Progress in Rendering and Modeling for Digital Planetariums

M. Magnor[1,2†] and P. Sen[2] and J. Kniss[2] and E.Angel[2] and S. Wenger[1]

[1] TU Braunschweig, Germany [2] University of New Mexico, USA

Abstract

Contemporary challenges in the production of digital planetarium shows include real-time rendering realism as well as the creation of authentic content. While interactive, live performance is a standard feature of professional digital-dome planetarium software today, support for physically correct rendering of astrophysical phenomena is still often limited. Similarly, the tools currently available for planetarium show production do not offer much assistance towards creating scientifically accurate models of astronomical objects. Our paper presents recent results from computer graphics research, offering solutions to contemporary challenges in digital planetarium rendering and modeling. Incorporating these algorithms into the next generation of dome display software and production tools will help advance digital planetariums toward make full use of their potential.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Viewing algorithms I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Physically based modeling I.3.8 [Computer Graphics]: Applications—Digital Planetariums J.2 [Computer Applications]: Physical Sciences and Engineering—Astronomy

1. Introduction

While researchers are currently exploring many innovative new uses for digital domes, the main application of public dome displays remains to be planetarium shows. Astronomy has a strong aesthetic appeal, and creating realistic vistas of the celestial hemisphere still constitutes the “killer app” that is making dome projection technology popular and marketable. Commercial vendors of digital dome displays, such as Sky-Skan, Evans & Sutherland or SCISS, all offer software to use their installations as digital planetariums.

Digital full-dome video projection systems have opened up various new degrees of freedom in how modern planetarium shows can convey knowledge about celestial mechanics, astrophysics, and cosmology. Present digital-dome planetarium software such as DigitalSky 2™ [Sky09], the Digistar™ systems [Eva09] or Uniview™ [SCI09] all offer real-time capabilities to allow for interactive show performance. However, rendering is typically based on OpenGL or DirectX techniques and so for many astrophysical phenomena, the results fall short from being physically realistic.

A challenging task for digital fulldome planetariums is to decide on how to present scientific content in the visually most intuitive way, given the innumerable possibilities offered by digital dome projection. This has revolutionized the way planetarium shows are being produced. For digital planetarium show production, computer-based image synthesis has become commonplace. Commercial animation tools, like Maya™, LightWave™ or 3ds Max™, are employed to build 3D models that resemble photographs of astronomical objects, which in turn are used to pre-render video sequences for planetarium shows [Dav05]. This approach, however, entails some fundamental limitations. Animation tools are not designed for real-time performance. Also, these tools had been developed with quite different applications in mind so they lack astrophysically realistic rendering algorithms which, however, are needed to correctly illustrate many effects. Finally, they offer little support for truthfully modeling astronomical objects, e.g., from observational data. Consequently, pre-rendered planetarium animations created with commercial software tools remain more-or-less artistic pieces of work, constrained by the limitations of the animation tools.

To overcome these limitations, we present recent graph-

† UNM Visiting Associate Professor, Fulbright Scholar

ics research contributions that address contemporary challenges in digital planetarium show production and live performance. In the survey that follows we can only cover a subset of relevant topics. Recent work on a number of important issues for digital dome displays, such as multi-GPU visualization systems, multi-projector calibration, and perceptual issues of domed displays must be left to a later survey paper. Here we concentrate on rendering and modeling aspects of astrophysical phenomena. While most of these methods have not been developed explicitly for domed displays, their incorporation into fulldome planetarium systems is, in general, straight-forward and constitutes a natural application scenario. We will cover the methods in two steps. The next section is concerned with advances to the digital display system, presenting specific rendering algorithms that facilitate physically correct rendering of various relevant natural phenomena. Sect. 3 then covers methods to assist in realistic content creation for digital planetarium shows, before we conclude with an outlook on future advances in digital dome displays.

2. Rendering

To fully exploit the capabilities digital planetariums have to offer, fast, realistic rendering algorithms are needed, enabling interactivity while maintaining scientific integrity.

2.1. Visualization Architecture

One challenge in modeling and rendering for planetarium-show purposes is the vast scale that must be covered, extending from the diameter of, e.g., a small crater on the moon to the size of the universe. In addition, pinpoint sources, planetary surfaces, as well as 3D volumes of interstellar gas and dust need to be convincingly represented and rendered, including immense regions of emptiness in-between. By now, several different commercial as well as freely available planetarium software products have risen up to the task. Power-scaled coordinates are one technique to generalize and optimize the conventional graphics framework to the scale domains of astronomical visualization [FH07]. Based on this architecture, an assortment of scale-independent modeling and rendering methods allows for scale-insensitive interactive visualizations of the physical universe, ranging in scale from the micro- to the macrocosmos. Similarly, the Uniview architecture is a real-time capable visualization platform that is based on nesting scene graphs containing data of arbitrary scale into a joint ScaleGraph representation [SCI09]. In professional astrophysics, endeavors are underway to build an internet-based virtual observatory which will encompass all observational data of the sky collected by astrophysicists worldwide in one database [IVO09]. Dome displays are ideally suited to browse, work with, and visualize this huge astronomical database [LAE*01], with digital planetariums serving appropriately as a virtual cosmos.

Figure 1: *Rendered appearance of two auroral curtains [BSR*00].*

2.2. Atmospheric effects

In addition to astronomical phenomena, digital planetarium shows often feature meteorologic and other atmospheric effects. Clouds, for example, make a frequent appearance on the celestial stage. Fast, realistic modeling and rendering of individual clouds has been extensively explored, e.g., by Harris and Lastra [HL01], Schpok et al. [SSEH03] or Riley et al. [RETH04]. To realistically render an entire cloud-covered sky, Olsson et al. developed a method to synthesize full dome, high-dynamic-range cloud cover for various weather conditions based on a database of HDR fisheye photographs [OYL03].

Another situation frequently occuring in planetarium shows is the rising and setting of the Sun. Close to the horizon, variations in the index of refraction of air with height can cause a variety of distortions to the appearance of the Sun's disc. These distortions have actually been used to probe atmospheric conditions [Bru96]. Employing non-linear ray tracing, the effect of an altitude-varying refractive index of air on the apparent shape of the sun can be computed to achieve realistic renderings of the solar disc close to the horizon [LHM05, GSMA06]. Varying air density, i.e., refractive index, in conjunction with air flow due to convection and/or wind is also the cause of star twinkling; interestingly, the twinkling effect appears to still await an elegant rendering solution.

Accompanying the rising and setting Sun is the colorful display of the twilight sky. Twilight colors are a volumetric effect that arises from multiple scattering off air molecules as well as aerosols and dust. Depending on the sun's elevation above or below the horizon and atmospheric conditions, the color palette across the sky varies tremendously. In contrast to the blue-whitish sky of daytime [PSS99], or the faint

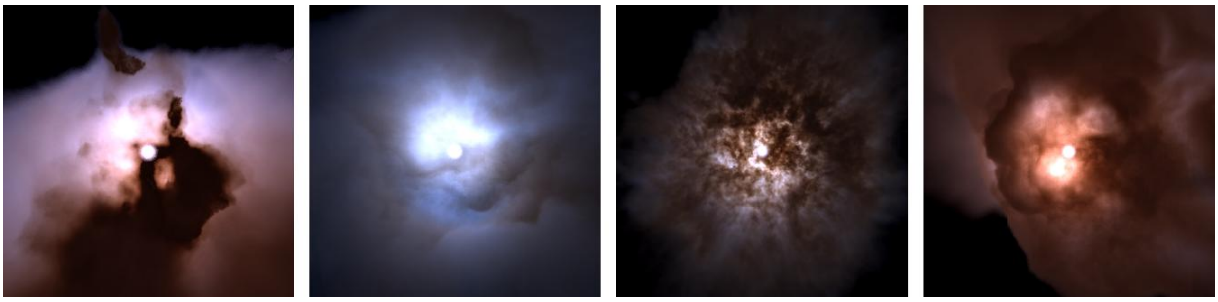

Figure 2: *Real-time rendering of four (synthetically generated) 3D reflection nebulae [MHLH05].*

airglow during the night [JDD*01], realistic rendering of the sky during twilight hours requires taking into account multiple scattering events in a volume 35km high and 1300km across [HMS05].Sunlight refraction, dispersion and scattering by volcanic ash in the upper atmosphere also affect color and brightness variations during lunar eclipses [YC09].

A different colorful phenomenon occurring in the upper reaches of the atmosphere are aurorae [BSR*00], Fig. 1. Electrically charged particles originating from the sun that are trapped by the magnetic field of the earth collide with air molecules which fluoresce at characteristic wavelengths, predominately in the green (oxygen) and red (nitrogen). Outside our atmosphere, finally, interplanetary dust in the ecliptic plane scatters sunlight to give rise to the Zodiacal light which is visible under dark skies [JDD*01].

2.3. Relativistic Effects

In Einstein's theory of special relativity, the properties of space, time, and light are frequently unexpected and often contrary to our experience from everyday perception. Digital fulldome planetariums are ideal instruments to intuitively illustrate the effects of relativity [WBE*06]. Two different techniques have been developed to visualize special relativistic effects. Relativistic ray tracing is an extension of normal 3D-ray tracing [HD89]. The ray starting at the eye point and at the intersection with the viewing plane is transformed according to special relativity, i.e., ray direction is changed according to relativistic aberration. In contrast, relativistic polygon rendering is based on the apparent shapes of objects as seen by a relativistic observer [CLC96, RWR98].

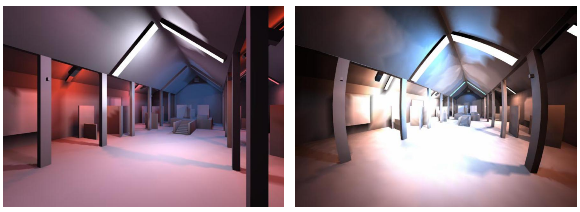

Figure 3: *Scene appearance for an observer at rest (left) and at 60% of the speed of light including all special relativistic effects (right) [Wei01].*

Relativistic illustrations typically only depict the apparent geometric distortion of space at velocities close to the speed of light. However, also the apparent radiance of objects is affected at relativistic speeds, Fig. 3. A photon-counting technique allows simulating the effects of relativistic transformations on radiance [WKR99]. The perceived image of a rapidly moving object shows Doppler shift as well as the so-called Searchlight effect. The Doppler effect causes a shift in wavelength of the incoming light, which causes a change in color of the observed object; the Searchlight effect increases the apparent brightness of an object ahead as the observer approaches the object at high velocity. Doppler shift, Searchlight effect, the relativistic aberration of light, and time dilation all contribute to the perceived appearance of objects when moving at relativistic velocities.

2.4. Nebula Rendering

Interstellar nebulae are clouds of gas and dust in our galaxy that are illuminated and/or ionized by nearby stars. For pure emission nebulae, visual appearance is completely determined by the 3D density distributions of the different ionized gas components. Typically, the visually most prevalent ionized gases are hydrogen (H-II) and oxygen (O-III). Each gas emits a characteristic line spectrum at a set of fixed wavelengths and with approximately constant, known relative line strengths [MKHD04].

In many nebulae, the ionized gases are interspersed with interstellar dust, or the dust constitutes the main component of the nebula. In this case, the complex interplay of emission, scattering and absorption within the nebula volume of varying gas and dust concentrations gives rise to the colorful and highly aesthetic appearance of reflection nebulae, Fig. 2. To realistically render such nebulae, the radiative transfer within the participating medium needs to be simulated to a sufficient degree of accuracy. Given suitable computational resources, this challenge can be solved by pure force: in a major effort to produce a 150-second video sequence of a journey through the Orion nebula for the Hayden Planetarium at the American Museum of Natural History in New York, 952 processors of an IBM RS/6000 SP supercomputer were kept busy for a solid 12 hours [Gen02]. With the aid of modern graphics hardware, on the other hand, realistic results can also be obtained at interactive rendering frame rates [MHLH05]. The rendering algorithm takes scattering phase function, albedo, and multiple scattering effects into account. To approximate the 3D rendering equation, multiple scattering is first considered locally before a volume resolution pyramid is applied to account also for wide-range scattering effects.

It must be noted that physically accurate renderings of nebulae can be at odds with images released by astrophysics agencies, the reason being that PR departments frequently "beautify" original scientifically correct images by altering the color palette, applying filtering operations or other image post-processing techniques offered by PhotoShop™. While these cover images set the expections of planetarium audiences, fortunately, astronomical nebulae still exhibit high aesthetic appeal if rendered authentically.

2.5. Astrophysical Simulation Visualization

Besides realistic rendering of actually observed natural phenomena, scientific visualization techniques make valuable contributions to digital planetarium shows. From pulsars and black holes to galaxy collisions and the Big Bang, many intriguing cosmic objects and events need to be put into pictures without having available any suitable observational image data. One way of creating impressive visualizations of such phenomena is to use commercial animation tools in conjunction with a lot of artistic imagination. On the other hand, what is known about these phenomena has frequently been derived from extensive scientific computer simulations. As an alternative to the artistic approach, astrophysical simulations enable creating physically more rigorous visualizations.

Creating appealing 3D renderings suitable for public display of astrophysical simulation results used to require tediously incorporating several visualization and VR software packages [KCP*02]. In recent years, techniques have been developed that are specifically tailored to astrophysical simulation visualization. For example, dynamic, three-dimensional galaxy and star formation simulation results can be rendered today in real-time using GPU-assisted raycasting of block-structured, locally refined grid data [KWAcH06]. But also for offline production purposes, ray tracing-based visualization tools specialized for astrophysical simulations are publically available [DRGI08]. Work on scientific visualization techniques has been extensive, and there exist many different methods today that can be useful to digital planetarium shows.

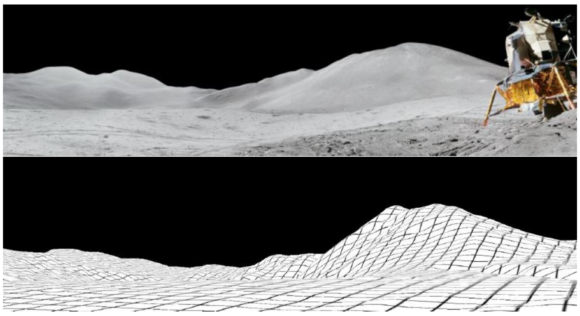

Figure 4: *Apollo 15 landing site: actual photograph (top) and perspective rendering of the reconstructed height map from a similar viewpoint (bottom) [WSSM09].*

3. Content Creation

Besides fast, realistic rendering of celestial phenomena, the creation of suitable 3D content for digital planetariums is another major challenge. Commercial animation tools originally designed for mainstream animation production need to be individually adapted to suit the needs of planetarium show production [Emm01]. In recent years, a number of methods have been devised to create physically realistic digital models of actual astrophysical objects and phenomena from observational data.

3.1. Moon Topography

For objects of the solar system, space missions have acquired a number of 3D models that are readily usable for digital production. Still, available models can become insufficient very quickly, e.g., when trying to render the lunar landscape from the perspective of the Apollo astronauts.

The highest-resolution, complete coverage of the Moon published to date is the Unified Lunar Control Network 2005 [ARKR06]. The network provides a global lunar topographic model that consists of 272,931 unevenly distributed measuring points, resulting in an average resolution of about 12 kilometers per pixel. Higher density topographic data is only available for a few limited areas of the Moon.

For convincing panorama renderings from viewpoints on the Moon's surface, lateral resolution must be 100 meters or less. The only (publicly available) complete coverage of the Moon's surface at sufficiently high resolution are the photographic images from the Lunar Orbiter IV mission, recorded on conventional film in 1967. Based on only a single photograph per region on the Moon, a robust shape-from-shading approach is able to augment the resolution of existing low-resolution height data [WSSM09]. A rendering of the reconstructed height map around the Apollo 15 landing site, Fig. 4, compares well to actual photographs of the landscape taken by the astronauts.

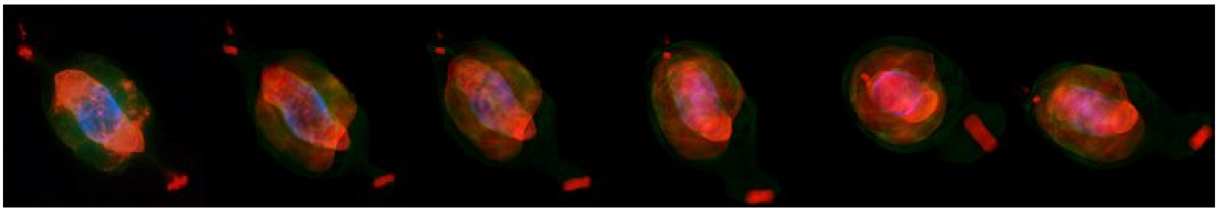

Figure 5: *Original view of the planetary nebula NGC 7009 (left) and its reconstructed 3D model rendered from various directions.*

3.2. Emission Nebulae

For objects beyond the solar system, observational information is available from essentially only a single perspective. To create a 3D model of a real nebula, e.g., for a fly-through sequence in a planetarium show, space artists will typically use Maya^{TM} etc. to hand-craft a volume model that visually resembles photographs of the nebula [Emm01, Dav05]. While the results are artistic pieces of work with considerable aesthetic appeal, they necessarily lack scientific rigor.

A notable exception is the work by Nadeau et al. on creating a scientifically well-founded digital 3D model of the Orion nebula for the Hayden Planetarium [NGN*01]. The rendered model is based on decades of observational data which was incorporated into one consistent spatial description by professional astronomers [ZO95]. To achieve the degree of visual detail needed for fulldome projection, however, additional fine-scale structure still had to be added to the model.

In astrophysics research, a special observational technique has been developed to recover the three-dimensional structure of spherically expanding planetary nebulae [STR*06]. For nebulae exhibiting a high degree of axial symmetry, simple deprojection techniques are able to recover main spatial structures from conventional photographs [Lea91]. More detailed 3D models of axi-symmetric planetary nebulae can be reconstructed from images using constrained inverse volume rendering [MKHD05]. Based on algebraic 3D reconstruction, also non-symmetric nebula features can be incorporated into the 3D volume model [WFMM09].

For more complex nebulae, the publically available software tool SHAPE is used by astronomers to create three-dimensional volume models of nebulae from astrophysical observations [SKW*10], Fig. 5. The tool allows for manual as well as automatic matching of geometric templates to observational data [WSK*10]. The resulting model can faithfully reflect a number of different observed physical properties of the nebula such as emission density of different gases, Doppler shift, or electron density.

3.3. Reflection Nebulae

With light emission, scattering and absorption all contributing to their appearance, the image formation model for reflection nebulae at visible wavelengths is considerably more complex than that of pure emission nebulae. For this reason, deriving 3D models of reflection nebulae must be based on more observational data as well as on additional assumptions.

In the astrophysical literature, descriptions of overall geometry can be found for a handful of reflection nebula, derived by combining various observational clues [WS86, GN03, ZO95]. For nebulae exhibiting spherical or axial symmetry, more detailed 3D models can be estimated based on multi-wavelength observations, recovering the individual distributions of dust and gas. Since observations at radio wavelengths are not affected by dust, the axi-symmetric gas distribution can be recovered directly from radio maps [LLM*07b]. In a second step, analyzing photographs at visible wavelengths while taking into account

Figure 6: *Original color-composited photos (left) and rendered 3D reconstructions (right) of the reflection nebulae NGC 7023 (top) and IC 5146 (bottom) [LHM*07]; field stars have been added to the rendered images for increased visual realism.*

the recovered ionized gas distribution also yields the axi-symmetric dust component. Similarly, observations in the mid- and far-infrared show only thermal emission by the dust [LLM*07a]. After recovering the axially symmetric dust distribution, visible-wavelengh photographs can be again be used to recover the absorption-corrected emission volume. But even for irregular reflection nebulae, it is still possible to derive physically consistent 3D models without user guidance, Fig. 6. Based on conventional, visible-wavelength photographs and identifying the nebula-illuminating star(s), an analysis-by-synthesis approach is able to estimate plausible 3D models of complex-shaped, real nebulae [LHM*07]. The method makes use of the real-time nebula rendering algorithm [MHLH05] in Sect. 2.4 to ensure that the resulting 3D models are physically consistent.

3.4. Galaxies

The visual impression of galaxies is the combined effect of billions of stars, ionized gas regions, and dark dust clouds. While such a detailed model is desirable for our own Galaxy, 3D renderings, e.g. of galaxy clusters, require much less model accuracy. Still, 3D galaxy models should closely resemble the appearance of galaxies in photographs.

A simple approach to derive coarse models of axi-symmetric galaxies is to deproject galaxy photographs [Pal94]. To obtain more refined 3D models of spiral galaxies, observations at infrared and visible wavelengths can be considered conjointly [HMF06], Fig. 7. By making use of a generic shape model of spiral galaxies, galactic dust distribution is estimated from infrared images via symmetrically back-projecting dust density across the equatorial plane of the galaxy model template. In a second step, visible-wavelength emission is incorporated into the model in an analysis-by-synthesis loop using the fast rendering algorithm for participating media of Sect. 2.4 [MHLH05].

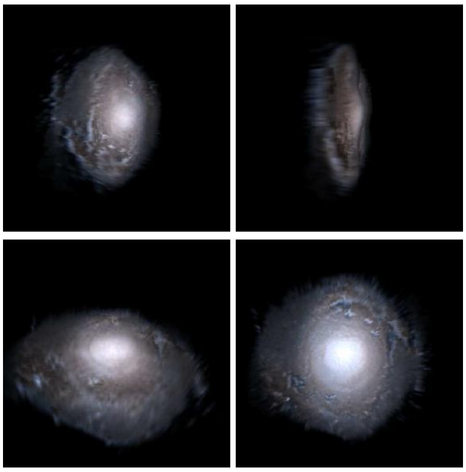

Figure 7: *Rendered images of the reconstructed 3D model of the spiral galaxy M81 [HMF06].*

Figure 8: *Digital planetariums excel in intuitively explaining astronomical relationships by realistically combining sky renderings with earthly environments [ZG05].*

3.5. Astrophysics Simulations

Astrophysics simulations used to require great computational resources way beyond the budgets of public planetariums. Fortunately, with today's high-performing and flexibly programmable graphics cards, simulating astronomical phenomena does not necessarily require a supercomputer anymore. Various PDE solvers have been efficiently implemented on GPU [OLG*07]. Magnetohydrodynamics [WWFT09], smoothed particle hydrodynamics [HKK09] as well as n-body gravitational simulations [NHP07] can all be run on a conventional desktop PC today. These methods are suitable for exploring astrophysical phenomena [WKM07]. They can also be directly employed to create input for scientifically meaningful, aesthetically appealing visualizations in planetarium shows [HNY*09].

3.6. New Themes

Other research in computer graphics that is directly linked to digital planetariums include work on historical astronomical navigation instruments [Zot08] and virtual archeoastronomy [ZG05, ZWP06, BZB09]. By design, planetariums are ideal instruments to explain celestial mechanics and astronomical calendarial events like equinox or solstice. Planetariums are also "time machines" in that historical celestial events as well as long-term changes in the sky, such as precession, can be faithfully reproduced. Today, digital fulldome planetariums offer the ability to combine realistic vistas of the sky with faithful digital reproductions of ancient environments, buildings, or instruments. By using digital planetariums to render the sky as it appeared during prehistoric times and incorporating virtual reconstructions of archeological sites, ruins can be understood in their celestial context, illustrating the significance of and the knowledge about astronomy in earlier civilizations.

4. Outlook

For many natural phenomena that are relevant for digital planetarium shows, physically realistic, fast rendering algorithms are available today. Suitably implemented on multi-projector platforms, these algorithms provide scientifically meaningful, interactive visualizations on dome displays. There also exist a number of methods to assist planetarium show producers in creating realistic content while, of course, always leaving open the opportunity to artistically guide and retouch the results.

Despite recent advances and contributions to digital planetarium technology, a number of open challenges remain for future work. One important issue will be to develop tools for assisting and accelerating show production. Currently, production of a 30-minute digital planetarium show can take several man-years of work. Examples for useful computer assistance may include automated path-planning, synchronization of visual and audio, and suggestions based on script text analysis. But also automatic generation of suitable 3D digital models from scientific data needs to be explored further to aid in realistic content production. Finally, new, innovative uses for domed displays will continue to emerge, ranging from various visualization and training simulation applications to potentially becoming also instruments of basic research, e.g., in visual perception.

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