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Building and Mining Knowledge Graphs

ExoKG: A Knowledge Graph for Planetary Systems with Confirmed Exoplanets

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Contents

Abstract

In recent years, the field of exoplanet research has experienced significant growth. This work introduces ExoKG, a user-friendly Knowledge Graph comprising 617,137 triples, aimed at providing insights into confirmed exoplanetary systems to non-experts. The goal is to represent the data in a more semantically rich manner, and therefore allow broader participation. Built upon data from the NASA Exoplanet Archive, ExoKG offers an intuitive interface for exploring planetary systems and their host stars. Through conscious data collection and processing, ExoKG ensures accessibility, interoperability, and reusability. Sample queries addressing key research questions highlight the usability and effectiveness of ExoKG in providing valuable and meaningful insights. ExoKG can be seen as a powerful technique combining a visualization of exoplanets with semantic facts.

1 Introduction

The interest in space exploration has significantly grown over time. The historic Moon landing in 1969 marked a turning point that strengthened a dedicated commitment to improve our understanding of the universe. Nowadays, the space industry is partly focused on Mars, with missions like the Mars Exploration Rovers (2003) and the Perseverance rover (2021) exploring Martian soil. However, the broader scope has shifted towards exploring planetary bodies beyond our solar system.

Exoplanets refer to planets located outside our solar system. Over the last two decades, thousands of candidate exoplanets have been identified, predominantly through NASA's Kepler Space Telescope (Kepler). Some candidates turn out to be "false positives"; a planet is considered "confirmed" once it is verified through additional observation using two other telescopes. There are currently thousands of planet candidates awaiting confirmation.

Scientists prioritize hunting for a specific type of exoplanet: those resembling Earth in size, orbiting a star similar to our sun within the habitable zone. Different methodologies such as analyzing the age, atmosphere, and composition of exoplanets can be used to understand and identify planets similar to ours. Where computers might miss a single transit, humans can detect small brightness dips in data that might tell us there is a planet to be found.

In this work, ExoKG, a user-friendly and interoperable Knowledge Graph (KG) specifically for planetary systems hosting confirmed exoplanets is introduced. The ontology is built as a combination of the planetary systems data set NASA Exoplanet Archive (2020) and the stellar hosts NASA Exoplanet Archive (2021) data sets from the NASA Exoplanet Archive. The initiative behind creating ExoKG is to provide new insights into exoplanetary systems, addressing the challenge of accessibility for non-experts, potentially leading to broader participation in exoplanet research and fostering a collaborative and inclusive approach to advancing our understanding of the celestial bodies. The ontology is linked to standardized ontologies and follows the FAIR (Findable, Accessible, Interoperable, and Reusable) principles, as discussed in Sec. 3. Example queries are also formulated to answer key questions, helping users find their way through the graph.

2 Related work

State-of-the-art methods for detecting exoplanets involve various techniques such as such as radial velocity (2018), transit photometry (2018), direct imaging (2023), and relativistic beaming (2013), among others. Recently, Sekhar et al. (2023) introduced a novel approach to exoplanet detection using the You Only Look Once (YOLO) model, one of the most popular algorithms for object detection. Their method, when compared to existing algorithms, demonstrates significantly higher accuracy in predicting brightness dips in light curves and requires less training time.

Although extensive research has been conducted on exoplanet identification, a specific focus is on identifying Earth-like planets which may be habitable. To date, NASA reports over 5,000 identified exoplanets (2024), with around 200 potentially Earth-like (2024). Capistrant et al. (2024) present the discovery of HD 63433 d-a nearby (22 pc), an exoplanet with a similar size to Earth that orbits around a young Sun-like star

(TOI-1726, HD 63433). At the time of writing, they reported that HD 63433 d is the confirmed nearest young Earth-sized planet.

While many of the existing studies employ specialized methods, accessibility to people with general knowledge remains a common issue. To address this, this project proposes a simplified approach to facilitate understanding within a broader community, focusing on a knowledge graph that is semantically meaningful as well as easy to understand and use.

On the other hand, in the knowledge graphs domain, public communities such as Wikidata[1] (2014) and DBpedia[2] (2015) have made significant progress by constructing ontologies for vast amounts of datasets, making them openly accessible to anyone. However, the data often suffer from inconsistencies and lack of clarity. Additionally, the European Space Agency (ESA) has devised its own data ontology[3], albeit operating at a higher level, encompassing space-related information rather than focusing specifically on exoplanetary data. In response to these concerns, ExoKG aims to address them by enhancing accessibility and promoting intuitive comprehension through its specialized vocabulary, tailored specifically for exoplanetary data.

3 Methodology

In this section, the planetary data used as part of this project as well as the technique used to collect this data and the elementary data processing are described. Next, the vocabulary specifically designed for ExoKG is detailed. Finally, details regarding the construction of the graph are presented.

3.1 Data, collection and processing

3.1.1 Data and collection

As mentioned earlier, the NASA Exoplanet Archive was extensively used to build ExoKG. The data were accessed using a Table Access Protocol (TAP) provided by the archive[4]. Two tables were retrieved:

Planetary systems (`ps`) table This table comprises essential parameters associated with planetary systems. It provides a comprehensive overview of various attributes related to exoplanets and their host stars, including planet names, stellar identifiers, discovery methods, orbital characteristics, and detection techniques. Each column within the PS table corresponds to a specific data field, facilitating systematic organization and efficient retrieval of pertinent information.

Stellar hosts (`stellar`) table This table presents information about host stars within verified planetary systems. It outlines the system composition, including the count of stars, planets, and circumbinary configurations. Essential stellar parameters such as temperature, radius, mass, metallicity, and rotational features are included. Additionally, positional data like right ascension, declination, and distance contribute to a deeper understanding of planetary system dynamics.

3.1.2 Data processing

Firstly, not all data from the original tables was incorporated into ExoKG; a conscious decision was made to prioritize information that users can easily understand. Next, The conversion of the detailed data tables into an RDF representation required minimal processing. Missing values were omitted during the mapping process. However, an issue arose in the pipeline when generating spectral types for stars, leading to one value being recorded as “F0+ V (lambda Boo)...”. This discrepancy was corrected by replacing it with the accurate value “A5 V”.

[1] https://www.wikidata.org/
[2] https://www.dbpedia.org/
[3] https://data.esa.int/esado/
[4] https://exoplanetarchive.ipac.caltech.edu/docs/TAP/usingTAP.html

Additionally, certain columns, such as the mass or radius of exoplanets, were originally provided relative to Earth or Jupiter. To enhance usability, actual mass and radius values were extracted and included alongside the relative observations.

3.2 Vocabulary

This section begins by outlining the specialized vocabulary tailored for ExoKG. Subsequently, it delves into the integration of various links with standard ontologies. Lastly, a comprehensive discussion is presented to argue that the proposed ontology adheres to the FAIR principles.

3.2.1 ExoKG Ontology

The ExoKG vocabulary incorporates user-friendly and easily identifiable terms, along with intuitive URIs that convey semantic significance. All definitions are organized within the `https://example.org/ontology/` namespace. Additionally, sub-namespaces are established for distinct entities or properties related to planetary systems, celestial bodies, stars, exoplanets, discoveries, and units. In addition to these proprietary namespaces, standard ones such as OWL, DCTerms, RDF, RDFS, schema, SKOS, time, and XSD are utilized within the ontology to enhance interoperability and adherence to established standards.

Each entity within ExoKG, including planetary systems, stars, and planets, is assigned identifiers that link directly to NASA's website. This linkage allows users to visualize the respective system and access additional properties that may not be encompassed within ExoKG.

Since ExoKG focuses on accessibility for all users, to achieve this goal, comprehensive descriptions are provided for most relations and self-defined classes. These descriptions, based on NASA's definitions as outlined in table descriptions, aim to enhance user understanding of the semantic meaning behind each relation.

3.2.2 Links to standard ontologies

Another significant advantage of ExoKG is its integration with existing ontologies, providing users access to a broader range of properties for entities within the knowledge graph. This is known as the interoperability of a graph, enhancing the graph's usability.

For example, units defined within ExoKG's namespace are also linked to standard Unified Code for Units of Measure (UCUM) units, accessible through the UCUM ontology[5]. Additionally, certain units of measurement, such as solar mass and Earth radius, are defined within the OM2 ontology[6], to which a link is provided.

Moreover, many relations within ExoKG are linked to DBpedia, further expanding the scope of accessible properties for entities within the knowledge graph. Additionally, the discovery methods are linked to ESA's data ontology. These integrations enhance the richness and depth of information available to users of ExoKG.

3.2.3 FAIR principles

The ExoKG ontology follows the FAIR principle as it is

- **F**indable: as it is published in the open GitHub repository[7];
- **A**ccessible: as discussed in Sec. 3.2.1;
- **I**nteroperable: as discussed in Sec. 3.2.2;
- **R**eusable: as it is openly available and accessible.

[5] `https://w3id.org/uom/`
[6] `http://www.ontology-of-units-of-measure.org/resource/om-2/`
[7] `https://github.com/Aurelien-Bertrand/BMKG-Project-ExoKG`

3.3 Graph construction

To build the graph, a Python pipeline was created to systematically add parameters of planetary systems, stars, and exoplanets. The process is detailed in the `build_graph.ipynb` notebook.

4 Experiments

To showcase the comprehensive capabilities of ExoKG, a multi-step evaluation process is undertaken. Initially, Experiment I evaluates the intrinsic quality of ExoKG through SPARQL queries. Subsequently, Experiment II formulates four research questions to extend the demonstration of ExoKG's usability.

4.1 Experiment I: Knowledge graph quality

This experiment is designed to assess ExoKG's quality. The following scenarios are considered: number of triples, number of classes, number of properties, "NaN" values, empty strings, and multiple values.

4.2 Experiment II: Research questions

This experiment aims to demonstrate both the accessibility of ExoKG as well as its effectiveness in prediction tasks which may involve machine learning methods. The primary focus of this work is on creating an accessible KG. To achieve this, sample queries have been formulated to address the following research questions:

1. **RQ1**: Which planetary system hosts the largest number of exoplanets?
2. **RQ2**: Which laboratory has discovered the most exoplanets?
3. **RQ3**: What are the key characteristics of exoplanets?
4. **RQ4**: Which exoplanet most closely resembles Earth?

While the first three questions aim to showcase the usability of ExoKG, **RQ4** is specifically designed to demonstrate its effectiveness in prediction tasks. This question is well-studied, with a known answer against which the obtained result will be compared. According to NASA, Kepler-452b and its star are considered the closest analogue to Earth and the Sun discovered thus far. Despite being 60% larger than Earth, Kepler-452b is believed to be rocky and situated within the habitable zone of a G-type star similar to our Sun.

5 Results

In this section, the results of the experiments detailed in Sec. 4 are shown. They can also be found in the `sample_queries.ipynb` notebook.

5.1 Experiment I: Knowledge graph quality

The queries used to assess ExoKG's quality can be found in the `sample_queries.ipynb`. The results are provided in Table 1.

5.2 Experiment II: Research Questions

Answering RQ1 Query 1 is designed to address **RQ1**. The output reveals that KOI-351 stands out as the planetary system with the highest number of confirmed exoplanets, totalling 8, equivalently to our Solar System. This is in line with what NASA reported[8].

[8] `https://www.nasa.gov/image-article/planetary-systems-by-number-of-known-planets/`

Statistic	Value
Number of triples	617126
Number of classes	7
Number of properties	28
Number of NaN values	0
Number of empty strings	0
Number of multiple observation values	0

Table 1: Quality summary of ExoKG

Answering RQ2 To tackle **RQ2**, Query 2 was formulated. It identifies Kepler as the most prolific "facility" in discovering exoplanets, with a total of 2779 detections. This aligns with the truth reported by NASA[9].

Answering RQ3 Query 3 offers insights into key characteristics of exoplanets, given in Table 2.

Property	Average Value	Units
Orbital Period	$80,000.80$	days
Longest Radius	10.19	AU
Radius	$27,303.00$	km
Mass	4.57×10^{27}	kg
Density	3.29	g/cm^3
Orbital Eccentricity	0.16	-
Insolation Flux	$603,363.23$	W/m^2
Equilibrium Temperature	1019.41	K
Inclination	85.93	degrees
Obliquity	39.00	degrees
Ratio of Planet to Stellar Radius	0.04	-

Table 2: Average values of various exoplanetary properties

Answering RQ4 Query 4 is tailored to address **RQ4**, identifying the exoplanet most similar to Earth in terms of orbital period, as well as its star's radius and mass in comparison to the Sun. The analysis reveals Kepler-452 b as the closest match to Earth, with a mere 19.8 days difference in orbital period. Its host star, Kepler-452, exhibits a mass and radius of 87% and 79% respectively, relative to those of the Sun. This finding corroborates with NASA's observations[10].

6 Discussion

6.1 Data quality and accessibility

Based on both **Experiment I** and **II**, it is evident that ExoKG demonstrates a decent level of quality. This quality is attributable to the systematic pipeline devised for generating the RDF representation of the ontology. Furthermore, the various research questions offer insights into the usability of ExoKG. It is contended here that the sample queries not only showcase the efficacy of ExoKG but also highlight its user-friendliness. This is facilitated by the semantic nature of knowledge graphs, which renders the data more accessible to individuals with general knowledge compared to raw data usage. Additionally, the inclusion of diverse definitions and links to existing ontologies enriches the user experience by providing extensive contextual information.

[9] https://www.nasa.gov/general/scorching-seven-planet-system-revealed-by-new-kepler-exoplanet-list/

[10] https://www.nasa.gov/image-article/spin-around-an-exoplanet-most-like-earth/

6.2 Future work

For future work, ExoKG's efficacy and scope could be enhanced through several approaches. One approach entails integrating updated datasets to ensure alignment with the latest advancements in exoplanet research, thus enhancing the accuracy and currency of ExoKG's contents.

Expanding ExoKG to include supplementary planetary data, such as Kepler Object of Interest (KOI) datasets and candidates from missions like K2, TESS, and TOI, offers another way to enrich its coverage. By encompassing both confirmed exoplanets and potential candidates, ExoKG could provide a more comprehensive view of the exoplanetary landscape, fostering deeper insights into celestial bodies beyond its current scope.

Furthermore, exploring opportunities to merge ExoKG with complementary datasets could deepen its interdisciplinary relevance. By fostering collaborations and interoperability with other knowledge repositories, ExoKG could tap into synergies that transcend disciplinary boundaries, enriching the exoplanetary knowledge base with insights from diverse domains.

7 Conclusions

In this work, ExoKG is introduced. ExoKG is a knowledge graph designed to provide accessible insights into confirmed exoplanetary systems. By leveraging data from the NASA Exoplanet Archive and employing systematic data collection and processing, ExoKG offers a user-friendly interface for exploring the complexities of exoplanetary systems.

Through adherence to the FAIR principles and integration with existing ontologies, ExoKG ensures its accessibility, interoperability, and reusability. Sample queries addressing key research questions demonstrate ExoKG's usability and effectiveness in providing valuable insights into the exoplanetary landscape.

Looking ahead, ExoKG's potential lies in its ability to evolve and expand, integrating updated datasets, and fostering collaborations to enhance its depth and interdisciplinary relevance.

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A Appendix

A.1 SPARQL queries

```
SELECT ?ps_label ?n_planets
WHERE {
    ?ps a ex:Planetary_system ;
        rdfs:label ?ps_label ;
        pl_sys:number_of_planets ?n_planets .
}
ORDER BY DESC(?n_planets)
LIMIT 1
```

Query 1: Query used to answer **RQ1**

```
SELECT ?facility (COUNT(?facility) AS ?count)
WHERE {
    ?discovery a schema:Observation ;
        ex:place ?facility .
}
GROUP BY ?facility
ORDER BY DESC(?count)
LIMIT 1
```

Query 2: Query used to answer **RQ2**

```
SELECT
    ?average_orbital_period
```

```
    ?average_longest_radius
    ?average_radius
    ?average_mass
    ?average_density
    ?avg_orbital_eccentricity
    ?average_insolation_flux
    ?average_equilibrium_temperature
    ?average_inclination
    ?average_obliquity
    ?average_ratio_planet_stellar_radius
WHERE {
    {
        SELECT (AVG(?orbital_period_value) AS ?average_orbital_period)
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet exo:orbital_period ?orbital_period .
                ?orbital_period schema:value ?orbital_period_value .
            }
            FILTER(BOUND(?orbital_period_value))
        }
    }
    {
        SELECT (AVG(?longest_radius_value) AS ?average_longest_radius)
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet exo:longest_radius ?longest_radius .
                ?longest_radius schema:value ?longest_radius_value .
            }
            FILTER(BOUND(?longest_radius_value))
        }
    }
    {
        SELECT (AVG(?radius_value) AS ?average_radius)
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet cb:radius ?radius .
                ?radius schema:value ?radius_value ;
                    schema:unitCode unit:kilometer .
            }
            FILTER(BOUND(?radius_value))
        }
    }
    {
        SELECT (AVG(?mass_value) AS ?average_mass)
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet cb:mass ?mass .
                ?mass schema:value ?mass_value ;
                    schema:unitCode unit:kilogram .
            }
```

```
            FILTER(BOUND(?mass_value))
        }
    }
    {
        SELECT (AVG(?density_value) AS ?average_density)
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet cb:density ?density .
                ?density schema:value ?density_value .
            }
            FILTER(BOUND(?density_value))
        }
    }
    {
        SELECT (AVG(?orbital_eccentricity_value) AS ?avg_orbital_eccentricity)
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet exo:orbital_eccentricity ?orbital_eccentricity .
                ?orbital_eccentricity schema:value ?orbital_eccentricity_value .
            }
            FILTER(BOUND(?orbital_eccentricity_value))
        }
    }
    {
    SELECT (AVG(?insolation_flux_value) AS ?average_insolation_flux)
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet exo:insolation_flux ?insolation_flux .
                ?insolation_flux schema:value ?insolation_flux_value ;
                    schema:unitCode unit:watt_per_square_meter .
            }
            FILTER(BOUND(?insolation_flux_value))
        }
    }
    {
        SELECT (AVG(?equilibrium_temperature_value) AS ?average_equilibrium_temperature)
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet exo:equilibrium_temperature ?equilibrium_temperature .
                ?equilibrium_temperature schema:value ?equilibrium_temperature_value .
            }
            FILTER(BOUND(?equilibrium_temperature_value))
        }
    }
    {
        SELECT (AVG(?inclination_value) AS ?average_inclination)
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet exo:inclination ?inclination .
```

```
                ?inclination schema:value ?inclination_value .
            }
            FILTER(BOUND(?inclination_value))
        }
    }
    {
        SELECT (AVG(?obliquity_value) AS ?average_obliquity)
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet exo:obliquity ?obliquity .
                ?obliquity schema:value ?obliquity_value .
            }
            FILTER(BOUND(?obliquity_value))
        }
    }
    {
        SELECT (
            AVG(?ratio_planet_stellar_radius_value) AS ?average_ratio_planet_stellar_radius
        )
        WHERE {
            ?exoplanet a ex:Exoplanet .
            OPTIONAL {
                ?exoplanet exo:ratio_planet_stellar_radius ?ratio .
                ?ratio schema:value ?ratio_planet_stellar_radius_value .
            }
            FILTER(BOUND(?ratio_planet_stellar_radius_value))
        }
    }
}
```

Query 3: Query used to answer **RQ3**

```
SELECT
    ?exoplanet_label
    ?difference_orbital_period_relative_to_Earth
    ?star_label
    ?star_mass_value
    ?star_radius_value
WHERE {
    ?exoplanet a ex:Exoplanet ;
        rdfs:label ?exoplanet_label ;
        exo:orbital_period ?orbital_period ;
        exo:orbits_around ?star .
    ?orbital_period schema:value ?orbital_period_value .
    ?star a ex:Star ;
        rdfs:label ?star_label ;
        cb:mass ?star_mass ;
        cb:radius ?star_radius ;
        star:has_spectral_type ?spectral_type .
    ?star_mass schema:unitCode unit:solar_mass ;
        schema:value ?star_mass_value .
    ?star_radius schema:unitCode unit:solar_radius ;
        schema:value ?star_radius_value .
    ?spectral_type a star:Spectral_type ;
```

```
        rdfs:label ?spectral_type_label .
    FILTER(CONTAINS(LCASE(?spectral_type_label), "g2"))
    BIND(ABS(?orbital_period_value - 365) AS ?difference_orbital_period_relative_to_Earth)
}
ORDER BY ?difference_orbital_period_relative_to_Earth ?star_mass_value ?star_radius_value
LIMIT 1
```

Query 4: Query used to answer **RQ4**