

ExoplanetExplorer: Contextual Visualization of Exoplanet Systems

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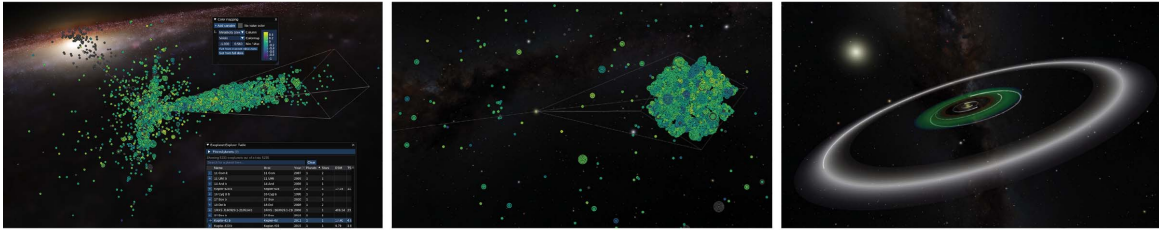


Figure 1: Different modes of the ExoplanetExplorer. The first two images show the overview mode with glyphs representing exoplanets from two different spatial positions, first from an outside-in view, with the camera at far distance, and second from a position closer to Earth. The glyphs show the host star's metallicity, and the dense area is the planets within the Kepler telescope's field of view. The third image shows the focus mode with a 3D representation of the HD 34445 exoplanetary system. The user changes between these modes by selecting a system of interest and zooming to the system, which toggles between the modes.

ABSTRACT

An exoplanet is a planet outside of our solar system. Researchers study known exoplanets and gather data about them through observations and derived data. Ongoing efforts involve finding planets with an environment that supports life, which likely exists in what is known as the habitable zone around a star. Through a participatory design process, we developed a tool that enables the exploration of exoplanet attribute data and provides contextual visual information in a 3D spatial view that seamlessly presents an overview and a system view showing particular exoplanet systems.

Index Terms: Human-centered computing—Visualization—Visualization systems and tools; Human-centered computing—Visualization—Visualization application domains—Scientific visualization

1 INTRODUCTION

Exoplanet research studies planets orbiting other stars than our Sun. We are currently in an exciting era of this field as powerful spacecraft such as the James Webb Space Telescope [16] and Gaia [13] are providing immense data quality improvements and increases in the number of detected planets available for detailed analysis [23, 24]. Many domain scientists are particularly interested in the search for habitable conditions, where initial efforts aim to study detected planets' atmospheric composition, their habitable zone, and other aspects that characterize their habitability [21, 22]. However, available tools lack the ability to adequately display this vast and multi-dimensional attribute space needed to enable such analyses.

The contribution of this work is an exploration [29] tool addressing the needs of exoplanet scientists by providing a 3D view

of the dataset that provides an overview scenario and a seamless transition into a focused mode. In an overview scenario, a simplified glyph is used, and when the user picks one system as focus and zooms in, the representations change to enable richer data representation and exploration of the exoplanet system. The overview uses spatially embedded glyphs that present user-filterable attribute information about individual exoplanets while simultaneously providing visual access to the selected population's spatial distribution. The exoplanet system mode visualizes known data and their uncertainty about a specific system's exoplanets, including the system's habitable zone. The habitable zone is the region around a star where planets might have the right temperature conditions to support liquid water on the surface. Through a participatory design process with senior experts from the Atmospheric Physics of Exoplanets department at the Max Planck Institute for Astronomy [2] and the Department of Astrophysics at the American Museum of Natural History [1], we determined the needs of domain experts and created a tool that enables them to quickly combine and visually explore datasets of interest. The experts described a need to analyze different groups of planets in a spatial context, grouped on attributes such as the presence of water or whether the star has a specific chemical composition. The ability to view the relevant data, compute derived data, and support query-based filtering of data was also expressed.

2 RELATED WORK

The work builds on the *OpenSpace* [10] software, which is an open-source visualization framework designed to visualize the entire universe for scientists and the general public. Another powerful open-source software is *Gaia Sky* [26], which is used to showcase data collected by the Gaia mission. It is, however, lacking the capabilities to display detailed information about the available exoplanets and is limited to positional information gathered from the Gaia mission.

A few visualization tools are focusing on showcasing and exploring exoplanets data specifically in 3D. NASA's *Eyes on Exoplanets* [6] is a browser-based explorer of the exoplanets in the NASA Exoplanet Archive that visualizes the star and its system. Users can visually compare the exoplanet systems and planets to our own, and get descriptions of both individual planets and the exoplanet research field. It is, however, targeting public outreach rather than experts in the field. Another similar, web-based application is the *ExoPlan-*

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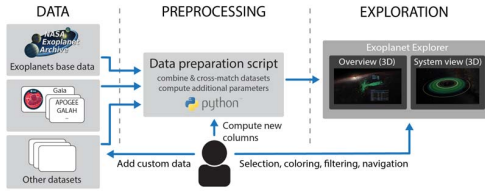


Figure 2: Schematic overview of the data flow and expert interaction at the different information stages in an exoplanet exploration scenario. Data from different sources is collated and inspected through the tool.

etSystems [7], which provides less information about the exoplanet systems, but allows for easier comparison between planetary systems by spatially overlaying the representations of the systems. The *exoExplorer* [8] helps users to visualize exoplanet environments by viewing the habitable zone or virtually visiting imagined planetary surfaces. It also provides access to the data columns through a table view in the application, but none of these tools present an overview that allows data exploration of the entire exoplanet population.

3 EXOPLANETEXPLORER

The *ExoplanetExplorer* tool consists of two different modes: in the *3D Overview* mode (see Sect. 3.2) the exoplanets are shown in their correct position in the galaxy using a glyph-based visualization (see Sect. 3.2.1). In the *System* mode a specific planetary system is presented in detail (see Sect. 3.3). In both modes the exoplanet data with other relevant spatial datasets such as the Milky Way galaxy is contextually displayed and follows the overview first, then details-on-demand mantra [27]. The user first gains an overview in the *3D Overview* and can then select a specific system to inspect in detail. The tool's virtual camera then zooms in on the system until it is visible on the screen, at which point the spatial glyphs fade away to reduce the visual clutter and provide the ability to focus on the selected system, which finalizes the transition to the *System* mode.

3.1 Data and Preprocessing

The data in the NASA Exoplanet Archive [9] was parsed, extended, and exposed to the users to enable the interactive exploration of their parameters of interest. This database includes data about planets, orbits, host star, and system composition. Currently, the archive covers over 5000 confirmed exoplanets orbiting over 3000 stars, but that number will grow rapidly over the coming years. Many numerical values in the database also include uncertainties, provided as absolute values or an asymmetric uncertainty range. A challenging aspect of this data is that the uncertainties are often large, up to several hundred percent of the value. Furthermore, there is also missing data due to the nature of this observational data. Following the need of the scientists, the exoplanet dataset was further extended with additional datasets such as the stellar chemical abundances (based on the GALAH [11], APOGEE [17] surveys), and the detected molecules in planetary atmospheres from the ExoAtmospheres database. Furthermore, the expert is able to easily include any additional dataset. The datasets are cross-matched either by name or by their Gaia Data Release 2 [14] identifier. The complete dataset provided with the system contains 215 dimensions, out of which 135 correspond to unique data values, and 80 represent uncertainty.

The data preparation step is provided as a Python pre-processing script, which fetches the latest data from the Exoplanet Archive, cross-matches this data with any other datasets of interest, computes any additional parameters, and also provides the ability to ingest the experts' own datasets. Fig. 2 shows an overview of the data flow and available data-related interactions available to the user.

3.2 Overview Mode

The 3D overview mode provides a quick overview of the currently selected exoplanet population and enables the expert to study specific

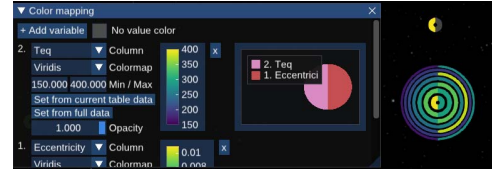


Figure 3: Color mapping window with glyphs showing two parameters. The right half is mapped to the orbit eccentricity and the left to the equilibrium temperature (T_{eq}). Missing values are shown in gray.

properties for each system. They can also overlay other spatial datasets to, for example, examine where the planets are located relative to other astronomic phenomena in the galaxy such as star clusters or the galactic center. In contrast to other existing tools with spatial views, we chose to immediately provide information about all the individual exoplanets in the system, rather than just the star, by mapping planetary data values to the individual components of a glyph, described in Sect. 3.2.1. This enables the expert to quickly overview the data visually in its accurate spatial context.

3.2.1 Glyphs and Color Mapping

Each planet in the overview is rendered as a camera-aligned, ring-shaped glyph with a given width and inner radius and placed at the correct 3D spatial position of the host star. The visibility of the rings can be toggled by the user and is also affected by custom global filtering operations. The inner radii of the glyphs correlate to the planets' semi-major axis such that rings of the same system are rendered in a layered configuration and do not overlap but maintain the spatial ordering between the individual planets. The layered ring design was chosen to let the user compare information about all planets in a selected population at once while preserving the spatial context and the mental model of the system. To accommodate for the multi-variate nature of the dataset, the glyphs are colored by up to eight selectable parameters. Each ring is then divided into a number of angular segments equal to the number of selected colors or parameters. Fig. 3 shows an example of the color map window and glyphs when showing two parameters. The width of the rings is computed so that each ring gets a similar visual weight by proportionally decreasing the width of the outer rings. For equal visibility, the rings are rendered as billboards in screen space, where rings at different distances are rendered with the same overall size. Furthermore, the user can highlight a glyph with the mouse, which brightens the visual appearance of the ring in the view and show a label with the planet's name adjacent to it. A schematic circle in the color mapping window highlights which portion of the rings that correspond to which parameter. Here, the user can also select the color map, mapped parameters, value ranges, and representation for missing data values. To speed up the process of setting the value ranges, the min and max values can also be set directly from the entire dataset or the currently shown (filtered) subset.

3.2.2 Interaction

To support the exploratory analysis in this mode, the tool includes different interfaces for interacting with the data and visualization by selection, coloring, and filtering (see Fig. 2). The user navigates through the glyph cloud and inspects the dataset from different perspectives to visualize their relative spatial distribution. Fig. 1, left shows the planets from an outside-in view, with the camera close to the edge of the Milky Way. In contrast, the center image shows the planet from an inside view, with the camera closer to Earth. The planets then match their position in the night sky.

Linked and Embedded Table View. To provide the expert with a familiar access to the data and their exact values, a core part of the tool is an interactive table that supports interactions such as selection, reordering, and filtering columns, as well as searching

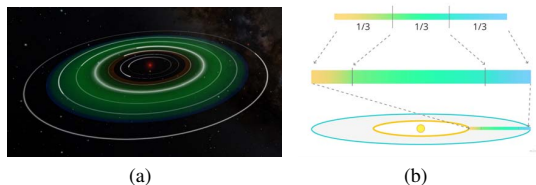


Figure 4: (a) The Trappist-1 exoplanet system with its habitable zone clearly visible, and (b) a schematic of the mapping to the four different boundary values (inner conservative in green, and outer optimistic).

for planets. The table is displayed on top of the 3D rendering in both exploration modes, making it accessible at all times. Selected planets are also highlighted in the 3D view and it is possible to pin planets to the top of the table to ease comparisons. The first two table columns include special controls and are pinned even when scrolling horizontally. The first is the planet name column, through which a context menu gives access to controls such as pinning/unpinning the planet from the top table. It also includes a link to the reference paper (as provided by the NASA Exoplanet Archive), that is used by the experts to validate data values or read more about the specific planet. There are also controls to navigate to the selected planet which causes a transition into the *System* mode (see Sect. 3.3). The remaining table columns are loaded from the preprocessed data file and are customizable by the user. This enables the expert to easily load and view data values they have computed and then use them for selection, coloring, or filtering. Some examples that were computed for the involved experts were metrics for estimated signal-to-noise ratios for spectroscopy [18] and whether water molecules have been detected in a planet's atmosphere, both of which are useful for finding targets of interest for future observations.

Filtering in the tool should be fast and flexible to support interactive data exploration. To give the expert full control, we implemented two categories of filters: column-based and a row-limit. For numerical data, the column-based filtering uses comparative operators ($>$, $<$, $>=$, $<=$, or $=$) and null value checks (*null* or *!null*). For text columns, the filtering is performed using an inclusive or exclusive check against the query. Multiple query conditions can be combined using the comma operator. Any filter can quickly be toggled in the user interface, and all filters are successively applied resulting in the intersection of the individual selections. A common filter desired by the experts is to hide planets without data for a certain data column. To accommodate that, if no query is entered, the default is to check for existing values. Furthermore, to give the expert easy access to some common filter queries, the system includes predefined column filters, such as planets matching certain discovery methods or radius-based categories of planets. The row-limit filter is used to limit the number of rows shown to the n number of matches with either the highest or lowest value for a column. This lets the expert quickly find a set of planets with a high or low score for certain metrics while simultaneously reducing visual clutter in this mode, for example, planets with a high estimated signal-to-noise ratio for spectroscopy.

3.2.3 Visual Cues

It is difficult to maintain a mental model of the planets' spatial location, especially when a large number of planets are filtered away. To guide the understanding of the glyphs and their position, two visual cues were added: a line from Earth to the Milky Way center and the field of view of the Kepler telescope. Both are well-known references to exoplanet researchers and provide further information about the displayed planets. For instance, all planets detected through microlensing should be towards the Milky Way center.

3.3 Exoplanet System Mode

The Exoplanet System mode provides the full (known) picture of the host star, planets, and orbits, in the system's correct spatial location, together with the data values for the planets in that system.



Figure 5: The CoRoT-7 system, including visual context cues in the form of a 90-degree inclination plane and the direction towards Earth.

It acts as a visual aid when presenting research or doing science communication on a specific system, and can also be extended with other visualizations related to the star or planets since they are part of the OpenSpace scene graph. One example may be to include visualizations of magnetic field lines, or visual representations of atmosphere compositions of specific planets [12]. Transitioning from the *Overview* mode to this mode is done by selecting a planet in the overview, and then either flying there manually or automatically. The core of this view is based on previous visualization work by Reidarman [25]. Since Reidarman's work, the data source has been updated from the previous Exoplanet Orbit Database [28], which is no longer maintained, to the NASA Exoplanet Archive. Furthermore, visual representations, such as the habitable zone, have been added as planets within this region, and systems with multiple planets in the region, are interesting targets for further observations in the search for habitable conditions on other worlds.

Stars and Planets. The exoplanet system visualization uses Keplerian representations of the planetary orbits, including eccentricity and orbit period. This also enables the simulation of planetary motion over time. The uncertainty of the semi-major axis is represented by the orbit disc, which shows the variance of the orbit based on its estimated eccentricity and potential semi-major axis values. Fig. 1, right shows an example of an orbit with high uncertainty in its semi-major axis represented by an almost gray-scale disc to not conflict with the habitable zone visualization. When radius values are available, the celestial bodies are also represented with their correct size. Furthermore, the host star is given a representative texture and color based on its temperature. This texture is replaced with a checkerboard texture as a visual cue that the temperature value is missing, instead of not rendering the star at all.

Habitable Zone. Fig. 4(a) shows the Trappist-1 system with a visualization of its habitable zone as a colored circular disc around the star. The inner and outer radii of the disc are determined from limits computed based on a climate model by Kopparapu *et al.* [19, 20]. Their model provides four different boundary values: two corresponding to an inner conservative estimate, for Earth-like planets, and two for an outer optimistic one, where planets with alternative atmospheric conditions can have the right temperature. To communicate the different boundaries, a red-green-blue one-dimensional texture is stretched based on these distances using linear transformations of the texture coordinates, as illustrated in Fig. 4(b). This results in a visualization where the conservative region is green, and the inner and outer optimistic regions show a transition from green to red or blue, respectively. Planets within the green region have a high likelihood of supporting liquid water, whereas those in the red or blue region have some likelihood given the right conditions, but may be too hot or too cold. Furthermore, to clearly show which planets are within the zone, the disc plane is aligned to match the average inclination of the planets' orbits.

Context Cues. In addition to the star and planet visualizations, visual cues have been added to give information about the size and location of the planet system. The first is a 1 AU-sized ring, that shows the size of Earth's orbit around the Sun. Similar features that show the size of the system exist in both the *ExoPlanetsSystems* and *Eyes on Exoplanets*. A second cue is a plane that shows the edge-on (or 90-degree) inclination plane to demonstrate the inclination of the planetary orbits. This is important to the experts as it provides information about whether the planet will transit in front of its star, and hence can be a target for future transit spectroscopy observa-

tions. A third is an arrow that shows the direction to Earth and thus provides information about the direction from which the system can be observed. Each of these cues can be toggled by the user. Figure 5 shows an example of the inclination plane and arrow cues.

4 FEEDBACK AND DISCUSSION

Throughout the design, qualitative feedback was collected in an iterative process, through various meetings with expert users from multiple institutions [1–5]. Two exoplanet researchers [1, 2] were involved throughout the project and participated in the design and provided domain-specific knowledge to steer the development of the tool. One had prior familiarity with the 3D visualization software and used them frequently for research purposes. The other had no previous experience with 3D visualization tools but had an interest in using such tools for exoplanet observation planning for the James Webb Space Telescope. Additional feedback was collected from a larger group of experts throughout the design using remote participation, organized in-person group workshops, as well as individual consultation. The format was similar, starting with a demonstration of the tool, followed up by an open discussion session with feedback and dialog about how such a tool could be useful in their research and which parts could be improved. In total, we gathered feedback from eight different experts with a high degree of seniority in their respective fields, ranging from senior scientists to professors.

3D Overview Mode. One expert particularly emphasized that it is vital to inspect the data in its spatial context, embedded with other relevant spatial datasets and that this should be integrated in workflows to not accidentally disregard important aspects of their data and lead to faulty conclusions. Furthermore, they expressed that the ability to study the spatial distributions of certain planet populations, identify outliers, and quickly and easily explore different values for certain planets are useful features of this view. One limitation some participants mentioned is that the view can be overwhelming at first glance, especially when multiple attributes are visualized using the spatial glyphs. They did however express that it might be something to get accustomed to if interacting with it more, which aligns with previous studies of learning curves using advanced interactive visualization tools [27]. The visual clutter is also mitigated through the use of the existing navigation and filtering features in the tool, making it less significant in the more common use case of studying smaller subsets of planets.

Exoplanet System Mode. This view was generally well-received as a science communication feature for communicating scientific results. The visuals were considered very well-designed and useful for production of images for proposals and public presentations, to communicate what the system actually looks like. For research purposes, having both the data and visuals of the planets in the system in one view was considered useful. This does, for example, allow for easy examination of which planets in the systems are located in the habitable zone, while also having access to the data of the planet size, temperature, and so-far detected molecules in the atmosphere, as well as assessment of whether it is a good target for future observations or not; all important aspects when investigating conditions for habitability. It was clear that having the data and visuals in one place not only enabled in-depth design discussions on visuals and unique visual features of certain systems but also contributed to facilitating scientific discussions among the experts and enabled them to identify aspects of the data that they were not previously aware of. Some experts also expressed interest in the System View as a visual aid when working on research related to a specific system; the view could then potentially replace the “mental model” they usually have of the system. To further increase its usefulness, it could be useful to highlight data that an expert would want to inspect at first glance. This would turn the tool from a general exoplanet exploration to a more specific use case, but decrease the time required for the expert to find out the important details of the system. Another comment

was a lack of trust when it comes to the detailed exoplanet mode, as there is no easy way to know whether the orbits are created using default values or actual data. It would be fruitful to further investigate additional representations of uncertainty and missing data in this view and create novel visualization techniques that can adequately visualize the interesting and highly-structured 6-dimensional space of Keplerian orbital parameters. Another challenge that remains is to visualize systems with different types of binary or ternary stars, for example from data of the recent Gaia data release [15].

Teaching. The researchers that participated in the discussions are often also teachers at university-level courses and several expressed an interest in using the tool for teaching, both for creating content for lecture presentations as well as student assignments. The ExoplanetExplorer can be a visual aid to show and explain different characteristics of exoplanet populations, present available discovery methods, and create visuals that aid the students’ understanding of the course content. One expert mentioned that an advantage of this tool is that it can be used to quickly make consistent visuals and create videos. The usability for the tool in teaching was further emphasized when presenting to a group of young exoplanet researchers at the 2022 Sagan Exoplanet Summer Workshop. This presentation aimed to expose the participants to the idea of using visualization tools for their research, but also as an opportunity to collect feedback from novice users with a knowledge of exoplanet research. After the workshop, two students provided feedback which was done through a semi-structured interview with open-ended questions over Zoom, using screen-sharing, to investigate the visual components and their usage. Both students were engaged by the visuals and found exploration using the tool to be an interesting learning experience.

Data and Credibility. The use of the well-established NASA Exoplanet Archive as the main data source combined with providing access to the data processing and reference papers was adding to the credibility of the data and visual representations. This is something we found important and a necessity for the tool to be acceptable by the experts we interviewed as many of them approached the use of visualization skeptically. However, its credibility could be further increased by including the uncertainty ranges in more of the visuals, as well as communicating when default values are being used.

5 CONCLUSION

We presented an exploratory visualization tool, the *ExoplanetExplorer*, for exoplanet researchers that enables novel ways to analyze the vast dataset of the exoplanet archive to enhance their research process, facilitate scientific discussions, and allow the experts to raise new questions related to their data when viewed in the spatial context. The system is built on top of the open-source visualization software OpenSpace and developed through a participatory design process identifying and addressing the specific needs of exoplanet researchers. The tool provides a 3D view consisting of two modes. The *3D overview* mode presents a glyph-based representation of the entire dataset in a 3D context and supports selection and filtering. By selecting a specific planet and flying to its location, the system transitions to the *Exoplanet System* which provides a detailed system view of that particular exoplanet system. The tool was created through participatory design with exoplanet experts and evaluated in several contexts as described. While there remains future work to extend and enhance the tool, researchers have expressed interest in utilizing the tool to further their research and outreach.

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