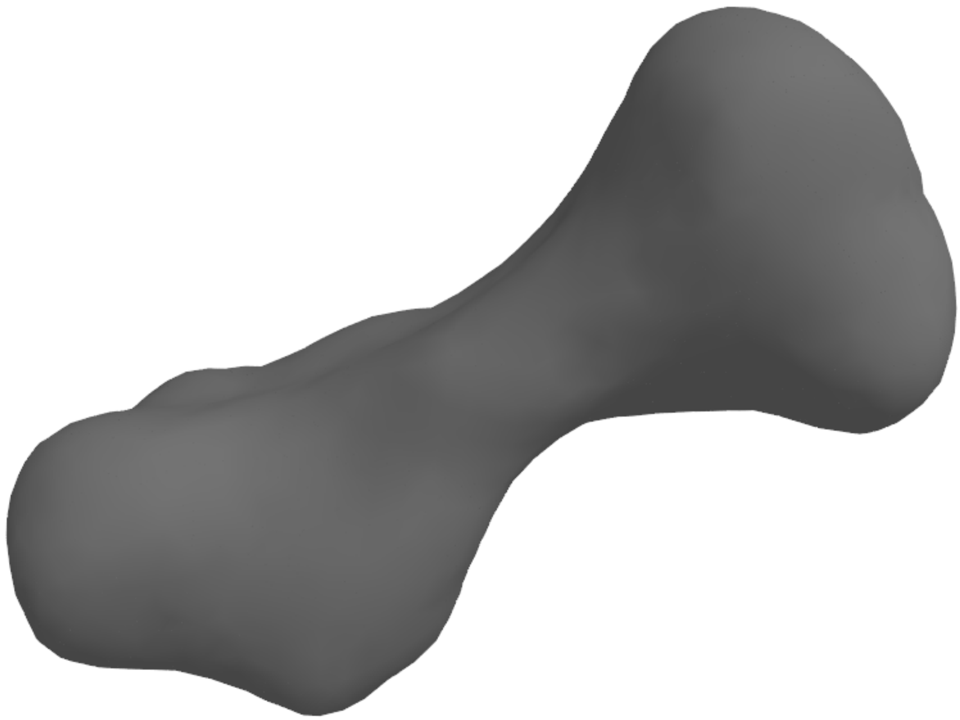

**Figure 3.** Asteroid 216 Kleopatra. The shape of this asteroid was determined using the S-band radar system of the Arecibo Observatory to create a series of delay Doppler images that are combined to determine the 3-d shape. See Ostro et al. (2000) for details.

## 3.4 The 3-d Distribution of Nearby Stars

Our next example takes us out of the Solar System and into the Milky Way. Using data from the HIPPARCOS catalogue (Perryman et al. 1997), the 3-d distribution of stars with measured parallaxes within 100 light years is shown in Figure 4. For a star with HIPPARCOS parallax $p$ (milliarcseconds), the distance is $d = 3260/p$ light years. Stars are colored according to spectral type, and coordinate lines are drawn at 25, 50, 75, and 100 light years. This figure introduces reader control of diagram *content*. Clicking a button selects which stars are shown, based on their distance to the Sun. A separate button controls the visibility of the coordinate lines. With the Sun at the center, the stellar distribution is fairly uniform out to 100 light years because this is well below the thickness of the galactic disk.

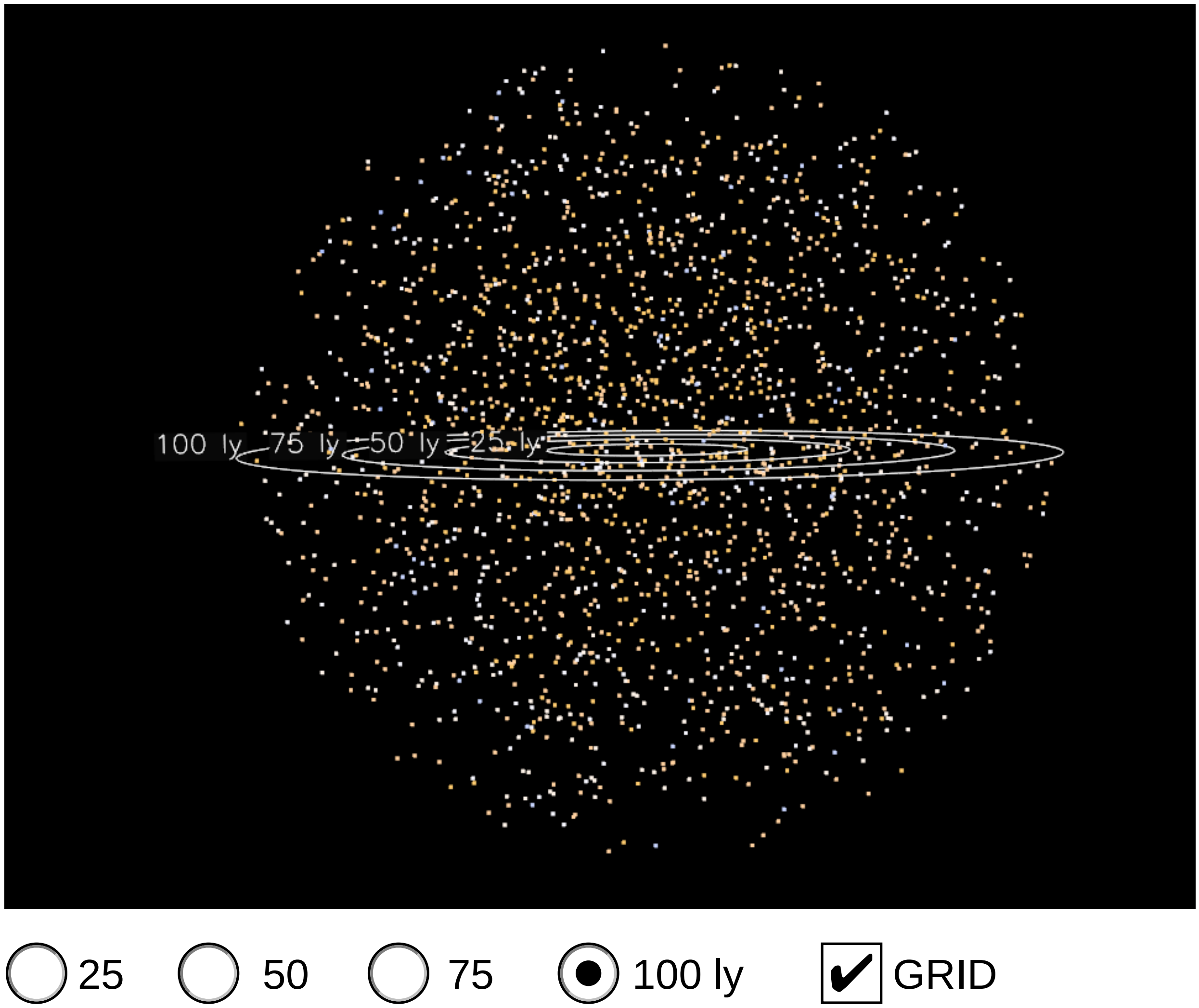


**Figure 4.** The 3-d location of stars within 100 light years of the Sun. Stellar distances are calculated using parallax data from the HIPPARCOS catalogue. Stars are colored according to spectral type. By clicking on one of the four buttons, stars within the indicated radius are displayed. The GRID button controls the visibility of the coordinate grid.

## 3.5 Pulsars

Pulsars represent an end point of stellar evolution for massive (> 6–10 solar masses) stars. They are extremely compact (radius < 10 km) and rapidly rotating (spin rates from 1ms to 10s), with characteristic masses of about 1.4 solar masses and magnetic field strengths above $10^9$ Gauss. Because their formation is quite violent, the pulsar spin axis and the magnetic field are usually not aligned. Although there are currently ~ 1,600 known pulsars, this probably represents less than 5% of the pulsar population in the Milky Way. Pulsars are only seen if the "lighthouse" beam of their emission intersects the Earth. This effect is demonstrated in Figure 5, where we present a conceptual model of a pulsar. The reader can move the camera position and angle of view to discover that the beamed pulsar radiation is only visible from special locations in space.

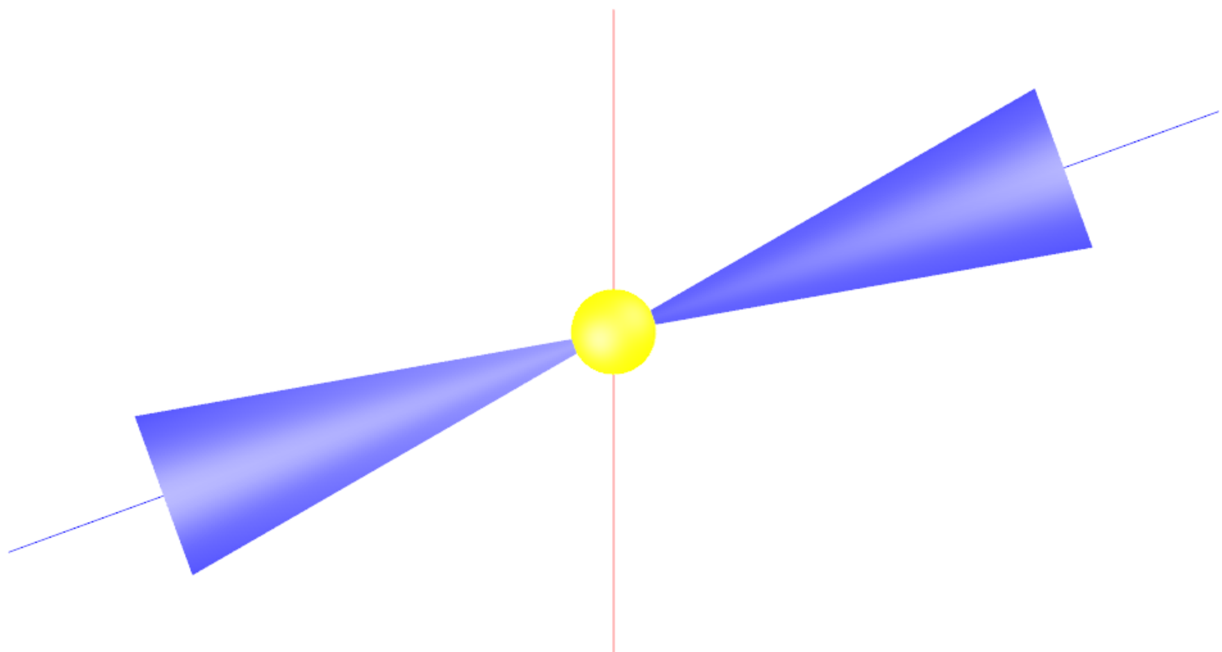

**Figure 5.** The "lighthouse" beams of emission (blue cones) from a pulsar (yellow sphere). The magnetic axis (blue line) is not aligned with the rotation axis (red line). The pulsar can only be detected with a radio telescope if the emission cone sweeps across the Earth. The JavaScript-enabled animation in this figure may be controlled using the Pause/Play button on the Adobe Reader 3-d toolbar.

## 3.6 The Filamentary Large-Scale Structure of the Universe

Galaxy redshift surveys mapping the 3-d distribution of galaxies have been growing in complexity since the Centre for Astrophysics (CfA) surveys of the 1980s (Davis et al. 1982; De Lapparent, Geller, & Huchra 1986; Geller & Huchra 1989). The 2dF Galaxy Redshift Survey (Colless et al. 2001), the Sloan Digital Sky Survey (Stoughton et al. 2002), and the 6dF Galaxy Survey (Jones et al. 2004) have now mapped ~$10^6$ galaxies, confirming the discoveries of the original CfA survey: that the large-scale structure of the Universe comprises a complex array of filaments, walls, sheets, and voids. The customary way to plot galaxy surveys is to use a cone or wedge diagram of right ascension, declination, and redshift (RA, Dec, z) triples. Figure 6 shows data from the CfA2 survey, selecting galaxies between declination 0 and 15 degrees, and velocities below 10,000 km/s. When displayed in 2-d, it is much harder to identify specific structures because of projection effects. Interactive exploration of a 3-d galaxy map is much more instructive because changes in orientation allow features like the Great Wall of galaxies (the extended, overdense region between 9h and 15h RA) to be easily discovered. It is important to remember that redshift maps are not spatial maps; they use redshift as a proxy for distance via the Hubble law. Proper motions of galaxies within clusters are superimposed on the Hubble flow, leading to the "fingers of God" artifacts pointing toward the origin.

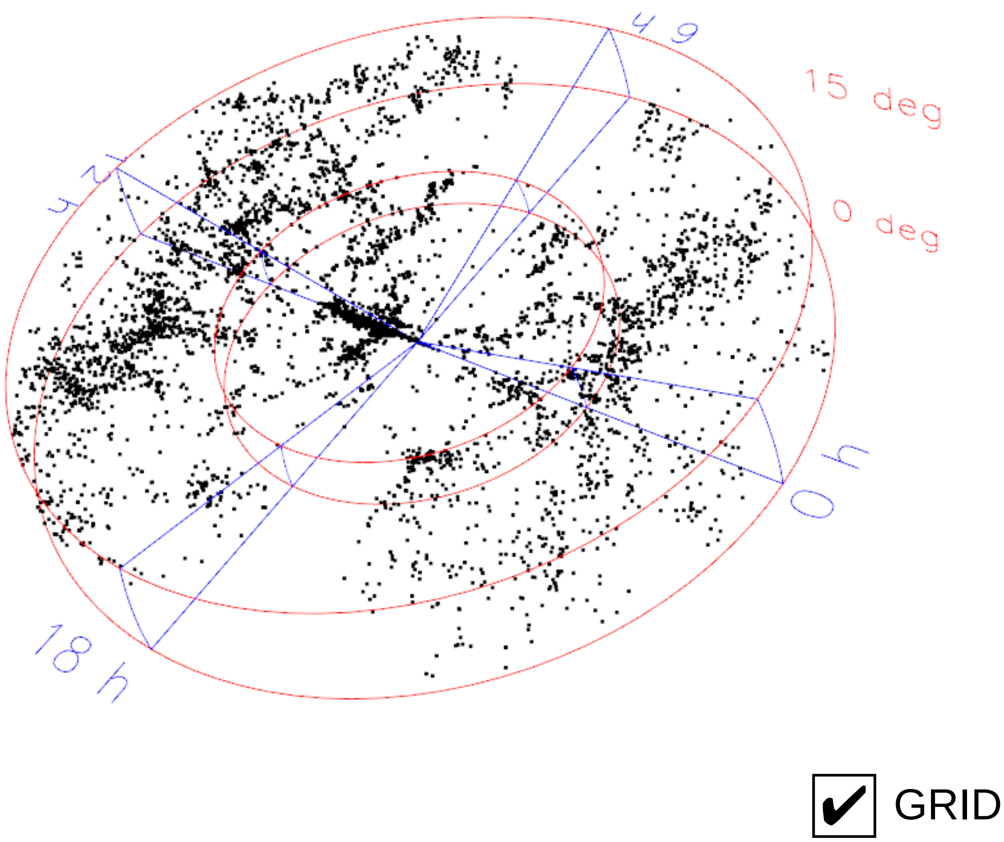


**Figure 6.** The large-scale structure of the Universe from the CfA2 galaxy survey. Plotted on this 3-d wedge diagram are galaxies between declination 0 and 15 degrees, and velocities below 10,000 km/s. There are gaps in the right ascension coverage between RA 5h30m to 6h30m, and 18h to 20h. The two sets of red declination rings indicate velocities 5,000 km/s and 10,000 km/s. Clicking the GRID button toggles the visibility of the coordinate lines.

# 4. CONCLUSIONS

In this article, we have demonstrated how 3-d PDF can be used to provide an active learning experience for students by embedding interactive models within a digital document. We have included examples ranging from conceptual models (Pluto's orbital inclination, the cause of the seasons, the rotation of a pulsar) to 3-d geometry (the shape of Kleopatra) and astronomical data sets (HIPPARCOS star catalogue and CfA2 galaxy redshift survey). It is easy to envisage numerous other cases in astronomy teaching in which an interactive presentation, combined with features such as animation and selection, can enhance the student learning experience.

Consider a traditional PDF file containing narrative text and vector or bitmap graphics. Add one or more embedded 3-d models, a few GUI elements (buttons, checkboxes, and so on), and some relatively simple JavaScript code. The result is a self-contained document that, when viewed with the Adobe Reader, constitutes an application of sorts. The reader has access to all the customary content of a text article, plus in situ interactive visualizations of 3-d objects. This is the interactive textbook.

### Acknowledgments

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## Web Links

Adobe Systems Inc.: http://www.adobe.com

Autodesk: http://www.autodesk.com

NewTek: http://www.newtek.com

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