TimeTubes: Design of a Visualization Tool for Time-Dependent, Multivariate Blazar Datasets

Longyin XU*, Masanori NAKAYAMA*, Hsiang-Yun WU*,
Kazuho WATANABE†, Shigeo TAKAHASHI‡, Makoto UEMURA§, and Issei FUJISHIRO*
*Keio University, Yokohama, Japan
†Toyohashi University of Technology, Toyohashi, Japan
‡University of Aizu, Aizu-Wakamatsu, Japan
§Hiroshima University, Higashi-Hiroshima, Japan

***Abstract*—Blazars are active galactic nuclei whose relativistic jets ejected from the central black hole are pointing toward the Earth. Astronomers have attempted to classify blazars, but analyzing the time-dependent multivariate datasets with conventional visualization methods, such as scatter plot matrices, is difficult. This paper presents *TimeTubes*, a new visualization scheme that allows astronomers to analyze dynamic changes in and feature causality among the multiple time-varying variables. We target six representative time-varying variables from the originals, including two polarization-related parameters and their corresponding errors, intensity, and color. The four polarization parameters with a common time stamp are transformed to an ellipse, and a series of such ellipses are aligned in parallel along the time line to form a volumetric tube in 3D space. The resulting tube is then colorized by the observed intensities and colors of the blazar. We designed a designated interface with nine functions to control the view of the tube interactively. The usability of TimeTubes is discussed with feedback from astronomers.**

***Keywords*-3D information visualization; time-dependent data; multivariate data; blazar.**

I. Introduction

Blazars belong to a class of active galactic nucleus, which is a compact region at the center of a galaxy that has much higher luminosity than normal ones [1]. The center of a blazar is considered to be a black hole, and relativistic jets ejected from it are pointing towards the Earth (Figure 1). Astronomers observe blazars for a period of time to obtain time-dependent multivariate datasets in order to classify the blazars based on the observed data. Their aim is to peer into the dynamic behavior of the time-varying variables and to identify the feature causality among them.

In [2], the astronomers extracted representative variables from the originally observed data to ensure effective classification by visualization. These time-varying dimensions include two parameters describing linear polarization (Q/I and U/I) and their corresponding errors, color, and intensity (see Table 1). Scatter plots has commonly been used to visualize such blazar data, as shown in Figure 2. As time evolves, current plots highlighted in red flounce synchronously in the three plotted planes, making the plots too crowded and cluttered for astronomers to scrutinize the data.

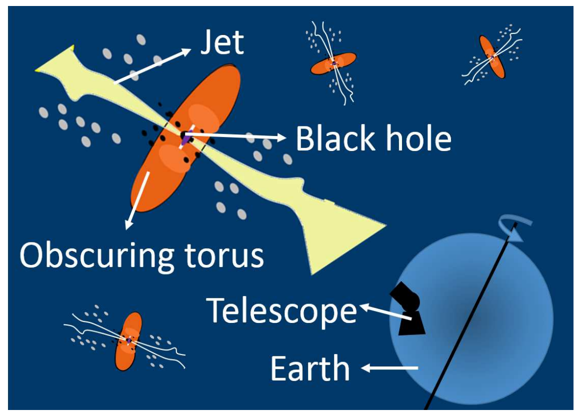
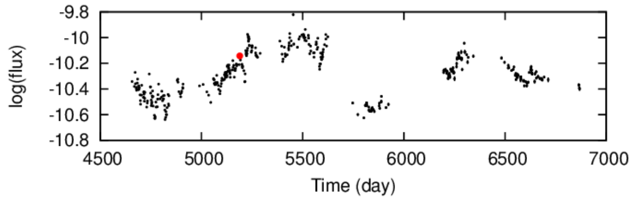


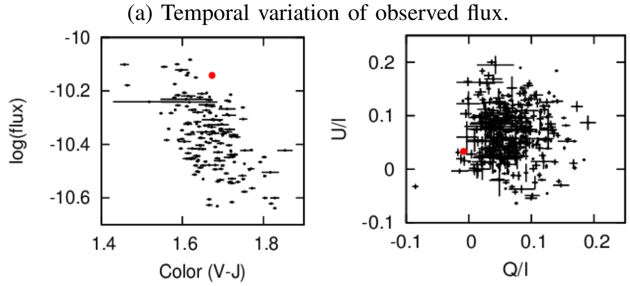
Figure 1: The structure of a blazar. The ellipse and its center represent an obscuring torus and a black hole, respectively. The jets ejected from the central black hole are pointing toward the Earth.

The main contribution of this paper is to propose a new visualization method, called *TimeTubes*, that allows astronomers to visually analyze the dynamic behavior of and relationships among the representative variables. The geometrical transform of the time-dependent multivariate data and designated interactions are provided for users to perform their visual analysis effectively. Specifically, TimeTubes visualizes the blazar data in a 3D tube structure in which we use an elliptic shape to encode four polarization-related dimensions with a common time stamp and align a series of such ellipses along the time line to form a tube in the 3D space. The resulting tube is then colorized by observed intensities and colors.

Following a brief review of related work in Section II, the spatial design of TimeTubes is described in Section III and designated interaction functions are introduced in Section IV. A current prototype system is demonstrated with application to actual blazar datasets and evaluated by astronomers in Section V. Finally, Section VI concludes the paper with a few remarks on future issues.



(a) Temporal variation of observed flux.



(b) Observed (color, flux) plots. (c) Observed (Q/I, U/I) plots.

Figure 2: Scatter plots to visualize time-dependent multivariate data for blazars [2].

II. Related Work

Various techniques have been developed for visualizing time-dependent data. Comprehensible surveys on these techniques can be found in [3]. Conventional methods, such as Sector Graph, Stacked Bar Chart, and Circle Graph, are simple in that they are tailored for only one or two time-varying variables in a target dataset [4]. Several approaches have been extended to deal with more variables. For example, Harve et al. [5] developed ThemeRiver, a method that depicts thematic variation of documents over time. It is a pioneering method allowing users to create a smooth stacked-graph layout automatically to handle many time series. Rose et al. improved Storyflow from ThemeRiver as a technique for keeping track of the evolution of themes in text streams [6], and it has been revisited by Liu et al. to generate an aesthetically pleasing and legible storyline visualization [7]. These studies rely on free-form curves to illustrate the time flow of time-dependent data and facilitate the comparison of relationships among the variables and analysis of the hierarchical relationship throughout time. However, since the blazar data stem from astrophysics, which uses dimensions that are described with parameters of polarization, these methods cannot visualize blazar data intuitively to illustrate the characteristics of polarization, such as deflection.

Both 2D and 3D visualization techniques have been developed for visualizing time-dependent multivariate data. Tominski and Schulza [8] extended the Great Wall of the space-time continuum for visualizing spatio-temporal data, which refers to 2D geographical space and 1D linear time. Users cannot use the Great Wall without changes to evaluate polarization intuitively. However, respecting the Great Wall, a certain 3D (2D plus time) space is defined in TimeTubes.

Table 1: Six time-dependent representative variables for observed blazars. Each variables is measured using Julian time.

Variable	Description
Q/I	linear polarization component at 0 or 90 degree
E_Q/I	Error on Q/I
U/I	linear polarization component at +45 or -45 degree
E_U/I	Error on U/I
$Flx(V)$	Observed intensity of blazar
V-J	Observed color of blazar

Perspective Tunnel [9] exploits 3D space through mapping information on the ceiling, floor, and walls of a tunnel perspectively. It was developed for overcoming occlusion of overlapping items, ambiguity of symbols in representation, and physical display limitations. It could possibly visualize part of the time-dependent multivariate data in 3D space, but the relationship between the pairwise information mapped on the opposite sides, e.g., the floor and roof or the left and right walls, is relatively difficult to observe.

III. Design of TimeTubes

We have respected the concepts of the Great Wall and Perspective Tunnel to develop our TimeTubes and further designed a novel visual representation for showing the relationship between pairwise information. The six representative variables we visualize are listed in Table 1. To visualize the these time-varying dimensions simultaneously throughout the time sampled, we designed TimeTubes to possess the following two particularly important features:

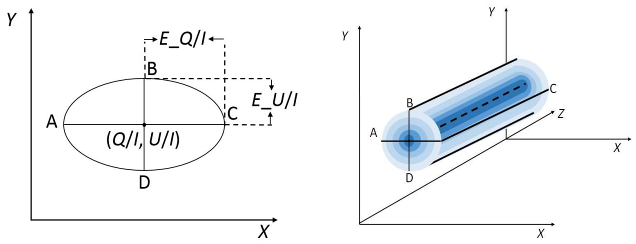
- rely on 3D geometry instead of 2D plot animation, and
- show multiple variables with each time stamp.

In order to fulfill these requirements, we chose an elliptic shape to visualize the four polarization-related variables with a common time stamp. Then, we considered a time line in the z direction to align such ellipses with different time stamps. The resultant tube can have intensity and colors as its retinal properties and allows astronomers to keep track of change in the six variables intuitively, even from a still image. If multiple TimeTubes for different blazar datasets were juxtaposed side by side, it would allow users to look from one to the other to classify blazars in a more effective manner.

A. Spatial Mapping

Linear polarization, which is a significant property of a blazar, is described by the degree (P) and angle (θ) of polarization. As Table 1 shows, the parameters Q/I and U/I are two linear polarization parameters, where I is the total flux of the blazar and Q and U are Stokes parameters. Those values are related as follows:

$$P = \sqrt{(\frac{Q}{I})^2 + (\frac{U}{I})^2}, \quad (1)$$



(a) (b)

Figure 3: Spatial mapping of TimeTubes: (a) One data sample at a time is visualized as an ellipse. (b) The neighboring ellipses are connected by centripetal Catmull-Rome splines to form a tube. A TimeTube is composed of multiple concentric tubes with different opacities.

$$\theta = \frac{1}{2} arctan(\frac{U}{Q}). \quad (2)$$

As shown in the scatter plot in Figure 2(c), the two parameters *Q*/*I* and *U*/*I* were set as the horizonal axis and vertical axis, respectively. The errors of the parameters *Q*/*I* and *U*/*I* are indicated as a cross-cursor at the point (*Q*/*I*, *U*/*I*). Following these mapping strategies, an ellipse is placed using (*Q*/*I*, *U*/*I*) as its center coordinates, and the errors of *Q*/*I* and *U*/*I* were chosen as the radius values on the major and minor axes, respectively. As a result, the confidence interval of each data sample can be illustrated intuitively with the ellipse width. Astronomers want to see a trajectory on the scatter plots, whereas the technique suffers inherently from visual clutter artifacts since points are crowded and overlap. To address this problem, we rely on 3D geometry. Indeed, our idea is to align the ellipses along the time line in parallel and connect the series of ellipses to form a tube. In this way the time-varying nature of those four representative astrophysical variables can be clarified by evaluating how fast and how much the tube twists, and the trajectory can be observed intuitively in 3D space.

Assuming a sort of temporal coherence of the observed parameters, we decided to connect the series of ellipses. To this end, we chose centripetal Catmull-Rom spline for simple computation [10]. Unlike other variants, a centripetal Catmull-Rom spline can avoid self-intersection and cusp. Five centripetal Catmull-Rom splines are used to approximate the tube. One of them is used to connect the ellipse centers (the dotted line in Figure 3(b)), while the four remaining splines connect four right perimeter points of the ellipses as the control points, as illustrated by black lines in Figure 3(b).

For substantializing the tube in 3D space, we employed *pseudo* volume rendering and thereby added a sort of uncertainty visualization flavor. In practice, the tube is rendered volumetrically with multiple concentric tubes with semi-translucent colors, as illustrated in Figure 3(b). In our experiment, we set eight as the number of the concentric

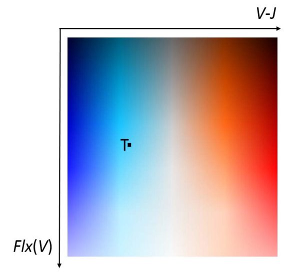
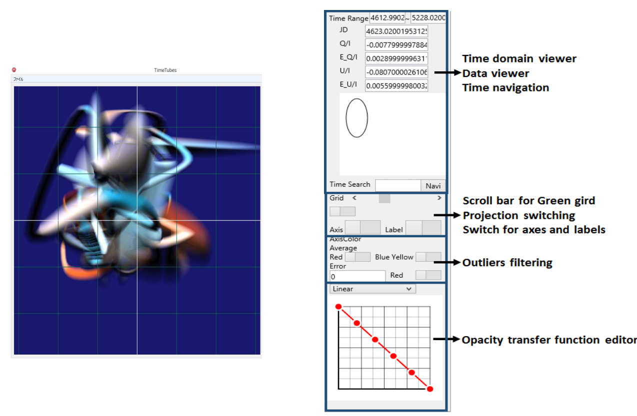


Figure 4: The domain of 2D color transfer function represents the color and the intensity of a blazar, respectively. The translucent color of a texel T is actually mapped to the corresponding portion of the tube. The definition of the current color transfer function appears on top of the control panel in Figure 5(b) (upper part of the control panel).

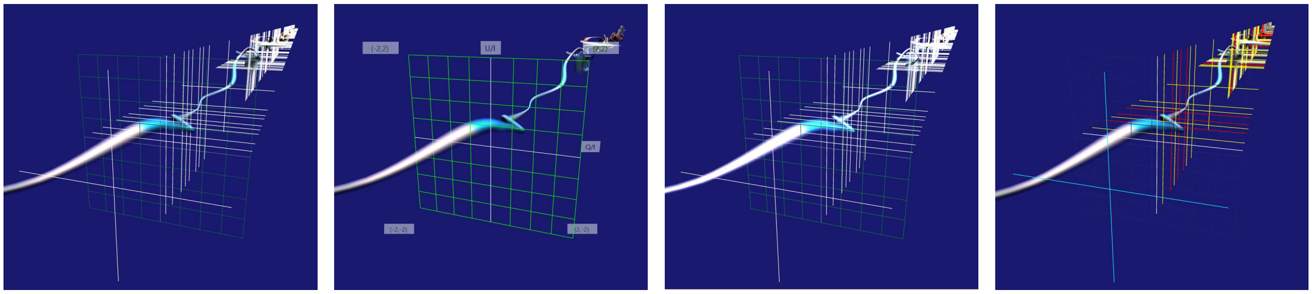


(a) Visualization part. (b) Control panel (lower part).

Figure 5: The interface of TimeTubes.

tubes. Moreover, to enable users to observe the tubes from any angle in 3D space, those concentric tubes are built as the slices in shell texture, which has often been used in fur rendering [11].

The color is assigned to the tube by referring to blazar data. To colorize the tube with the color (V-J) and the intensity ($Flx(V)$) data, a 2D color transfer function was introduced. After incorporating the above design, the resultant tube allows users to observe the six time-varying variables and their relationships at the same time. The actual 2D transfer function is stored as a bitmap (Figure 4) in which we reflected the change in colors commonly used in astrophysics, while users are still allowed to modify the 2D color transfer function for their own illustrative purposes. Note that in order to determine the final color of a point inside the tube, an opacity transfer function is referred to as well. In general, a point is rendered more transparent the further out it is located; this reflects the tendency of observation reliability.



(a) (b) (c) (d)

Figure 6: Interactive visualization results with the same time stamp: (a) visualization results in perspective projection; (b) labels, disabled white axes, and grid with adjusted opacity; (c) the tube with a flat opacity; (d) excluding the outliers whose *Q/I* and *U/I* are larger than their averages by coloring the axes. Red color represents the data sample both of whose *Q/I* and *U/I* are larger than the averages, and yellow and blue mean that either *Q/I* or *U/I* is larger than its average, respectively.

IV. Interaction with TimeTubes

Until obtaining satisfactory insights, users need to adjust visualization-related parameters. For example, they might want to observe the tube from different viewpoints or to get detailed information about a specific part of the tube on demand. Hence, nine interaction functionalities have been developed, each of which can be categorized as either overviewing, zooming & filtering, or showing details-on-demand [12]. Figure 5 gives a snapshot of the interface. Figure 5(a) shows the visualization result, while Figure 5(b) illustrates a lower part of the control panel of the interactions. Figure 6 exemplifies how several interactions have actual effects on the visualization result in Figure 5(a).

A. Overviewing

To help users observe the entire view of the tube, we designed projection adjustment (Figure 6(a)), labels, white axes, and a green grid (Figure 6(b)).

- The projection adjustment allows users to switch between parallel and perspective projections, while the default is set to parallel projection according to the preference of astronomers (Figure 5(a)). We can take advantage of the perspective projection in a focus+context manner.
- The green grid is built for confirming the current snapshot to analyze, and the grid opacity can be adjusted by a scroll bar so as not to interrupt the analysis itself.
- The labels to show the coordinates and the names of axes can be enabled.
- The white axes to represent time stamps can be disabled.

B. Zooming & Filtering

For zooming in the concentric tubes, their opacity distribution can be adjusted (Figure 6(c)). A transfer function editor is incorporated that allows users to change the opacity distribution by dragging points on the definition curve with a mouse. Three typical opacity distributions are built in for users to choose, including linear, flat, and valley-shaped. As we mentioned in Section III-A, the linear setting is chosen by default.

To help users inquire about the outliers of datasets, specific styles of filtering are offered as an important option by TimeTubes. Outlier filtering includes two choices. One is to locate the data samples whose *Q/I* and *U/I* are both larger than the averages over the whole time domain with red axes (Figure 6(d)). Furthermore, users can view the data samples where only *Q/I* or only *U/I* is larger than its average, the data samples will be shown with blue and yellow axes, respectively (Figure 6(d)). The other way allows users to specify a threshold to locate samples such that the values of the following amount are larger than the threshold with colors:

$$\sqrt{(E\_Q/I)^2+(E\_U/I)^2}. \tag{3}$$

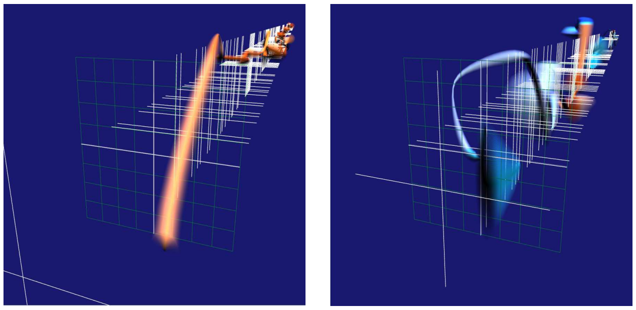
C. Showing Details-on-Demand

Users are allowed to view the tube along the time line by scrolling a mouse, while a time domain viewer, data probe, and time navigation are provided to obtain detailed information (Figure 5(b)).

- The time domain viewer shows the time domain of the selected dataset so that users can confirm the time period of their observation.
- The data probe returns detailed data and the sectional shape of a current snapshot, and the information will change as the green grid moves along the time line.
- Time navigation allows users to randomly search for the data with a specific time stamp.

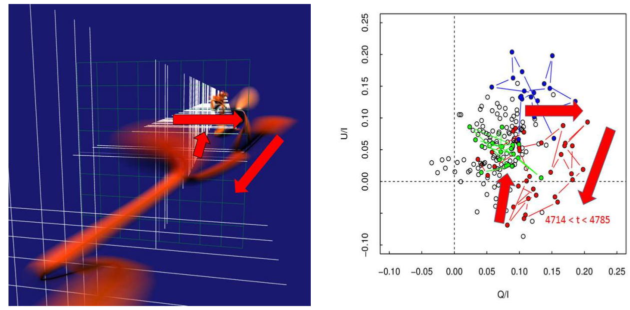
V. Results and Discussion

A prototype of TimeTubes has been implemented using Delphi on an Intel(R) Core(TM)2 2.00 GHz laptop with 16 GB RAM.



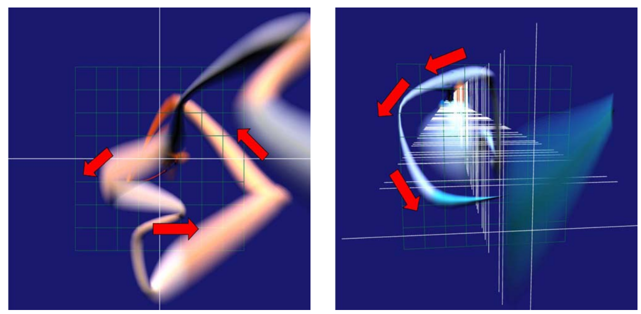
(a) (b)

Figure 7: The visualization results of blazar datasets: (a) Blazar named "3C 66A." (b) Blazar named "PKS 1749+096."



(a) (b)

Figure 8: Rotation found in TimeTubes and scatter plots. (a) A rotation in the visualization results of blazar "3C 66A." (b) The same rotation appears in the scatter plots; red arrows correspond to the rotation in (a).



(a) (b)

Figure 9: Rotation found in different blazar datasets with TimeTubes: (a) Blazar named "3C 454.3." (b) Blazar named "PKS 1749+096."

A. *Results and Feedback*

Figure 7 shows two examples of results to visualize observed blazar datasets in which the twists and trajectory of the tubes are clearly illustrated. These allow users to evaluate the polarization variables intuitively, which could hardly be achieved by conventional visualization techniques.

As we mentioned in Section II, blazar data could be visualized by known visualization techniques, such as ThemeRiver and Perspective Tunnel. Although the temporal change in each dimension can be illustrated in ThemeRiver, users cannot directly observe the trajectory of polarization that astronomers want to observe in the scatter plot.

Other multidimensional data visualization techniques might also suffer from these kinds of problems. For example, in parallel coordinate plots, the relationships among nonadjacent axes cannot be effectively illustrated although multiple dimensions are shown.

We asked astronomers to evaluate the current version of TimeTubes, and their feedback was as follows:

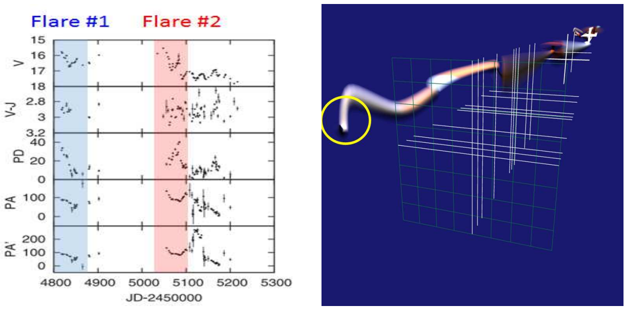
- Choosing an elliptic shape to visualize four polarization-related variables is of great help, especially the errors of Q/I and U/I are shown nicely with the width of the tube.
- Aligning samples along the time line is better than using animation since the visual clutter disappeared and the relationship among the representative time-varying variables can be easily observed.
- Four representative astrophysical variables can be evaluated intuitively mainly due to clear delineation of the size and rotation of the tube.
- Visualizing color and intensity with the color of the tube is convenient since the variation trend can be observed synchronously with the change in polarization.

B. *New Discovery*

With TimeTubes, the astronomers found new features that have not been recognized so far. Figure 8(a) shows an example of a blazar named "3C 66A." Three rotations can be found in the tube: one is shown in red arrows. The astronomers obtained the time period of the rotation and plotted the corresponding points sequentially with the scatter plots. Surprisingly, the same rotation was confirmed, as shown in red arrows in Figure 8(b). This kind of rotation has not been found when only using scatter plots because when the scatter plots remain static, such dynamics features cannot become visible spontaneously.

Similar rotations also can be confirmed in other blazars. Figure 9 illustrates two other examples of rotations, which are marked by red arrows. These rotations reflect polarization swings, which have not been noticed before. The astronomers discovered that these polarization swings are associated with flares of the objects. Note here that flare means a light burst where the intensity of a blazar suddenly becomes stronger.

Furthermore, the astronomers recognized that flares of some blazars have a common polarization angle in the visualization results. An example is shown in Figure 10 where a blazar named "MisV1436" has two flares. Flare



(a) (b)

Figure 10: Flares having a common polarization angle: (a) Two flares in blazar dataset named "MisV1436." (b) A favored angle corresponding to Flare #1 in (a).

#1 in Figure 10(a) corresponds to the angle that is marked with a yellow circle in Figure 10(b). As twists in TimeTubes are decided by polarization-related variables, flares can be confirmed easily in TimeTubes, and astronomers can analyze the relationship between flares and polarization parameters intuitively.

VI. Conclusion

In this paper, we presented a new visualization method, TimeTubes, for analyzing time-dependent, multivariate blazar data. TimeTubes is designed with 3D geometry instead of 2D animated plotting to allow astronomers to interactively observe dynamic changes and the relationships among the representative time-varying variables. Moreover, important phenomena, such as polarization swings and flares of blazars, could be confirmed effectively with the help of TimeTubes.

In the future, we will polish TimeTubes with further feedback from astronomers. Several suggestions are as follows:

- adding view frustum culling, which means making the tube invisible in front of the green grid.
- filtering the dataset with color and intensity, and
- federating TimeTubes with scatter plots and parallel coordinate plots.

Furthermore, TimeTubes will be utilized for other time-dependent multivariate data, for example, visualizing music data with TimeTubes to analyze the similarity of the melodies [13] or visualizing economic data to forecast the changes in stocks.

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