Interactive Visualization and Simulation of Astronomical Nebulae

Stephan Wenger, Marco Ament, Wolfgang Steffen, Nico Koning, Daniel Weiskopf, and Marcus Magnor

Abstract— Interactive visualization and simulation of astrophysical phenomena enable digital planetariums and television documentaries to take their spectators on a journey into deep space and explore the astronomical wonders of our universe in 3D.

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When thinking about astronomical objects, the first thing that comes to mind is probably stars. Interstellar space, however, is also full of other fascinating phenomena: among the most popular ones are nova and supernova remnants as well as emission and reflection nebulae. What makes these objects so attractive is their intriguingly complex, intricate, and often colorful structure. Observing and investigating them is not only an aesthetic pleasure but helps physicists and astronomers deduct information about our universe and its laws of nature, for example by exploring cosmological effects from the theory of special [13] and general [12] relativity.

With the advent of the Hubble Space Telescope (HST), high-quality imagery of many distant objects has become available and popular. Unhindered by the Earth's atmosphere, the HST is able to capture images of unprecedented resolution. Through the use of filters, objects can be observed at distinct wavelengths, such as the emission lines of various ions outlining the distribution of different elements in the gaseous cloud of astronomical nebulae. Combining multiple such photographs produces the colorful, yet typically falsely-colored images we know from NASA and HST press releases (http://hubblesite.org/). Not only space-based telescopes yield spectacular new images, but also adaptive optics reducing the blurring effect of the atmosphere have led to high resolution images in the optical and near-infrared region of the spectrum. With highly sensitive CCD cameras, even amateur astronomers with relatively small telescopes are today taking incredible images.

One fundamental limitation of images captured from within our solar system is that they are inherently flat and two-dimensional. Because of the huge distance to most astronomical objects of interest, our fixed vantage point provides no useful parallax: wherever and whenever we take a photo of an interstellar object, its view remains the same. For nebulae, galaxies, and other complex objects, this makes it notoriously hard to identify their three-dimensional structure.

Three-dimensional structural information, however, is the key to many astrophysical questions. Scientists use 3D models of galaxies and nebulae to validate their theories about the formation and evolution of these objects. In addition, the wide public appreciates high-quality 3D visualizations of astronomical phenomena. Television documentaries disseminating advances in physics and space sciences make frequent use of animations to explain our universe. Modern planetariums have evolved from "indoor starry skies" to full-blown surround-video dome theaters with high-resolution digital projection systems and cinema sound systems [9]. Many planetariums already show more full-dome movie productions than traditional astronomy shows. Such educational shows can be spiced up with astronomical 3D content. Whether the show is pre-rendered or interactively presented, three-dimensional visualizations of otherwise abstract and complex subjects stimulate imagination and aid in the process of conveying scientific information.

Artists and astronomers face several challenges when creating three-dimensional visualizations of astronomical content. Sometimes it is sufficient for simulated data to provide an impression of what a general class of objects looks like and how it evolves in principle; often, however, it is more interesting to show the reconstruction of an actual astronomical object. In some cases, it is enough to present plausible but not scientifically exact reconstructions of existing objects; in others, scientific accuracy is called for. For an audience that is used to high-resolution renderings and high-quality special effects, the realism and resolution of the visualization is of utmost importance, often driving current hardware and algorithms to their limits. Especially for interactive presentations, rendering algorithms do not only have to model the physical light propagation and image formation as accurately as possible, but the algorithms also need to do so at real-time framerates for images the size of several megapixels.

While these challenges can be diminished with more or faster hardware, the fundamental problem in astronomical modeling and visualization is that of missing 3D information about astronomical objects. In past and current research, several methods have been proposed for generating three-dimensional visualizations from two-dimensional imagery in a more or less automatic way. The scientific accuracy of the results can, however, only be judged by human specialists, and many complex objects can only be modeled by hand. Specialized modeling tools aid astronomers and artists in this task. Other interactive tools support the simulation of fictitious objects to illustrate general concepts. Last but not least, sophisticated rendering algorithms process the resulting models to generate aesthetically pleasing and scientifically sound visualizations on the screen in real-time.

3D RECONSTRUCTION

Astronomers, planetarium show presenters, and directors of documentaries all benefit from being able to generate 3D visualizations for astronomical phenomena with the least possible amount of manual work. The easiest way to create three-dimensional content is to download a high-resolution image of the desired object from an online database and feed it into an automatic reconstruction algorithm. However, the reconstruction algorithm faces a difficult problem: the image contains only information in two dimensions, but does not directly provide any insight into depth or distance. Additional information, in form of a general model of what we expect the object to look like, is necessary to resolve this ambiguity. This includes both our knowledge about the emission and transport of light in astronomical objects and assumptions about their presumed geometry.

How exactly the two-dimensional image is formed depends on many physical properties of the phenomenon. Most objects of interest are at least partially transparent, so that the intensity we observe is a superposition of the object brightness at different depths. Some objects, like reflection nebulae, contain large amounts of interstellar dust that absorbs or scatters light from surrounding stars. When the dust is very dense, we can only see the outmost layers of the object before our view is effectively blocked, and no information about anything behind these layers can be reliably deduced from the image.

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DOPPLER EFFECT

The Doppler effect plays a key role in the observation of the universe. It describes the change of frequency and wavelength for radiation from an object that moves towards or away from the observer. Without the Doppler effect, we would probably be unaware of the *Big Bang*. When the relative speed along the line between a source of radiation and the observer is v, the observed frequency of a spectral line of frequency f changes by

$$\Delta f = f \cdot \frac{v}{c}.$$

Here, Δf is the change in observed frequency and c is the speed of light. By measuring Δf and solving for v, the Doppler effect can be used to measure relative speed along the line of sight.

For some astronomical objects, the speed towards or away from the observer correlates with the distance from the observer. For instance, in ballistic explosions the velocity $\mathbf{v}$ may be different for each particle but is constant over time for every part of the expanding material. Therefore, the position $\mathbf{p}$ of a particle varies with the time t as

$$\mathbf{p} = \mathbf{v} \cdot t.$$

In a ballistic expansion from a single point, the structure of the overall object remains constant; it is said that the expansion is *homologous*. Since the time since the explosion is usually unknown, the velocities do not translate directly into distances from the center of the explosion. Instead, an additional constraint—typically a symmetry assumption—is needed to fix the factor of conversion. Alternatively, the expansion velocity in the image plane can be measured directly by comparing two images taken several years apart. The time of the explosion can then be computed by extrapolating the expansion back to the center of the object.

EULER EQUATIONS

In computer animation, hydrodynamics is used to simulate various phenomena such as water waves, swirling clouds in air and water, or fire and fiery explosions. Except for explosions, all these fluid effects can be convincingly simulated using the *incompressible* Navier-Stokes equations. A key difference in astrophysical fluid dynamics is that most observable phenomena precisely arise from the compressibility of the gas in the extreme conditions of interstellar space. Therefore, the numerical methods commonly applied in computer graphics are unsuitable to simulate astrophysical fluids. As long as we can ignore magnetic and gravitational forces, the inviscid Euler equations are employed instead, which permit compression:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} + \frac{\partial \mathbf{H}}{\partial z} = \mathbf{S}$$

Here $\mathbf{F}$, $\mathbf{G}$, and $\mathbf{H}$ are the fluxes along the cartesian coordinate directions x, y, and z, respectively. They represent the mass, momentum, and energy that flows between the volume cells per unit time and area. Furthermore, $\mathbf{U}$ is the total internal energy, $\mathbf{S}$ represent sources and sinks of energy and t denotes time. The source and sink terms describe heating, cooling, and other possible energy changes due to external forces or nuclear or chemical reactions.

When appropriate solvers are used, the Euler equations allow for the formation of *shock fronts*. They are created when matter moves through a medium faster than the speed of sound, compressing the surrounding gas to many times its original density, heating it and thereby making it visible. Such shock fronts are ubiquitously observed in space as supernova remnants, jets or stellar winds interacting with the interstellar gas, producing colorful "spacescapes" that have become widely known through images from the Hubble Space Telescope. The software *Shape* incorporates "astrophysics grade" hydrodynamics in an interactive 3D modeling and animation framework following the scheme by Raga et al. [14] on a uniform cartesian grid.

On the other hand, many objects contain only small amounts of opaque matter. Planetary nebulae and supernova remnants, for example, develop from stars close to the end of their lifetime. The star ejects gas into the surrounding space, sweeping away any potential interstellar dust in its proximity. Due to the radiation from the central star, parts of the gas become ionized. When the electrons and ions finally recombine, light is emitted at characteristic wavelengths depending on the specific kind of ion involved. Since the gas is highly transparent, radiation from all depths within the nebula can be observed simultaneously, and the image contains information about all parts of the object.

Aside from a model of light emission and transport, automatic reconstruction algorithms rely on assumptions about the geometry of the astronomical phenomenon we want to reconstruct. Often, such assumptions can be deduced from the physical theories describing its formation and evolution. For example, planetary nebulae and supernova remnants develop when a gaseous cloud is ejected from a dying star. Since the star itself is approximately symmetric, the cloud will exhibit some degree of symmetry unless external influences deform it. Deformations may arise for many reasons, including an irregular ambient medium or relative movement of the nebula with respect to the interstellar medium. For single stars with negligible rotation and magnetic field, the resulting nebulae are often of overall spherical symmetry, Figure 1. Otherwise, for example when fast rotation or a binary star are involved, axial symmetries can occur, Figure 2.

Such symmetries can help resolve the depth ambiguity. When an object exhibits only emission—no absorption or scattering—and is exactly axisymmetric or even spherically symmetric, its three-dimensional geometry is uniquely defined by a single image. A similar statement holds when the object absorbs light from some known source in the background without emission or scattering within the object. In both cases, reconstructing a symmetrical volume from a single image amounts to solving a large system of linear equations [17], applying a deconvolution method [3] or optimizing the volumetric distribution subject to given constraints [8]. As soon as emission and absorption occur within the same object, such as in a star formation region, the ambiguity reemerges: for example, light could be emitted and absorbed in the object without ever reaching the observer. Scattering complicates this process even further. Fortunately, for planetary nebulae, scattering and absorption can often be neglected.

While the assumption of exact symmetry completely resolves the depth ambiguity, in reality even planetary nebulae are seldom exactly symmetric. This may be due to interaction with the surrounding medium, asymmetries in the initial conditions or large-scale instabilities during the expansion of the gas. Reconstruction algorithms, even those based on symmetry assumptions, have to take this into account: a perfectly symmetric reconstruction from an only approximately symmetric image will not be able to explain the observational data completely, and will look unrealistic and rather boring in animation. However, any part of the object that is in conflict with the symmetry assumption raises the problem of missing depth information again, and those parts have to be dealt with using heuristic algorithms [17]. In this way, recent automatic approaches are able to create plausible high-resolution volumes rich in visual detail, Figures 1 and 2, albeit with less plausible geometry than manual approaches.

As we have seen before, the light transport in most planetary nebulae is particularly simple. Reflection nebulae, which contain both gas and dust and therefore combine emission with absorption and scattering, are much more complex. However, at radio wavelengths, the dust is almost transparent. Thus, radio maps can be used to determine the emissive gas distribution in conjunction with a symmetry assumption [6] in the same way as for planetary nebulae. Similarly, the dust distribution can be reconstructed based on its thermal radiation in the infrared part of the spectrum [5]. In both cases, the remaining distribution—gas or dust, respectively—is then uniquely defined by the optical image.
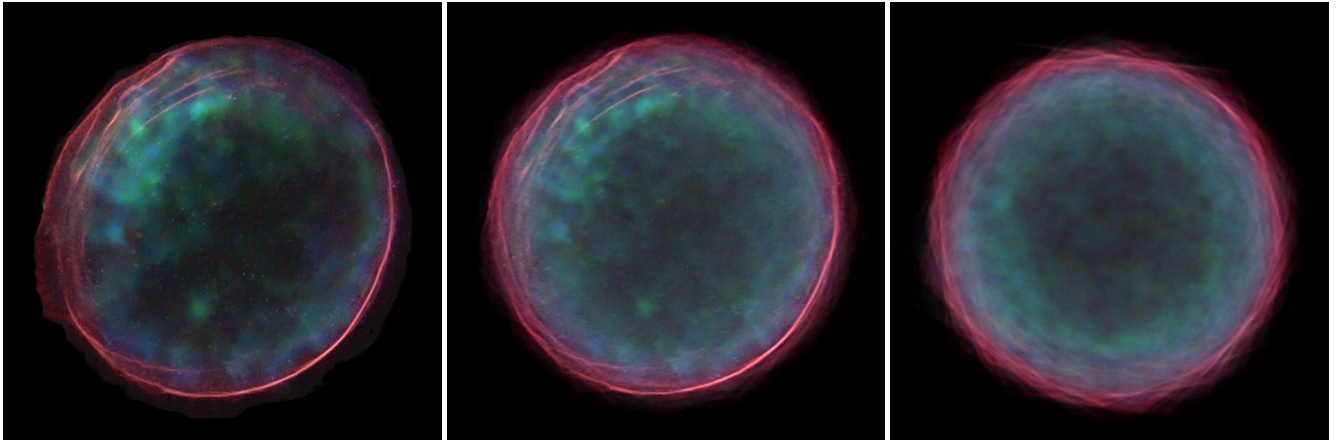
Fig. 1. Supernova remnant 0509-67.5 in the Large Magellanic Cloud. From left to right: observed image and reconstruction using spherical symmetry assumption seen from Earth and from space, respectively. *Original image: NASA, ESA, CXC, SAO, the Hubble Heritage Team (STScI/AURA), and J. Hughes (Rutgers University)*

The gas and dust distributions of a reflection nebula can also be reconstructed simultaneously. However, due to the complex mathematics of emission, absorption and scattering, the problem cannot directly be formulated as solving a system of linear equations. Instead, an *analysis-by-synthesis* approach is used: starting from a very simple initial guess for the gas and dust distributions, the algorithm renders the model and compares it to the image. The model is then iteratively fitted to the observational data, making small adjustments that are compatible with prior assumptions about the geometry. For example, instead of using a symmetry assumption as for planetary nebulae, we can assume that dust in reflection nebulae is located primarily close to the central star of the nebula. Based on this assumption, an analysis-by-synthesis algorithm [4] can generate plausible visualizations even for irregular nebulae, Figure 3, albeit at low resolution due to the computational complexity of the analysis-by-synthesis approach.

Even though the simple prior assumptions about the structure of astronomical objects are based on physical reasoning, they are only qualitatively valid for general classes of objects. The particularities of each individual object invariably cause deviations from the idealized model. Current automatic reconstruction results are therefore at best plausible, but never reliably physically correct. More complex and specific physical models—for example, including simulation of hydrodynamics or ionization in a nebula—could increase confidence in the accuracy of the results, but their computational complexity has hitherto prohibited their use in automatic reconstruction algorithms. No automatic system is yet on par with the expertise of an astronomer in resolving ambiguities in astronomical data.

3D MODELING

Only astronomers are able to judge what the real geometry of a planetary nebula or a supernova remnant looks like, and even among specialists, there is often disagreement: the morphology of many objects is the subject of current research. The model that astronomers and astrophysicists build of an object has to simultaneously explain different kinds of observational data. The most important source of information is imagery, whether from the visible, the infrared or the ultraviolet part of the spectrum, but other sources of data often provide more depth information.

For example, planetary nebulae continuously expand. The movement of the gas towards or away from Earth causes a *Doppler shift* of the wavelength of the emitted light, see box on page 2. Since the emission wavelengths of the different ions in a planetary nebula's gaseous shell are constant and exactly known, spectra with high wavelength resolution provide a way to determine the velocity component towards the observer with high accuracy. Interestingly, velocity often correlates with position. This is easy to see when we assume that the nebula was created by a single, instantaneous explosion: after a certain time,

faster particles have traveled further from the center of the explosion than slower ones. In this case, the shape of the nebula can be derived directly from the spectra [15]. However, the eruption of a nebula is often a continuous process, and magnetic fields, hydrodynamic effects or interactions with the surrounding medium can influence the velocity distribution. Thus, in general, all data have to be interpreted in the context of a holistic model of the formation and evolution of the object.

A complete model of an astronomical nebula comprises at least the current spatial distribution of different ions and their velocity distribution as a function of position. Based on these data, a rendering algorithm is able to reproduce typical types of observational data, such as optical images or Doppler shift spectra. In a typical workflow, the astronomer will create an initial model of the nebula based on their prior assumptions about its geometry. They will then try to reproduce the observational data from the model, making adjustments to the model until it is consistent with all available data.

The process of 3D modeling is facilitated by interactive 3D modeling systems. Traditionally, such systems are used by artists to generate various types of three-dimensional content for movies, animations, or games, and most provide integrated rendering engines to quickly check the results to expect. However, conventional modeling tools do not cover all physical properties that are needed for the accurate representation of astronomical objects, such as the velocity distribution of particles and the spectral characteristics of the different ions. Ordinary rendering engines also cannot reproduce all types of observational data obtained from scientific instruments, such as the Doppler shift spectra that provide information about particle velocity.

Therefore, custom tools for astrophysical modeling and visualization have been developed. The software *Shape* [16] allows users to interactively model astronomical objects and to generate physically accurate high-quality visualizations. Scientists use it, among others, to validate their theories about formation and morphology of planetary nebulae. Using the graphical interface of *Shape*, Figure 4, complex models can be built from simple deformable geometric primitives. The models can be visualized and compared directly to observational data from within the software, and selected parameters of the model can be automatically fitted to the data.

SPACE HYDRODYNAMICS

Astronomers can only claim to understand the structure of an astronomical object when they are able to explain its formation and evolution from appropriate initial conditions. For planetary nebulae, such initial conditions might be the characteristic physical variables of the dying progenitor star and its atmosphere. In the simplest case, the structure of the emerging nebula will then be determined by the equations of hydrodynamics. While many everyday fluid phenomena are
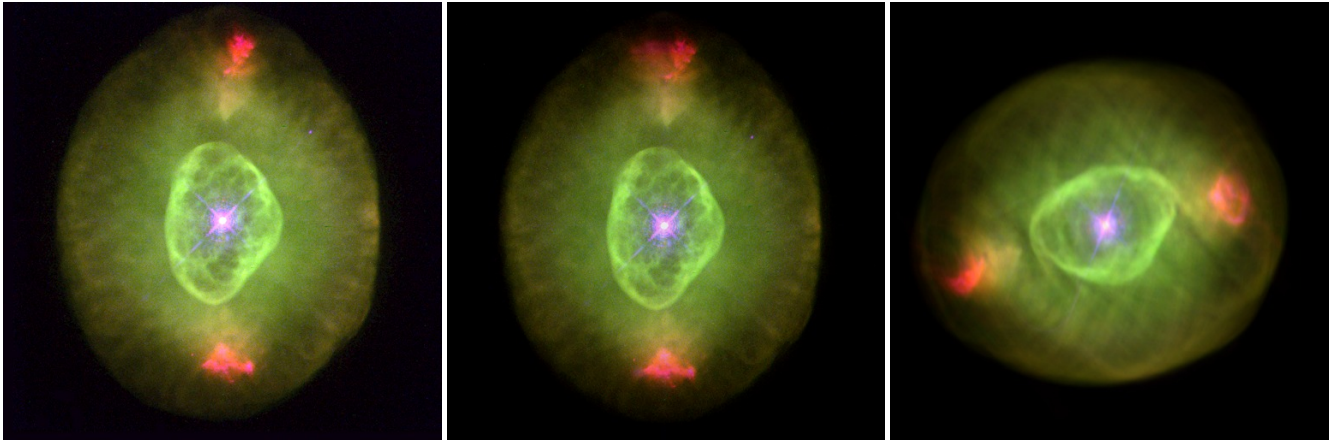
(a) NGC 6826.
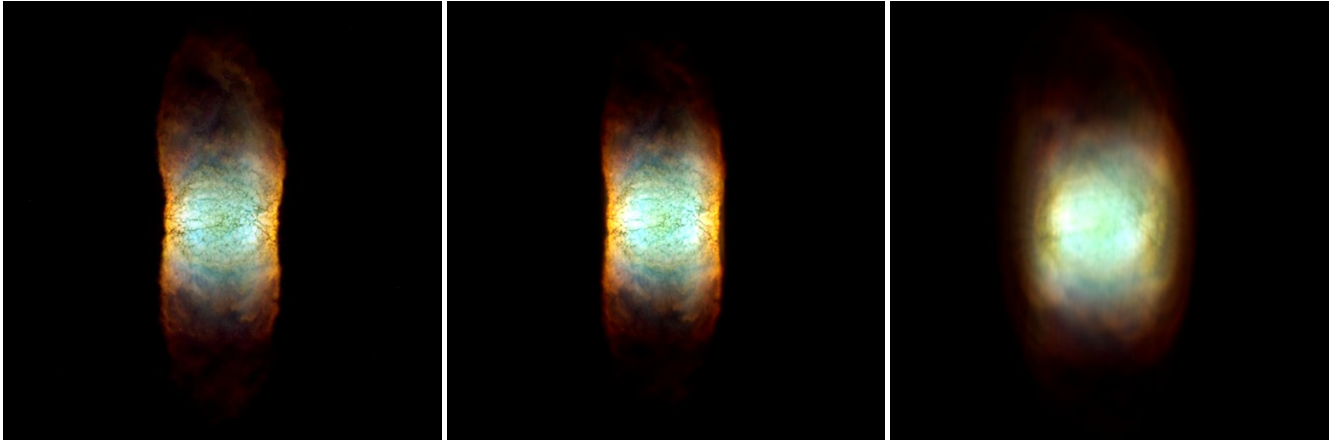
(b) IC 4406.

Fig. 2. Planetary nebulae NGC 6826, NGC 3132, and IC 4406. From left to right: observed image and reconstruction using axial symmetry assumption seen from Earth and from space, respectively. *Original images: B. Balick (University of Washington), J. Alexander (University of Washington), A. Hajian (U.S. Naval Observatory), Y. Terzian (Cornell University), M. Perinotto (University of Florence, Italy), P. Patriarchi (Arcetri Observatory, Italy) and NASA; The Hubble Heritage Team (STScI/AURA/NASA); NASA and The Hubble Heritage Team (STScI/AURA)*

readily described by the incompressible *Navier-Stokes* equations, this model is insufficient for the rarefied gases and high velocities that occur in astrophysics. The compressible *Euler* equations can be solved instead, see box on page 2.

Most conventional 3D modeling tools provide some kind of fluid simulation for water or flame effects. But because of the often supersonic motion in space, these simple hydrodynamic simulations are not adequate for the simulation of astrophysical phenomena. More complex simulation codes used in astrophysics research, on the other hand, are usually designed by and for specialists. Experimenting with such a simulation typically requires modifying the code, running the simulation, and visualizing the results in a separate step. *Shape* provides a more intuitive front-end to astrophysical hydrodynamics simulations by integrating the hydrodynamics simulation in the interactive graphical 3D modeling tool. Simulation results can freely be combined with manually modeled parts, Figure 5.

By modeling 3D initial and boundary conditions directly in the graphical editor, simulations can be run without having to do any programming. Parameters and boundary conditions can be altered while the simulation is running and intermediate results are visualized continuously. This allows even artists and hydrodynamics novices to quickly gain an intuition about astrophysical hydrodynamics.

PARALLEL GPU-BASED VISUALIZATION

After an astronomical model has been created using automatic reconstruction, manual modeling, or simulation, a method is needed to visualize it efficiently, accurately, and in high resolution. Digital planetariums, for example, provide full dome multi-projector systems with high image resolutions to create an immersive experience for the audience. Because creating high-quality images at the required resolution is a time-consuming task, animation sequences are often pre-computed. But pre-computed animations do not allow the presenters to interact with the spectators, adapting their presentation while the show is running. Therefore, modern planetarium systems like Digistar® (http://www.es.com) or Uniview™ (http://www.scalingtheuniverse.com) provide interfaces for visualizing digital content in real-time during a live performance. While such interactive features offer great possibilities for novel presentations, they also pose major challenges to the employed hardware and algorithms.

Many astronomical objects like nebulae or galaxies can be conveniently represented by sampling the properties of the physical medium on a discrete three-dimensional grid. In scientific visualization, such data is commonly visualized using *direct volume rendering* [1]. For each pixel, a viewing ray is traced through the medium, and the intensity is updated along the way according to the sampled values of light emission and absorption. When scattering occurs, such as for reflection nebulae, this simple scheme has to be extended because light that
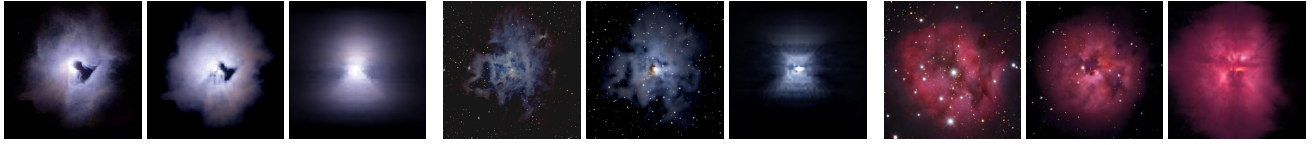
Fig. 3. Reflection nebulae NGC 1999, Iris Nebula, and Cocoon Nebula. From left to right: observed image and analysis-by-synthesis reconstruction seen from Earth and from space, respectively. *Images: [4]*
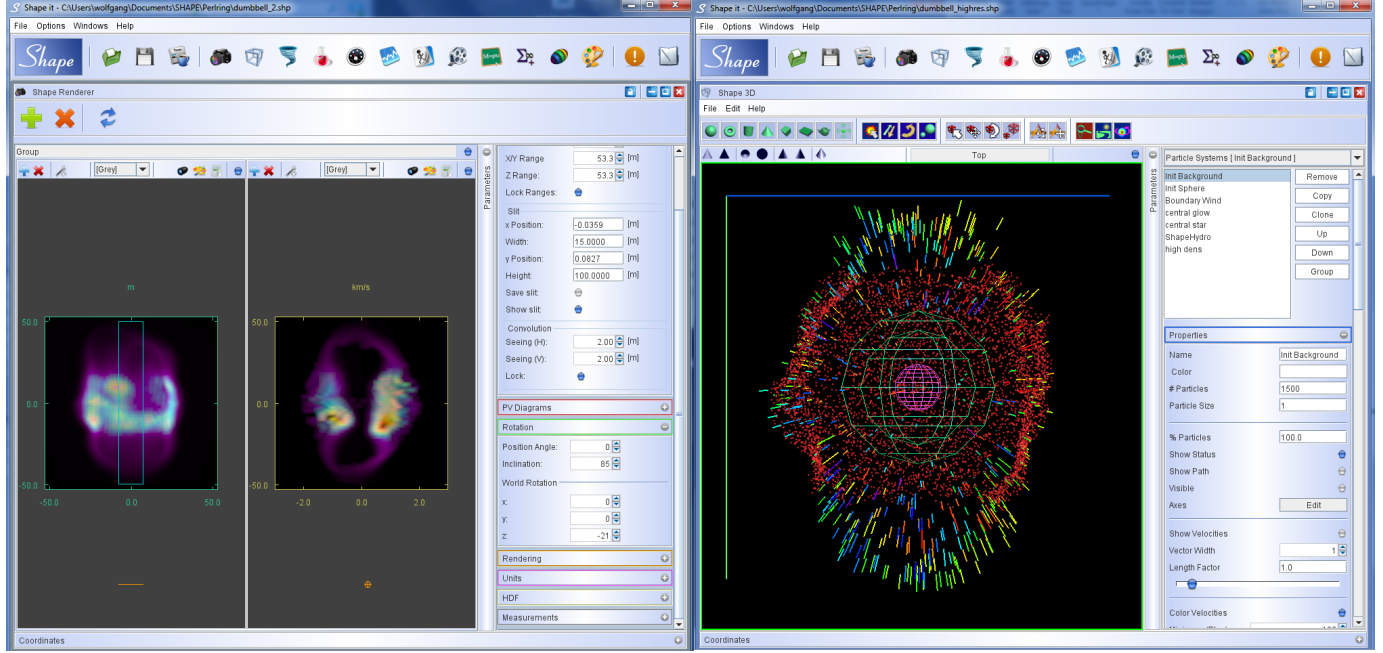

Fig. 4. Screenshots of the rendering (left) and 3D modeling (right) modules of the *Shape* software. The portrayed nebula was generated using *Shape*'s hydrodynamical simulation capabilities. The rendering module shows a false-color image (left) and a visualization of the Doppler shift of the spectral lines (right). The screenshot of the 3D module illustrates the structure and velocity information obtained from the simulation.

reaches the camera can now originate from positions that the original viewing ray never reaches. One solution is based on a multi-resolution rendering algorithm [7]. The volume is first sampled and rendered at very low resolution, and each sampling point receives scattered intensity from the neighboring sampling points. Because the resolution is low and each sampling points represents a large area within the volume, this accounts for long-range scattering in the object. The process it then repeated with successively increasing resolutions, adding more and more detail to the rendered image. Using this algorithm, reconstructed reflection nebula models can be rendered in real-time, Figure 3.

Most rendering algorithms require the casting of viewing rays through the volume to compute the color of the image pixels. For interactive presentations, this step cannot be pre-computed, and constitutes the most expensive operation especially for high-resolution images. To achieve real-time performance, rendering can be accelerated by performing many operations in parallel using graphics cards, or *graphics processing units* (GPUs) [2]. However, large data sets easily exceed the memory capabilities of a single GPU. High-performance real-time rendering algorithms for large data sets therefore require the development of distributed parallel algorithms running on compute clusters containing multiple GPUs.

The key idea of distributed parallel volume rendering is to decompose a large computational task into a set of smaller sub-tasks that can be processed concurrently by a set of GPUs, or render nodes. The two fundamental paradigms perform this decomposition either in image-space or in object-space [10]. The latter approach divides the volume into smaller chunks that are distributed to the different nodes in the cluster and rendered separately. Although this method scales easily to very large data sets, combining the images from the different nodes for display becomes increasingly costly when many nodes are involved. However, the size of present-day astronomical models is still small enough so that extreme data scalability is not the primary concern. In contrast, the image resolution of digital productions is growing continuously—modern projector systems feature resolutions of up to 8000×8000 pixels—and the increasing prevalence of stereoscopic shows requires to compute each image from two viewpoints simultaneously.

When the decomposition is performed in image-space, each node computes a different region of the image. Combined with multiple GPUs, image-space partitioning [11] is an efficient technique to compute images of very high resolution because the number of pixels per node decreases linearly by adding more nodes to the cluster domain. In contrast to an object-space decomposition, no additional compositing step is required, but only a final gathering of the tiles for display. Figure 6 shows how the computational effort is distributed in a setup containing four render nodes.

Image-space decomposition in its simplest form requires that the complete data set fits into the graphics memory of each compute node. When this is not possible, the required amount of memory can be reduced by dividing the data set into smaller bricks. Each node then only has to store the bricks that are visible in its subsection of the image, Figure 6(b). A further performance improvement can be achieved by dynamically adapting the image space decomposition. Whenever the viewpoint changes, the size of the image tiles is adapted such that each node has to perform the same amount of work. Figure 6(c) shows
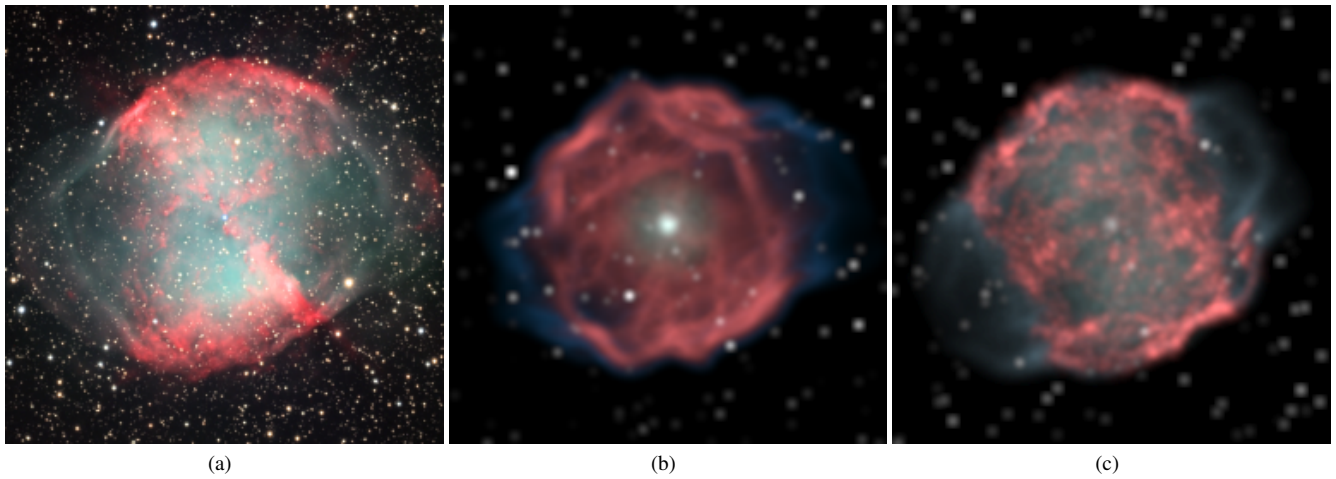
Fig. 5. The Dumbbell Nebula (a) and simulations done in *Shape*. The result of a hydrodynamic simulation is superimposed with manually modeled stars (b). By adding a noise texture, the small-scale structure of the red high density gas can be modeled more accurately (c). *Original image: Joe & Gail Metcalf, Adam Block, NOAO, AURA, NSF*
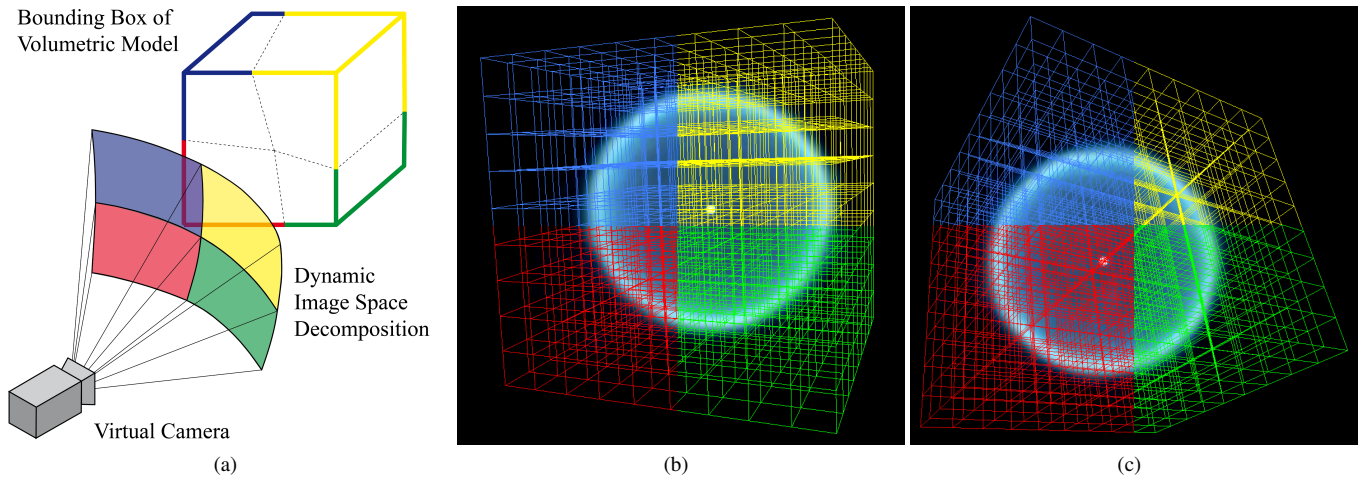

Fig. 6. In parallel volume rendering with dynamic image space decomposition, the computation of different parts of the image is split up between the four render nodes, here illustrated by different colors (a). To render its image tile, each node requires a different subset of the volumetric data, here a model of the planetary nebula Abell 39 (b). When the perspective changes, the required subsets of the data change accordingly (c), and with adaptive image space decomposition, the size of the image tiles is recomputed such that each node receives the same workload.

an example of how the decomposition is adapted as the view point changes.

OUTLOOK

The possibilities for astrophysical visualization and simulation have evolved enormously over the course of the last decades. Still, the future holds many challenges in this field. Computers are still not able to replace humans in the task of interpreting and understanding the world that surrounds us. We have seen that also in astrophysical visualization, manual work produces models that are far superior to automatic results in terms of scientific accuracy and plausibility. However, manual modeling of complex and detail-rich structures is extremely cumbersome. In the future, we expect automatic reconstruction techniques to be integrated with existing manual modeling tools, so that details are generated automatically while important geometrical features can be specified by an experienced astronomer.

In the area of astrophysical simulation, much improvement in terms of quality and speed has been achieved by the development of better numerical algorithms and the constant increase in computing power of current processors. Over the last years, however, this constant in-

crease seems to have come to a halt; instead, the number of processors in a single machine has started to increase. Due to their inherent parallelism, hydrodynamics simulations are well suited for simultaneous computation on a large number of processors. Notably, modern graphics cards provide the average customer with the technology to compute even large and accurate simulations at interactive rates. As this technology is being adopted in modeling and visualization tools, it may revolutionize the way we explore and experience our cosmos.

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