TimeTubes: Visual Exploration ofObserved Blazar Datasets

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Abstract. Blazars are attractive objects for astronomers to observe in order to burrow into the magnetic field in the relativistic jet. This paper presents TimeTubes as a novel visualization scheme that allows astronomers to interactively explore characteristic temporal variation patterns in observed blazar datasets. In the TimeTubes spatialization, the two Stokes parameters and their errors with a common timestamp are transformed into an ellipse. A series of such ellipses are aligned in parallel along the timeline to form a 3D volumetric tube. The resulting tube is then colorized by the observed intensities and colors of the blazar, and finally volume-rendered. A designated user interface is provided with visual exploration functions according to Shneiderman’s Visual Information Seeking Mantra. In the latest version, an auxiliary mechanism, called visual data fusion, was incorporated to ameliorate data- and mapping-inherent uncertainties for more efficient and effective visual exploration.
1. Introduction

Blazars are active galactic nuclei whose relativistic jets ejected from the central black hole are pointing toward the Earth [1] (see Figure 1). Astronomers have observed blazars for a long period of time to acquire time-dependent multivariate datasets for optical polarization, since they can obtain a clue to the magnetic field structure in the jet from the observed temporal variation features of the position angle of polarization. To visually analyze the datasets, they have commonly used animated scatterplots [2], as shown in Figure 2. The conventional visualization scheme suffers from visual clutter and low interactivity, and thus the limitations unfortunately compromise astronomers’ ability to carefully scrutinize the original dataset.

![Figure 1. Observation 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 position angle of the optical polarization is perpendicular to the direction of the magnetic field of the emitting region in the optically-thin regime.](image)

In our initial report [3], we attempted to present a novel visualization scheme, termed TimeTubes, whose geometrical transformation of the time-dependent multivariate data and designated interactions are provided for astronomers, allowing them to effectively perform their visual exploration. More specifically, TimeTubes spatializes the blazar data into a 3D volumetric tube structure, in which an elliptic shape is used to encode the two Stokes parameters and their errors with a common timestamp and align a series of such ellipses along the timeline to form a tube in the 3D space (see Figure 3). The resulting tube is then colorized by observed intensities and colors, and finally volume-rendered. The tube makes it easy for astronomers to detect universal patterns in the trajectory of the polarization parameters, which may correlate with the intensity and color variation (see Figure 4). Some new behaviors of blazars have been found through the use of TimeTubes and reported in [4, 5].

In previous reports [6, 7], we improved the TimeTubes tool to help astronomers analyze datasets more effectively and obtain more information at a time by incorporating a novel mechanism, visual data fusion, into the 3D spatialization. By visually fusing another dataset from a different observatory but for the same blazar into the originally targeted dataset, TimeTubes can ameliorate two types of uncertainty: data-inherent uncertainty, which arises from errors and missing periods in the dataset; and mapping-inherent uncertainty, which arises as a result of interpolation when TimeTubes transforms the data into a continuous geometry. The visual data fusion enables astronomers to validate the datasets in a meticulous manner.

Following a brief review of related work in the next section, the spatial design of TimeTubes is described in Section 3, and designated user interface and exploration functions are introduced in Section 4. Section 5 is devoted to the description of the basic mechanism of visual data fusion. Finally, Section 6 concludes the paper with a few remarks on on-going challenges.
Figure 2. Animated scatterplots as a conventional way to visualize time-dependent multivariate blazar datasets. The descriptions of the variables are tabulated in Table 1. In (a), crucifix glyph is used to represent polarization parameters as well as their error intervals. The three scatterplots are mutually linked with current dots highlighted in red as a cross-reference.

2. Related Work
Various techniques have been developed for visualizing time-dependent data, some of which have been extended to deal with multivariate data. For example, Bach et al. [8] developed Time Curves, which is a general approach to visualizing time-dependent data. In this approach, data similarity is naturally expressed by folding a timeline. ThemeRiver, which was proposed by Havre et al. [9], depicts thematic variation of documents over time using a smooth stacked-graph layout. Storyflow, which was developed by Liu et al. [10], improved the ThemeRiver by enabling it to visualize storylines legibly.

In addition, 3D visualization techniques have been developed for visualizing time-dependent multivariate data. The Great Wall, which was proposed by Tominski and Schulz [11], visualizes spatiotemporal data with reference to 2D geographical space and 1D linear time. To express time variation, Gruend et al. [12] expanded parallel coordinate plots into 3D space. Perspective Tunnel [13] exploits 3D space through mapping information on the ceiling, floor, and walls of a tunnel in a perspective manner. It was developed for overcoming occlusion of overlapping items, ambiguity of symbols in representation, and physical display limitations.

However, these techniques do not provide an optimal way to explore the blazar datasets in an astrophysics context; indeed, blazars fluctuate drastically in a wide time range, which can be from a few minutes to several years, and the observed datasets intrinsically become error-prone. This has motivated us to come up with a new visualization scheme: TimeTubes.
3. Spatial Design
In this section, we describe the target blazar datasets and spatial mapping of TimeTubes [3].

3.1. Target dataset
As tabulated in Table 1, the target dataset consists of six representative variables, which have been chosen from eight variables in the original blazar dataset to facilitate effective blazar classification. All the variables are measured in Julian day (JD).

Optical polarization, which is a significant property of a blazar, is described by the degree ($PD$) and angle ($PA$) of polarization. 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. These quantities are related in the following equations:

$$PD = \sqrt{(\frac{Q}{I})^2 + \left(\frac{U}{I}\right)^2}$$

$$PA = \frac{1}{2} \arctan\left(\frac{U}{Q}\right)$$

In the conventional method of visualizing the dataset, three specific kinds of animated scatterplots have been used in combination with one another, as shown in Figure 2. Two scatterplots are used to correlate $Q/I$ and $U/I$ (a) and color and flux (b), respectively. Note that in (a), the errors of the parameters $Q/I$ and $U/I$ are indicated by a crucifix glyph at the point ($Q/I; U/I$). The last scatterplots, called light curves in (C), is used to see the temporal variation of observed flux. When these three scatterplots are animated, current dots highlighted in red are used as a cross-reference. Since the points become too crowded and mutually overlap, especially when the observation period gets longer, these representations suffer from visual clutter artifacts and low interactivity. These limitations unfortunately compromise astronomers’ ability to carefully scrutinize the dataset.

| Variable | Description |
|----------|-------------|
| Flux($V$) | Observed intensity of blazar |
| $Q/I$ | Linear polarization component (0 or $\pi/2$ degrees) |
| $E_{Q/I}$ | Error on $Q/I$ |
| $U/I$ | Linear polarization component ($\pi/4$ or $3\pi/4$ degrees) |
| $E_{U/I}$ | Error on $U/I$ |
| $V-J$ | Observed color of blazar |

3.2. Spatialization
We have respected the concepts of the Great Wall and Perspective Tunnel described in Section 2 to design how TimeTubes spatializes the six variables in Table 1.

TimeTubes relies on 3D geometry to visually encode the Stokes parameters with each timestamp as an ellipse, whose central coordinate is given as $(x, y, z) = (Q/I, U/I, JD)$ and whose radius values on major and minor axes are given as $E_{Q/I}$ and $E_{U/I}$, respectively. As shown in Figure 3(a), the confidence interval of each data sample can be illustrated intuitively with the ellipse width. Then, assuming a sort of temporal coherence of the observed parameters, the neighboring ellipses are connected to each other by five centripetal Catmull-Rom splines (one for connecting the ellipse centers and the remaining four for connecting four right perimeter
points of the ellipses), to approximate a 3D volumetric tube, as shown in Figure 3(b). Note that, unlike other variants, a centripetal Catmull-Rom spline can avoid self-intersection and cusp [14].

For substantializing the tube in 3D space, pseudo volume rendering was employed to add a sort of uncertainty visualization flavor. The tube is actually volume-rendered with multiple (empirically eight) concentric tubes with semi-translucent colors, as illustrated in Figure 3(b). Moreover, to enable users to observe the tubes from any angle in 3D space, these concentric tubes are built as the slices in shell texture, which has often been used in fur rendering [15]. To colorize the tube with the color $V - J$ and the intensity $Flux(V)$, a 2D color transfer function was introduced. To reflect the reliability of observations, an associated opacity transfer function was introduced as well. The translucency of the outer tube is generally defined to be larger than that of the inner. Small errors result in a sharply rendered tube, whereas a tube associated with a large range of errors has a vague appearance.

The time-varying nature of the six variables in Table 1 can be clarified by evaluating how fast and how much the tube twists, and the colored trajectory can be observed intuitively in 3D space, even from a still image.

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Figure 3. Spatial mapping in TimeTubes: (a) Stokes parameter samples with each timestamp are shown as an ellipse. (b) The neighboring ellipses are connected by centripetal Catmull-Rom splines.

4. Exploration Functionality
A prototype of TimeTubes has been implemented using Delphi on a laptop with an Intel Core i7-4510U CPU, an NVIDIA GeForce GT750M GPU, and 16GB RAM. Throughout the draft, we chose the dataset for a specific blazar named 3C 454.3 to show all visualization results.

Figure 4 gives a screenshot of the up-to-date user interface of TimeTubes. Figure 4(a) shows the visualization result of the dataset, where users are allowed to interactively change several viewing parameters of the tube. For example, they might want to observe the tube from different viewpoints or get detailed information about a specific part of the tube on demand. If the orthographic projection is chosen, the resultant view uses an aggregate of elliptical glyphs to imitate the Stokes $QU$ plane scatterplots in Figure 2(a). On the other hand, Figure 4(b) shows federated (linked) scatterplots, whose axes can be selected freely by users. A light curve as in Figure 2(c) is actually plotted here. The menu shown in Figure 4(c) allows for camera control, switching the display of the cruciform axes, and placing a glyph that expresses the contour of the tube at each data sample. The operation panel shown in Figure 4(d) enables users to perform their visual analysis through overview, filtering, zooming, details on demand, and relating with the scatterplots. In the upper part of the panel, the selected 2D transfer function is shown,
in which we reflected the change in colors commonly used in astrophysics like the scatterplots (\textit{Flux vs.} \(V - J\)) in Figure 2(b), while users are allowed to modify the 2D color transfer function for their own illustrative purposes. In the lower part of the panel, the editable opacity transfer function is also delineated. A built-in transfer function editor allows users to change the opacity distribution by dragging points on the definition curve. Users may choose from three standard opacity distributions: linear (default), flat, and valley-shaped.

Astronomers have evaluated several versions of TimeTubes, and we have obtained positive feedback from them, as reported in [3].

In the following sections, we will describe the effects of the basic exploration functionality of TimeTubes according to Shneiderman’s \textit{Visual Information Seeking Mantra} [16].

\subsection{Overview}
Figure 5 gives an overview of the dataset. The projection adjustment allows users to switch between parallel and perspective projections. The default is set to parallel projection in Figure 5(a), according to the preference of measurability. We can take advantage of the perspective projection in Figure 5(b) in a focus+context manner. To confirm the current snapshot for analysis, the grid plane is shown. The grid opacity can be adjusted so as not to interrupt the analysis itself.

\subsection{Zooming \& Filtering}
Figure 6(a) is a zoomed view of Figure 5(b). When zooming in the concentric tubes, color and/or opacity distribution can be adjusted. In Figure 6(a), brightness has been accentuated to highlight flare patterns (see Section 6).

On the other hand, Figure 6(b) is a filtered view of Figure 5(b). To help users inquire about the outliers of datasets, TimeTubes offers specific filtering styles. We can locate the data samples whose \(Q/I\) and \(U/I\) are both larger than the averages over the whole time domain with red axes. Furthermore, users can view the data samples where only \(Q/I\) or only \(U/I\) is larger than its average, and the data samples will be shown with blue and yellow axes, respectively.
4.3. Details on demand
Figure 7 shows a details-on-demand view of the dataset. Users may view the tube along the timeline by scrolling a mouse, whereas time navigation allows users to randomly search for the data with a specific timestamp. As seen in Figure 7, the data probe panel returns detailed data and the sectional shape of the current ellipse. The information will change as the green grid moves along the timeline.

5. Visual Data Fusion
As described above, the observed blazar datasets exhibit uncertainty due to their errors and missing periods, whereas periods interpolated by TimeTubes result in a different type of uncertainty. In the previous reports [6, 7], such data- and mapping-inherent uncertainties were ameliorated by visual fusion of datasets for the same blazar from two different observatories: one from Hiroshima University (HU) [2] and the other from the University of Arizona (AU, http://james.as.arizona.edu/~psmith/Fermi/).

Some differences can be found between HU and AU datasets. The astronomical telescope at HU allows us to simultaneously observe all six time-dependent variables in Table 1, whereas the observation timestamps of polarization and intensity in the AU dataset do not match. Therefore, we need to interpolate each of these variables respectively to treat the AU datasets the same way we treat the HU datasets.
Figure 7. Details-on-demand display.

To visually identify the existence of data samples, and if the shape of the tube is formed by observed or interpolated values, the latest version of TimeTubes places white crosses at all observation timestamps, and elliptical glyphs at timestamps where polarization was observed. Moreover, to clarify whether the currently-focused-on JD in TimeTubes has observed data or not, the colors of the grid, cross, and elliptical glyph will change when the currently-focused-on JD coincides with an observation time in the dataset. Note that the color of the tube generated from the AU dataset is determined in an ad hoc manner; this is because the color data is not available from the data source.

Two modes of visual data fusion are introduced. Note that the Merge mode corresponds to visual data fusion at the filtering stage of the conventional visualization pipeline: fusing the datasets numerically to ameliorate both data- and mapping-inherent uncertainties by increasing the amount of observed data used to form a single tube. In contrast, the Juxtaposition mode corresponds to the mapping stage: fusing the datasets optically to ameliorate data-inherent uncertainty by comparing the datasets from two observatories.

5.1. Juxtaposition mode
The Juxtaposition mode offers the most straightforward method of visual data fusion, and it would be best to begin with this essential mode. The observation values are not completely reliable due to their errors like $E_Q/I$, $E_U/I$, but we can increase their reliability by using datasets from two different observatories in a comparative manner. Moreover, users can identify differences between multiple datasets with the Juxtaposition mode, which may lead to the estimation of the true observed value.

With the Side-by-side option, users can compare two observed datasets in separate windows, as shown in Figure 8(a). This option can be used for datasets not only for the same blazar, but also for different blazars. With the Union option in Figure 8(b), users can overlap multiple tubes in the same window. The color of the tubes can be defined separately. This option is suitable for comparing datasets for the same blazar, where the arbitrarily focused time of the datasets in the visualization space fits automatically.
If the values of the observed data from different observatories are very close, we can consider these values to be more reliable than those from a single observatory. If they are dissimilar, we can estimate a true value by allowing for errors and observation conditions. Because of the differences between the observation conditions, the global centers of observed datasets may not coincide with each other. We can get a hint for proper calibration by comparing multiple observed datasets from different observatories with the Juxtaposition mode [7].

5.2. Merge mode
The number of data samples will increase when the datasets from two observatories are joined using the Merge mode. As a result, the missing period of observation can be shortened virtually, ameliorating the uncertainties of the missing periods. In the Merge mode, data samples from the AU and HU datasets have been merged into a single, chronological dataset before the tube is rendered. If multiple data samples contain the same observation timestamp, TimeTubes chooses the one with smaller errors. The color hue of the glyph expressing the tube contour distinguishes data sources: Green indicates HU and pink indicates AU. For the analysis of blazars, denser observation is required because blazars fluctuate very rapidly. However, there are many intrinsically unobservable periods in a dataset, due to daylight, bad weather, and so on, which may cause astronomers to miss important events of the blazar. Merging the two observed datasets, we can densify information rather than visualizing them separately. Using this mode, new features of the blazars are expected to be found.

With the All option, which is selected by default, all the data samples from the two observatories are merged into a single tube. This option leads to the densest information. The Selective option allows users to select arbitrary portions of the datasets with scatterplots. Outliers and/or unexpected values may be included in the dataset for various reasons. Visualizing the dataset without those values, users can analyze more correct visualization results. Moreover, when both HU and AU have data samples at an equal $JD$, users can choose to visualize either of them with this option, allowing them to visually validate the observed data.

We merged the observed datasets from HU and AU for the same blazar (that is, 3C 454.3 around $JD4,564$) using the all option. Figures 9(a) and (b) visualize the two datasets separately. The HU dataset does not have data samples for the period indicated by the red arrow in Figure 9(a), whereas the AU dataset does have the data samples for the same period, as indicated by the red circle in Figure 9(b). We relied on merge to fill in the missing period in the HU dataset with the data samples from the AU dataset. Contrasting the result shown in Figure 9(c) with the original shown in Figure 9(a) indicates that the uncertainty caused by the missing period is ameliorated and astronomers can get more information from one view than the result of visualizing a single dataset.
6. Concluding Notes

The use of TimeTubes has led to the recognition of noteworthy patterns in blazar variations [4, 5]. For example, Figure 10 (a) and (b) visualize the blazar dataset around $JD$ 5,156, where a counterclockwise polarization rotation feature is clearly illustrated, which appears around the lower-right region of the $QU$ plane for one month. Owing to TimeTubes, we can quickly find that the flare (a light burst where the intensity of a blazar suddenly becomes stronger) and color variation are closely associated with the rotation. Such a discovery could hardly be achieved solely by the conventional animated scatterplots in Figure 2, whereas the visual exploration with TimeTubes encourages us to investigate the phenomena more carefully by returning to the conventional scatterplots as shown in Figure 10(c).

After browsing the tube in the direction of time, a similar event was manually found also around $JD$ 5,504, as shown in Figure 11. If we could derive a specific metric from the time-varying multi-dimensional variables to quantize the relationship between the polarization rotation and flare, a new function of visual query for similarity search would be realized in a future TimeTubes framework.
From a visual design perspective [17], the TimeTubes spatialization could be thought of as a 2.5D design. This is because the elliptical plane respects observable light patterns, whereas we treat depth very differently to chase temporal alteration of the variables. Thanks to the flexibility in projection and the effect of view frustum culling, each of the ellipses can be observed with minimum occlusion.

In order to support more effective analytics tasks, we have recently attempted to emphasize the depth cues of the tube images in an immersive analytics environment for individuals. A novel method, relying primarily on the psychological factors of depth perception—mainly through anamorphosis and motion parallax—allows the viewer to easily perceive a 3D popup effect with the naked eye using only two standard display monitors which are orthogonally arranged, and a single Web camera [18], as shown in Figure 12. In anamorphosis, the distorted projection requires a viewer to occupy a specific vantage point so that he/she reconstitutes the intended image. However, such a constraint can be uncurbed by keeping track of the viewer’s line of sight in real time. By combining the relaxed anamorphosis with repeated off-axis projections of a 3D geometry content with spotlight rendering, we succeeded in inducing a sort of motion parallax. Good continuation of the projected content guarantees illusion of immersion for encouraging continuous and precise observation of TimeTubes.

![Figure 12. TimeTubes in an immersive display environment: A preliminary result.](image-url)

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References

[1] Antonucci R 1993 Annual Review of Astronomy and Astrophysics 431 473
[2] Ikejiri Y et al 2011 Publications of the Astronomical Society of Japan 63 3 639
[3] Xu L et al 2016 Proc. NICOGRAPH International 2016 pp 15–21
[4] Uemura M et al 2016 Galaxies 4 3 23
[5] Uemura M et al 2017 Publ. Astron. Soc. Japan (Preprint: https://arxiv.org/abs/1709.02524)
[6] Sawada N et al 2017 Proc. IEEE PacificVis 2017 pp 336–337
[7] Sawada N et al 2017 CGI'17 Proc. Computer Graphics International Conference 14
[8] Bach B et al 2016 IEEE Transactions on Visualization and Computer Graphics 22 1 559
[9] Havre S et al 2000 Proc. IEEE Symposium on Information Visualization pp 115–123
[10] Liu S et al 2013 IEEE Transactions on Visualization and Computer Graphics 19 12 2436
[11] Tominski C and Schulz H-J 2012 Proc. Workshop on Vision, Modeling, and Visualization pp 199–206
[12] Gruendl H et al 2016 Computer Graphics Forum 35 3 321
[13] Mitchell K and Kennedy J 1997 Proc. 8th Eurographics Workshop on ViSC pp 31–39
[14] Barry P J and Goldman R N 1988 ACM Computer Graphics 22 4 199
[15] Lengyel J E 2000 Proc. Eurographics Workshop on Rendering 2000 pp 243–256
[16] Shneiderman B 1996 Proc. IEEE Symposium on Visual Languages 1996 pp 336–343
[17] Ware C 2008 Visual Thinking for Design (Burlington MA: Morgan Kaufmann)
[18] Isaka T and Fujishiro I 2016 ITE Journal 70 6 J143