Automated Astrophysical Modeling with *Shape*

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Abstract

Three-dimensional models of complex astrophysical objects like galaxies or planetary nebulae have numerous applications in science, education and entertainment. The large distance of these objects, however, makes it difficult to obtain depth information, and conventional image-based 3D reconstruction algorithms and modeling tools are most often not able to faithfully reproduce their structure. Modeling is therefore typically performed manually by trained astronomers using specialized tools that incorporate additional information like spectral Doppler shift measurements into the modeling process. We present an extension to one such tool, Shape*, that alleviates the most tedious part of the modeling process by automatically optimizing consistency of the models with observational data. Our contribution significantly reduces the necessary time for obtaining high-quality models and will be incorporated into future releases of* Shape.

Categories and Subject Descriptors (according to ACM CCS): Computer Graphics [I.3.5.f]: Modeling packages—Image Processing and Computer Vision [I.4.8]: Scene Analysis—Physical Sciences and Engineering [J.2.c]: Astronomy—Physical Sciences and Engineering [J.2.i]: Physics—

1. Introduction

Many scientific problems in astrophysics rely on accurate three-dimensional modeling of complex objects. For example, many aspects of planetary nebulae can only be studied properly when three-dimensional information is available. The visualization of such phenomena for a broad audience, for example in planetariums, also profits from detailed models [MSK*10].Unfortunately, our fixed vantage point on Earth restricts the available imagery to two-dimensional projections of these objects from a single direction. Instruments with high spectral resolution provide information about the velocity towards the observer (via Doppler shift of spectral lines) which sometimes may be mapped to position. When the symmetry of the object is known, automatic reconstruction is possible [MKHD04]. In the general case, however, the under-constrained problem of reconstructing a three-dimensional model from data requires astrophysical knowledge and often involves educated guesswork. Therefore, complex models are still frequently generated manually by astronomers.

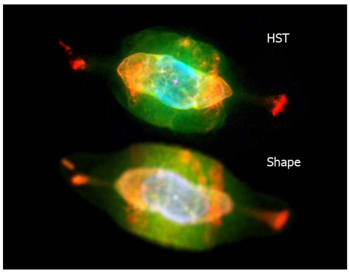

Figure 1: *The planetary nebula NGC 7009 in a photograph from the* Hubble Space Telescope *(top) and a rendered view of the 3D model created with* Shape *(bottom).*

Specialized modeling systems like *Shape* [SKW*10] combine realistic model rendering – reproducing different types of observations, e.g. spectral measurements – with the possibility to directly compare the renderings to actual observations (Fig. 1). *Shape* is a unique astrophysical modeling

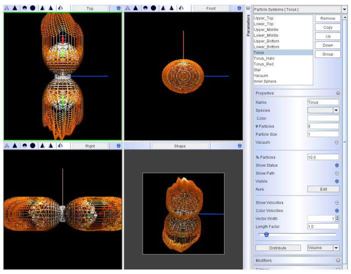

Figure 2: *Graphical interface of the* Shape *modeling system. In this example, the model is composed of twelve separate objects based on geometry (e.g. a torus) and modifiers (e.g. shear or translation). The view on the lower right presents the nebula as it is seen from Earth.*

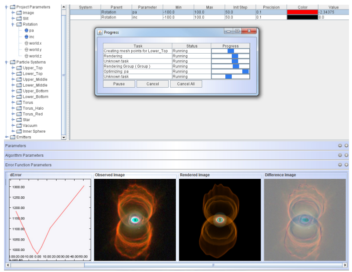

Figure 3: *Graphical interface of the* Shape *optimizer module. In this example, the spatial orientation of a model (bottom center) is fitted to an observed image (bottom left).*

tool, that for the first time applies interactive 3D mesh-based modeling to astrophysics. In a typical workflow, the observer will interpret observational data, form a hypothesis about 3D object structure, create an initial model (Fig. 2), compare the model to the data, and subsequently refine the hypothesis.

2. Automatic Optimization

This – often tedious – iterative process requires many steps to faithfully reproduce details of the object. On the other hand, physical knowledge of the astronomer mostly concerns its macrostructure. We make use of this fact by providing the astronomer with the option to automatically fit a suitable subset of the model parameters to the observational data, similarly to some object reconstruction methods in computer vision.

Shape models consist of base meshes (e.g. spheres or tori) that are deformed according to parameters for translation, rotation, shear, et cetera. Physical properties like volumetric or surface emission and absorption as well as particle velocity are defined with respect to these meshes, either using physically motivated analytical models or piecewise linear functions. An initial model can thus be parametrized by a set of (possibly hundreds of) real-valued parameters. We minimize the difference between spatial as well as spectral renderings and observations.

In realistic models, many parameters may be known to have very little influence on object appearance, or have even been determined exactly and do not need to be optimized. Some sets of parameters, e.g. rotation about different axes, are closely related, others, such as emission at different wavelengths, are entirely independent. We allow the user to select subsets of parameters that are optimized in order so that prior knowledge about interdependencies of the parameters can be exploited. In addition, initial guesses and bounds can be set for each parameter: for example, densities can be constrained to positive values, or the rotation of the main axis is limited within the error margin of established values.

A graphical interface is provided for easy interaction, Figure 3.

3. Conclusion

We have presented a method for model parameter optimization that greatly reduces the amount of manual work necessary to create faithful three-dimensional models of complex astrophysical phenomena by automatically fitting the model to various types of observational data. The resulting models are used in astrophysics research as well as for appealing visualizations, for example in planetariums.

Future extensions to the system include automatic modeling of smallest details – which cannot easily be modeled as geometry – as surface or volume textures, as well as plausible synthesis of additional detail for realistic zoom-in visualization in education and entertainment.

Acknowledgments

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