Fast Visualization Methods for Comparing Dynamics: A Case Study in Combustion

Kay A. Robbins* and Michael Gorman†

Abstract

Visualization can be an important tool for displaying, categorizing and digesting large quantities of inter-related information during laboratory and simulation experiments. Summary visualizations that compare and represent data sets in the context of a collection are particularly valuable. Applicable visualizations used in these settings must be fast (near real time) and should allow the addition of data sets as they are acquired without requiring rerendering of the visualization. This paper examines several visualization techniques for representing collections of data sets in a combustion experiment including spectral displays, tiling and geometric mappings of symmetry. The application provides insight into how such visualizations might be used in practical real-time settings to assist in exploration and in conducting parameter space surveys.

Keywords: Realtime visualization, steering, symmetry, tiling, pattern formation, movies.

1 Introduction

Laboratory experiments and field surveys of physical and geophysical systems usually produce complex data sets in which the relevant physical variables such as velocity, density, intensity, temperature, salinity, and vorticity have both spatial and temporal dependencies. A single experiment or field survey often encompasses the acquisition of a collection of spatiotemporal data sets, taken under varying conditions or experimental parameters. Scientists need fast methods for tracking changes in such data sets in order to adjust laboratory or acquisition parameters. Survey visualization techniques should also retain some historical summary of the data sets so that scientists can track where they have been. In addition the techniques should be amenable to on-the-fly generation. That is, as data sets are acquired, they should be added to the existing context without redrawing the visualization. The visualization requirements for the laboratory and field are similar to the well-documented requirements for visualization during computational steering [1, 2, 5, 7], but the need for speed is often more pressing and driven by external conditions [8].

This paper examines several methods for fast display, comparison and differentiation of scalar data sets that exhibit complex spatial and temporal behavior. We consider methods that can be applied on-the-fly to provide a comparative visual summary of behavior. We also examine methods that provide an iconization of the data set, that is, a small scale representation that accurately depicts a physically significant feature. Good iconizations can be used to compare, organize and navigate large collections of data sets [6, 9]. We apply the methods to a collection of data sets from a combustion experiment and discuss how such visualizations can be used while the experiment is in progress.

*Division of Computer Science, University of Texas at San Antonio, 6900 North Loop 1604 West, San Antonio, Texas 78249, krobbins@utsa.edu

†Department of Physics University of Houston Houston, Texas 77004, gorman@uh.edu

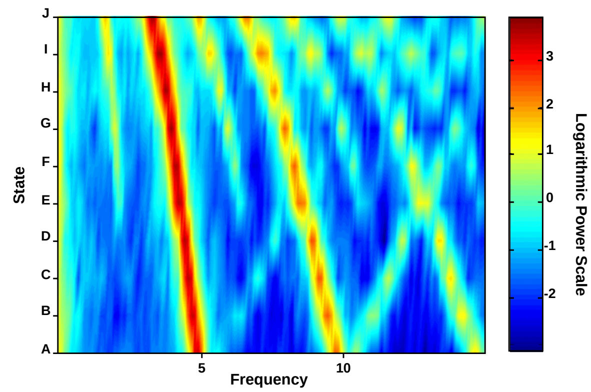

Figure 1: A tiling of the power spectrum for the radial extinction states. (See also the Color Plate.)

2 The Combustion Application

The experimental data sets used in this paper were generated from a combustion system that is prototypical of pattern-forming systems. A flame front is established over a porous burner in a combustion chamber. The controlling parameters are the flow rate (of a fuel/oxidizer mixture), the equivalence ratio (fuel to oxidizer) and the chamber pressure. Because the underlying dynamical variable is proportional to the light intensity of the flame front, video provides direct quantification of spatial and temporal behavior [3].

In a typical experiment, a series of data sets are captured as a parameter such as the flow rate is varied in incremental steps. The goal of the experiment is to characterize flame behavior as a function of system parameters and to detect and analyze transitions in behavior. The flame front exhibits hundreds of distinct dynamical states at different parameter values and provides insight about how symmetries limit possible transitions. Visualization during the experiment is important for this system, because changes in behavior are sometimes difficult to detect visually. It is also difficult for the experimentalist to categorize and remember the details of behavior during the run. A goal of this work is to explore techniques that would help the experimentalist classify and abstract these data sets for future reference.

To examine these issues, we focus on ten data sets (A through J) taken in the pulsating regime near the flame extinction limit at roughly equally spaced decrements in flow rate. Observationally, the flame front appears to be a flat, steady circular disk. As the flow rate is decreased, the flame front loses stability and begins to pulsate radially. As the flow rate is decreased further, the front loses symmetry and executes wild oscillations, extinguishing for very low rates.

3 Power Spectra Displays

The power spectrum of a data set (energy in the Fourier series expansion) provides a familiar assessment of the complexity of the data. A spectrum with sharp peaks indicates oscillatory behavior at specified frequencies. A broad background indicates more complex, aperiodic behavior. The original experiments were instrumented with a spectrometer that measured total intensity of the flame front and computed instantaneous power spectra. We also computed the power spectrum for each data set from the average image intensity in 128 frames. The power spectra from the two sources agree well.

Power spectra from multiple data sets can be stacked in a 3-dimensional display. As additional data sets are taken, they can be added behind the existing display. In order to see how the spectrum changes with parameters, the scientist must select an appropriate viewpoint for the visualization. The difficulty in discerning trends in such stacked graphs has been documented in another setting by van Wijk and van Selow [10].

An alternative to the stacked display is a two-dimensional pseudocolor map such as the one shown in Figure 1. The power spectra for each state is displayed as a horizontal line of colors. Bilinear interpolation is used to color the pixels between the horizontal lines corresponding to measured states to produce a continuously colored rendering of the power spectra. The color scale maps red to the highest intensity and blue to the lowest intensity. (See the Color Plate.) The dispersion in the pulsation frequencies is easily visible as an increase in the hot colors in the background. State E shows the appearance of a harmonic with half of the period of the dominant frequency, signaling the presence of a period-doubling bifurcation.

In addition to a lower computational cost, the pseudocolor display shows more clearly how major peaks of the spectrum change with parameter than do visualizations that stack the spectral curves successively in 3 dimensions. However color is not as good an indicator as height for representing widely varying intensity levels, making the pseudocolor displays more difficult to use in understanding how the background spectral levels broaden and how the behavior of the fall-off of the spectrum changes with parameters.

The pseudocolor display can also be used for on-the-fly generation of data. A color scale can be determined from the first data set. As additional data sets are acquired, additional rows are added to the display. One difficulty with setting the scale from the first data set is that when later data sets contain more power, the visualization saturates. Color sliders can alleviate scaling problems to some extent by allowing the user to dynamically adjust the colors to saturate different parts of the spectrum. Unfortunately neither type of spectral display provides information about spatial behavior.

4 Tiling

The simplest approach to comparing spatial and temporal behavior of movies is simply to use a tiling display. Frames of the movie collection are displayed in a rectangular array as shown in Figure 2. In this figure, six consecutive frames of video were displayed for four data sets. The tiling display, commonly provided in movie editing software such as Adobe Premiere, provides a direct visualization of the space-time behavior of the data sets.

The tiling display, while straightforward, presents some visualization difficulties. An obvious problem is the low contrast level of the images for this particular collection of data sets, which makes it difficult to distinguish the actual shape of the objects. The contrast problem can be addressed by using pseudocolor rather than grayscale for the display. (See the Color Plate.) The use of color clarifies the changes in shape of the front during its oscillations.

Another problem with tiling displays is the shear volume of data in a parameter survey. The survey discussed in this paper originally

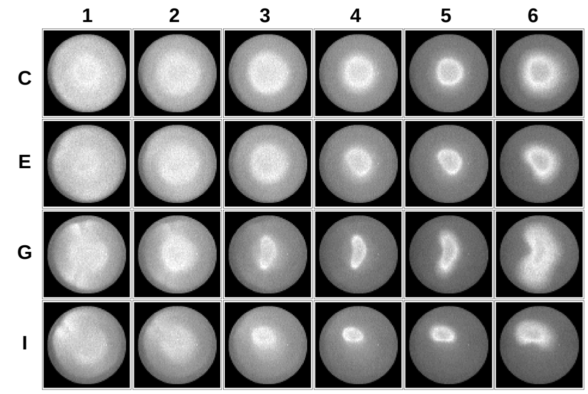

Figure 2: A tiling formed by arranging six consecutive video frames from four different radial extinction states in a rectangular pattern. The states are ordered from top to bottom by flow rate decreasing towards the extinction boundary.

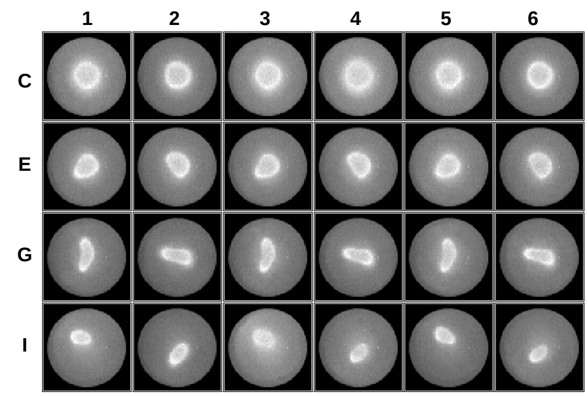

Figure 3: A tiling formed by arranging six consecutive video frames of flame front minima from four radial-extinction states at roughly equal flow rate increments. The states are ordered from top to bottom by fuel flow rate decreasing to the extinction boundary.

consisted of 16 data sets, the first 6 of which were far from the extinction boundary and eliminated as contributing no information to the understanding of the transition. One approach is to include all of the data sets in a very large tableau so that the frames provide a texture which summarizes global evolution of the shapes [4]. The scientists working with these displays found the large tableaus difficult to analyze, since they preferred to assess individual changes in shape. A careful study of the 10 data set tableau showed that States A through D fell into roughly the same class – periodic radial pulsations of decreasing temporal frequency and increasing temporal amplitude. The frequency results are consistent with the power spectrum display of Figure 1, but the increases in amplitude of the oscillation were only apparent from the tableau. States E and F, G and H, and I and J were similarly paired and each showed comparable behavior to its respective partner. The tableau of Figure 2 shows representatives from each class of behavior and is useful as an iconization as well as for extracting observational detail.

The natural tendency in interpreting the tiling display is to compare data sets by comparing changes in frames along columns of the tableau. The starting frames in Figure 2 have been selected so that a relative maximum in front size appears in the first column and successive frames are displayed after that. By aligning front max-

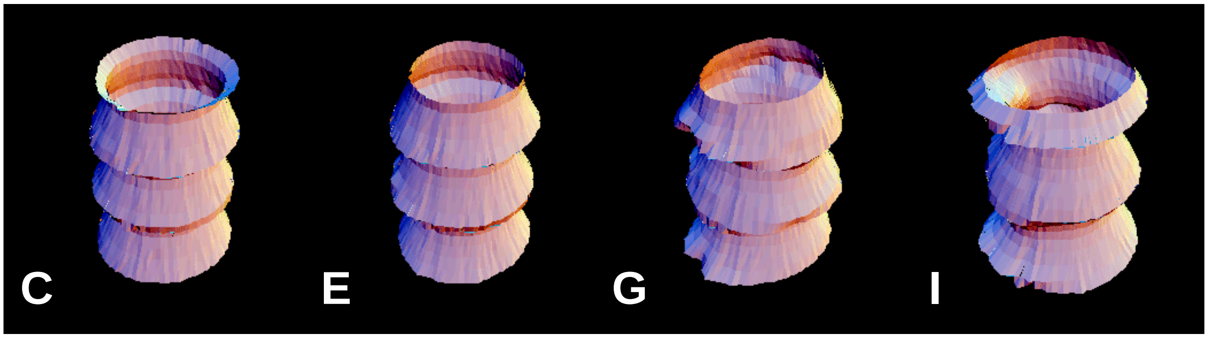

Figure 4: A geometric representation of States C, E, G, and I. Each cylinder represents the total radial intensity as a function of angle for 20 frames of the designated data set.

ima from different data sets of the tiling array, one can immediately see the frequency decrease of the radial oscillation as the fuel flow rate is decreased. While such alignment can be done by hand, it is desirable that the process by automated.

It may also be useful to display frames from the same data set based on a filter rather than to just display consecutive frames once a starting frame has been selected. Figure 3 shows the same data sets as in Figure 2 except that instead of consecutive, equally spaced frames, only frames in which the front extent was a local minima were selected. This filter process is analogous to restricting display to points on a Poincarê section in dynamical systems.

Physically relevant filters make it easier to make detailed observations about changes across data sets. The following information was more easily extracted from the filtered tiling of Figure 3 than from Figure 2. State C is a radial mode in which the flame front periodically changes its radial extent. The minima are circularly symmetric. As the flow rate is decreased, the minima occupy a smaller area of the burner. State E has minima that move between two overlapping locations near the center of the burner on successive oscillations. The minima, now asymmetric and bean-shaped, are similar in shape but differ in orientation. The system has period-doubled, because it now takes twice as long for the flame front to repeat by returning to its original position and intensity. In State G, the minima are elongated and the angular separation between the minima is closer to 90 degrees. In State I the minima are smaller in size and occur in physically disjoint regions, away from the center of the burner.

5 Geometric Mappings

Another approach for comparing extracted information of a collection is to create an abstract representation of a data set. Figure 4 illustrates this approach as a method of displaying changes in symmetry as a function of parameters. In this particular display, each frame of video is reduced in spatial dimension by integrating image intensity in the radial direction to obtain total radial intensity as a function of angle. To represent the variation of radial intensity with time, a triangulation is formed by using the total radial intensity as the radial coordinate and connecting the same θ positions in consecutive frames. The resulting figure is linearly interpolated and rendered. Each horizontal cross section is the radial intensity curve for that frame as a function of angle. The resulting geometric figure summarizes changes in symmetry and can be used as an icon to represent the data set in other visualizations.

A side-by-side comparison of the cylindrical icons reveals the decrease in oscillation frequency and the increase in oscillation amplitude as the flow rates approach the extinction boundary. A steady uniform flame is represented as a straight cylinder. The radial pulsations corresponding to States A-J appear as corrugations in the cylinder, producing ridges (oscillation maxima) and valleys (oscillation minima). States A through D (with C represented in Figure 4) are nearly circularly symmetric. The very slight asymmetry from front to back is probably an artifact arising from a slight nonuniformity intrinsic to the burner. The icon for State E shows slight dents that have appeared indicating the beginning of the loss of symmetry.

Due to the particular camera and focusing method used during acquisition, the data sets used in this study have relatively low contrast level. The background flame intensity determines the inner radius of these geometric figures. The details of the asymmetry can be visually enhanced in the icons by subtracting a percentage of the background intensity from the computed radial totals before constructing the icons and then decreasing the scale on which the icons are rendered.

All of the objects in Figure 4 are displayed using the same color scale. Care was also taken to render the geometric figures using the same spatial scale rather than computing the scale for each image individually so that a comparison of physical diameters of the figures provides meaningful information about the relative size of the oscillations in the data sets. While on-the-fly generation of an icon for each data set as it is acquired is not a problem, the spatial scale for the rendering is problematic and needs to be set a priori, possibly based on the scale of the first data set acquired.

The icons can also be used to animate dynamic behavior as shown in the Color Plate labeled Figure 4(Animation). In each frame of the animation, the original video image is displayed on the left (State I). A horizontal plane highlights the cross-section corresponding to this frame in the icon on the right. As the animation plays, the plane moves vertically upward, focusing attention on the relevant cross-section.

While not computationally intensive, the iconic representation of the data sets takes time to render. Figure 5 shows an alternative representation in which the cross section curves are overlaid. This representation allows a better comparison of the behavior across time for a single data set, but is difficult to use in cross-data-set comparisons.

Icons can also be used to represent relative temporal behavior across data sets. The icon in Figure 5 represents the data sets for States A, C, E, G, and I at a particular time. Each horizontal cross-section is the radial intensity curve of the specified data set, with State A on the bottom and State I on the top. The corresponding video frame for State I is shown on the left for reference. This type of combined iconic rendering emphasizes phase and symmetry differences that develop as the flow rate is decreased. An animation of this type of visualization shows how phase differences and asymmetry develop as a function of parameter. As with simple tiling,

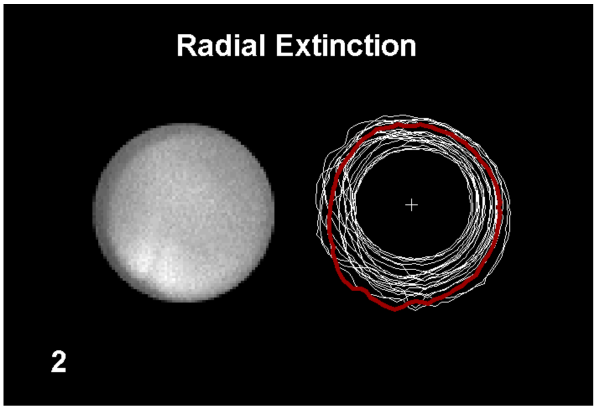

Figure 5: The curves represent the total radial intensity as a function of angle for twenty frames of video for State I. A frame of the original movie is shown for comparison. The curve corresponding to this frame is displayed in red. (See the Color Plate.)

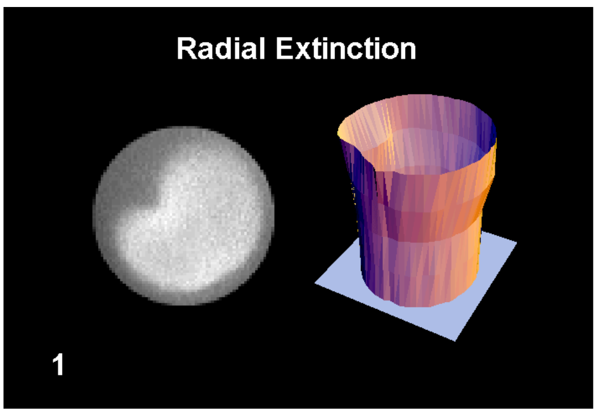

Figure 6: The icon shows a snapshot of the total radial image intensity as a function of angle for States A, C, E, G and I (increasing vertically upward) at a particular time. The corresponding video frame for State I is displayed on the left.

a key is picking the starting frame within each data set so that the behaviors being compared are aligned.

6 Discussion

Simple, fast visualization techniques can enhance experiments, but care must be taken in scaling and alignment so that side-by-side comparisons reveal accurate information about physical differences. The tiling power spectra of Figure 1 uses the maximum spectral value in the first data set as the scale, but can be augmented with user-adjustable color sliders to change the scale as later data sets are generated. Similarly, the geometric depiction of symmetry shown in Figure 4 uses the first data set to determine the overall icon size and a user-specified scale for the mapping intensity to cylinder radius. Again sliders can enhance user control.

Another issue is how to organize the representations of the multiple data sets into meaningful displays. The tiling power spectra visualization of Figure 1 assumes that the data sets can be distinguished by a numerical parameter that is used as the vertical coordinate in the display. Although the vertical axis of Figure 1 is labeled with state names, these states were acquired at equally spaced values of the fuel/oxidizer flow rate. As a result the pattern observed in the figure is in fact, a physically meaningful depiction of how the system changes as a function of this parameter. The icons of Figure 4 can be placed on a two-dimensional grid representing the values of two different parameters. The observer can then relate changes in structure of the cylinders to interrelated changes in the parameters. Tilings such as those of Figures 2 and 3 use the horizontal coordinate to represent time. Each row in Figure 2 consists of frames from the same data set spaced at equal intervals, while the frames in Figure 3 are successive local minima in intensity. The data sets are arranged vertically in order of increasing flow rate.

The visualization strategies discussed in this paper are applicable to many spatiotemporal systems and can be rendered in real-time on a desktop workstation, making them candidates for implementation as interactive tools for steering of experiments. Unfortunately visualization tools and acquisition tools are not usually integrated. As a result, either special purpose software must be written or the experimentalist must use a multistep process to transfer data from the acquisition to the visualization environment. This lack of integration is a barrier which prevents visualization from be exploited to its full potential. **Animations of the visualizations described in this paper can be seen at http://vip.cs.utsa.edu/pubs/vis2000.**

7 Acknowledgments

The authors wish to thank Mohamed el-Hamdi, who took the data sets analyzed in this paper. This work was partially supported by ONR N00014-97-0029 and NSF ACI 9721348. Some of the figures were rendered in Mathematica or Matlab.

References

[1] S. Bryson and S. Johan, Time Management, Simultaneity and Time-critical Computation in Interactive Unsteady Visualization Environments, *Visualization '96*, (1996).

[2] J. X. Chen, Advancing Interactive Visualization and Computation Steering, *IEEE Computational Science and Engineering* **3**(4) 13–17 1996.

[3] M. Gorman, M. el-Hamdi and K. A. Robbins, Chaotic Dynamics near the Extinction Limit of a Premixed Flame on a Porous Plug Burner, *Combustion Science and Technology*, **98** 47–56, 1994.

[4] C. Healy and J. t. Enns, Large Datasets at a Glance: Combining Textures and Color in Scientific Visualization, *IEEE Transactions on Visualization and Computer Graphics*, **5**(2), 145-167, 1999.

[5] J. D. Mulder, J. J. van Wikj, and R. van Liere, A Survey of Computational Steering Environments, *Future Generation Computer Systems* **15**(1) 119–129, 1999.

[6] F. J. Post, T. van Walsum, F. H. Post and D. Silver, Iconic Techniques for Feature Visualization, *IEEE Visualization'95* 288–295, 1995.

[7] W. Ribarsky, D. King, A. Gavrilovska and R. van de Pol, Time-critical Visual Exploration of Scalably Large Data, *Dagstuhl Workshop on Scientific Visualization*, 1998.

[8] K. A. Robbins, Visualization of Scientific Video Data Using KL Decomposition, *IEEE Transactions on Visualization and Computer Graphics* **4**(4), 330–343, 1998.

[9] C. D. Shaw, J. Hall, D. Ebert and D. Roberts, Interactive Lens Visualization Techniques, *IEEE Visualization '99*, 1999.

[10] J. J. van Wijk and E. R. van Selow Cluster and Calendar Based Visualization of Time Series Data, *IEEE Symposium on Information Visualization - INFOVIS'99*, 1999.

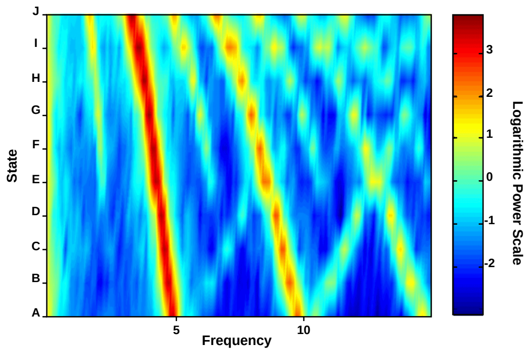

Figure 1 (Color Version)

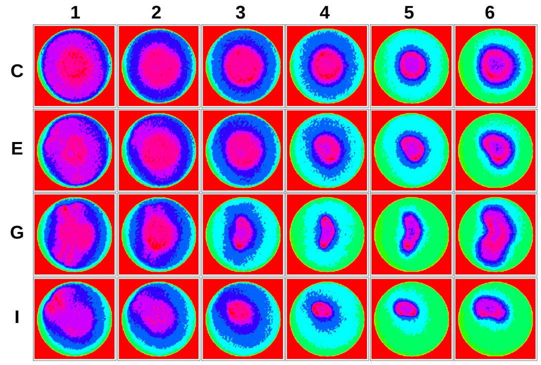

Figure 2 (Pseudocolor Version)

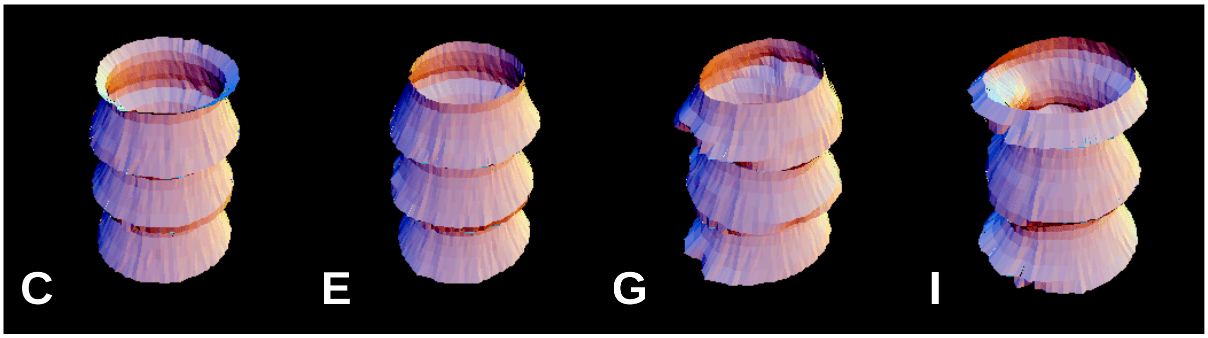

Figure 4 (Color Version)

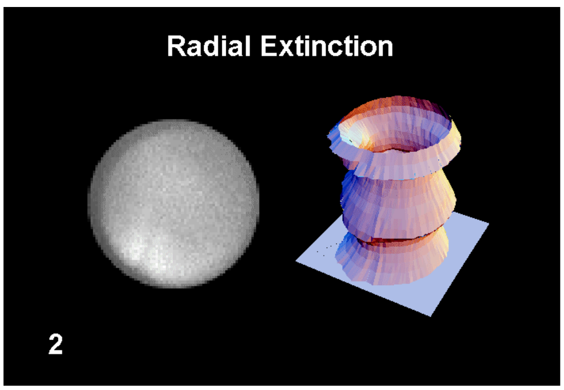

Figure 4 (Animation)

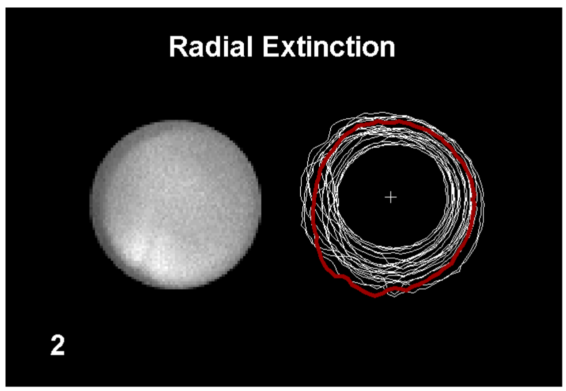

Figure 5 (Color Version)