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DS5023 Data Organization and Visualizations

October 18, 2024

Astronomy: Mining and Resources in the Solar System

Abstract:

Asteroid mining represents a groundbreaking frontier in space exploration, with the potential to reshape industries and support human expansion beyond Earth. As asteroids contain abundant resources such as rare metals (e.g., platinum, rhodium) and water, they offer both economic opportunities and critical resources for future space missions. The development of efficient methods to detect and extract these materials has become a focal point for private companies and governments, as decreasing launch costs make extraterrestrial mining increasingly feasible [1][2].

However, the economic viability of asteroid mining remains complex. A techno-economic analysis indicates that profitability will depend on multiple factors, including throughput rates, mission frequency, and spacecraft reuse. If the materials mined are used in space, the need to transport them back to Earth may be reduced, improving financial prospects. Conversely, an influx of rare metals could affect terrestrial markets by driving down prices, which may complicate long-term profitability models [1][3][7][14].

Technological challenges also abound. Mining under zero-gravity conditions, handling extreme temperatures, and returning payloads to Earth or space stations are hurdles requiring innovative engineering solutions. Nonetheless, advances in space mining technologies can have spillover benefits, fostering new technologies and industries on Earth [4][5][6]

Addressing these challenges may require robust legal frameworks as less capable principalities and industries may try to block innovation and technological advancement, collaboration across industries, and continued investment in research and development. If successful, asteroid mining could not only unlock new wealth but also provide the resources necessary to support humanity’s ambitions for deeper space exploration [1][2][4][5][6].

Literature Review:

1. Hein, Andreas M., Dan Fries, and Robert Matheson. *A Techno-Economic Analysis of Asteroid Mining*. arXiv, 2018. DOI: 10.48550/arXiv.1810.03836. This [source](https://www.sciencedirect.com/science/article/abs/pii/S0094576518316357) covers a proposed extended profitability model for asteroid mining, application to water and platinum mining, mining missions with multiple spacecraft per mission and reuse, viability of returning resources to Earth based on market reactions.
2. Hein, Andreas M., et al. *Exploring Potential Environmental Benefits of Asteroid Mining*. arXiv, 2018. DOI: 10.48550/arXiv.1810.04749. This source covers potential environmental benefits of asteroid mining. It mainly covers two cases: water supply to cis-lunar orbit (the space between the Earth and Moon) and platinum mining.
3. Hellgren, Vide. *Asteroid Mining: A Review of Methods and Aspects*. Lund University, 2016, lup.lub.lu.se/student-papers/record/8882371. This source covers a wide range of topics related to mining in space. Of particular interest is the section relating to determining the geology of asteroids. It explores several ideas associated with remote sensing techniques.
4. “The Economic Viability of Asteroid Mining.” *Metal Tech News*, 6 Jan. 2021, <https://www.metaltechnews.com/story/2023/11/01/mining-tech/the-economic-viability-of-asteroid-mining/1517.html>. This technical article looks at the viability of mining in space, how economists are reacting to this idea, and which key players in the industry are leading the way.
5. “Economics of the Stars: The Future of Asteroid Mining and the Global Economy”, *Harvard International Review,* 8 Apr. 2022, <https://hir.harvard.edu/economics-of-the-stars/>. This article covers some aspects regarding the cost to mine asteroids and looks at a particular case study that involved the extraction of sample material from an asteroid.
6. “Two groups look at the economic viability of mining asteroids”, *Science X, Phys.org,* 23 Oct. 2023. <https://phys.org/news/2023-10-groups-economic-viability-asteroids.html>. This article looks closely at how two teams of economists conducted economic assessments of mining asteroids.
7. Vergaaij, Merel, et al. *Economic assessment of high-thrust and solar-sail propulsion for near-earth asteroid mining.* Advances in Space Research, Volume 67, Issue 9, 1 May 2021. This research paper discusses in detail delivery mechanisms for asteroid mining payloads to Earth and orbital factories.
8. Calla, Pablo, et al. *Asteroid mining with small spacecraft and its economic feasibility.* [*arXiv:1808.05099v2*](https://arxiv.org/abs/1808.05099v2)*,* 24 Jun 2019. This research paper explores the possibility of performing asteroid mining with smaller spacecraft swarms to extract water.
9. Dong, Longjun, et al. *Exploration: Safe and clean mining on Earth and asteroids,* Journal of Cleaner Production, <https://doi.org/10.1016/j.jclepro.2020.120899>, 1 Jun 2020. This research paper highlights interesting aspects of space mining operations. Topics include safety, cleanliness, optimization, accident prevention, adaptations, merits, and defects of proposed off-world mining methods.
10. Basu, Victor, *Open Asteroid Dataset,* International Journal of advances in Electronics and Computer Science, [IJAECS](https://www.iraj.in/journal/journal_file/journal_pdf/12-555-156136953136-40.pdf). Jun 2024. This paper is a case study on predicting a feature of an asteroid within the Solar System asteroid belt. The methods involve suggest an approach to characterizing the nature of asteroids. In this article, the asteroid diameter is the focus of analysis and analysis other characteristics.
11. Ionescu, Liva, et al. *A multiple-vehicle strategy for near-Earth asteroid capture.* [Acta Astronautica, Volume 199, pages 71-85, Oct 2022](https://www.sciencedirect.com/science/article/pii/S0094576522003411). This research paper highlights a multiple-vehicle method for capturing near-Earth asteroids and studies the benefits of using multiple vehicles for returning more materials during a mining mission.
12. Astronomical Unit: See Wikipedia [here](https://en.wikipedia.org/wiki/Astronomical_unit#/media/File:Astronomical_unit.png)**.**
13. Jet Propulsion Laboratory, California Institute of Technology, [Small-Body Database Query](https://ssd.jpl.nasa.gov/tools/sbdb_query.html)
14. Truyshev, Slava G., et al. *Science opportunities with solar sailing smallsats,* [Planetary and space Science, Volume 235, 1 Oct 2023](https://www.sciencedirect.com/science/article/abs/pii/S0032063323001137). This research paper discusses methods for space propulsion using solar sailing and small satellites.

Materials and Methods:

* [Open Asteroid Dataset](https://ssd.jpl.nasa.gov/tools/sbdb_query.html): You can use this site, maintained by NASA Jet Propulsion Laboratory, to generate your data set. Under tools you can pick “Small-Body Database Query” and select the columns that are of interest to you.
* Jupyter notebook to organize the approach, analysis, and visualizations.
* Python 3 and the required data analysis and visualization modules will be implemented.

Analysis:

The analysis approach will be used to answer three basic questions as follows:

1. How clean is the data set?
2. Is the data generated complete?
3. Can the data be expanded to include other useful information?

For the purposes of answering these questions, the small-body database data [13] was limited to asteroids with assigned number id’s, cross the Earth’s orbit, and those within 1.3 astronomical units from Earth, where an astronomical unit (au) is the average distance Earth is from the Sun (approximately 3300 asteroids) [12].

1.How Clean is the Dataset?

The dataset contains several columns of interest (e.g., semi-major axis, eccentricity, inclination, and diameter). However, there are a few areas where the dataset required cleaning:

* Missing Values: Some of the columns, like diameter, had missing values. These missing values were filtered out using dropna().
* Zero Values: For columns like diameter, there were also rows with values set to zero, which were removed since they do not contribute to meaningful analysis.
* Spectral Type: A large portion of the dataset had missing or unknown values for spectral type (spec\_B), which limited our ability to analyze and visualize based on this attribute.

Overall, the dataset was generally clean, though some columns required handling of missing or zero values. The data required only moderate cleaning to make it useful for analysis.

2. Is the Data Generated Complete?

The dataset provides key orbital parameters: Semi-major axis (a), Eccentricity (e),

Inclination (i), Orbital Period (per\_y), and Diameter (for some asteroids). However, the dataset

lacks:

* **Spectral Information**: Many asteroids have missing or unknown spectral types, making it difficult to correlate asteroid composition with orbital characteristics.
* **Compositional Data**: Beyond spectral types, additional information about asteroid composition (e.g., carbonaceous, silicate, metallic) would enhance the analysis.

While the data covers many essential orbital characteristics, it is incomplete in terms of physical

and compositional details for a large portion of the dataset.

3. Can the Data be Expanded to Include Other Useful Information?

Yes, the dataset could be expanded in the following ways:

* **Spectral Type Completion**: Expanding the dataset to include more accurate and complete **spectral types** for each asteroid would allow for better analysis of how asteroid composition affects their orbital properties.
* **Compositional Information**: Adding detailed compositional data (e.g., iron content, carbonaceous properties) would help assess resource availability for asteroid mining and could lead to insights on how composition influences orbital dynamics.
* **Collision Risk Information**: Including data related to Minimum Orbit Intersection Distance (MOID) with Earth and other planets would provide valuable insight into the impact risk of each asteroid.
* **Size and Mass Data**: While diameter is provided for some asteroids, adding more comprehensive size and mass data would enhance analysis, especially in studying the relationship between size and orbital characteristics.

Results and Discussion

The dataset provided detailed orbital characteristics, such as semi-major axis, eccentricity, inclination, and diameter for asteroids, though missing and zero values were identified and removed. My analysis revealed a strong correlation between the semi-major axis and eccentricity, confirming expected orbital mechanics. However, the spectral type data was incomplete, limiting further composition-based analysis. Expanding the dataset to include additional compositional and risk-related information would enable a more comprehensive study, particularly for research into asteroid mining and planetary defense strategies [8][9][11]. Moreover, this dataset can provide useful training data for machine learning and artificial intelligence algorithms to predict asteroid features and formations [10].

A screenshot of a graph

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A screenshot of a computer screen

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Conclusion:

This study has provided important insights into the orbital characteristics of asteroids by analyzing parameters such as semi-major axis, eccentricity, inclination, and diameter. This information would be invaluable as a basis for mining missions and can be extended for collision threats to planet Earth. But here I limited the analysis to the potential of off world mining. Our analysis confirmed the expected correlation between the semi-major axis and eccentricity, revealing that larger orbits tend to exhibit more varied eccentricities, consistent with orbital mechanics. Additionally, the exploration of diameter data gave us a deeper understanding of asteroid size distribution, highlighting the vast differences in asteroid sizes.

However, the study faced several limitations, particularly concerning data completeness. A significant portion of the dataset contained missing or zero values, especially in columns related to asteroid diameter and spectral types. While I was able to clean and filter out incomplete data, the absence of sufficient compositional information limited our ability to analyze how material composition, and spectral characteristics affect asteroid behavior. This lack of spectral data also impeded efforts to classify asteroids based on composition, which would have been especially relevant for understanding the feasibility of asteroid mining.

Moreover, while the dataset provided key orbital parameters, it lacked critical information regarding potential collision risks, such as Minimum Orbit Intersection Distance (MOID) with Earth and other planets. This would have been valuable for assessing planetary defense strategies and identifying asteroids of interest.

In conclusion, while the study successfully uncovered important relationships between key orbital parameters, future research would benefit from expanding the dataset to include more detailed spectral data, compositional information, and collision risk metrics. These enhancements would allow for a more comprehensive analysis of asteroid behavior and properties, providing valuable insights for both scientific understanding and practical applications such as asteroid mining and planetary defense.

References:

1. Hein, Andreas M., Dan Fries, and Robert Matheson. *A Techno-Economic Analysis of Asteroid Mining*. arXiv, 2018. DOI: 10.48550/arXiv.1810.03836.
2. Hein, Andreas M., et al. *Exploring Potential Environmental Benefits of Asteroid Mining*. arXiv, 2018. DOI: 10.48550/arXiv.1810.04749.
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5. “Economics of the Stars: The Future of Asteroid Mining and the Global Economy”, *Harvard International Review,* 8 Apr. 2022, <https://hir.harvard.edu/economics-of-the-stars/>.
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7. Vergaaij, Merel, et al. *Economic assessment of high-thrust and solar-sail propulsion for near-earth asteroid mining.*
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11. Ionescu, Liva, et al. *A multiple-vehicle strategy for near-Earth asteroid capture.* [Acta Astronautica, Volume 199, pages 71-85, Oct 2022](https://www.sciencedirect.com/science/article/pii/S0094576522003411).
12. Astronomical Unit: See Wikipedia [here](https://en.wikipedia.org/wiki/Astronomical_unit#/media/File:Astronomical_unit.png)**.**
13. Jet Propulsion Laboratory, California Institute of Technology, [Small-Body Database Query](https://ssd.jpl.nasa.gov/tools/sbdb_query.html)
14. Truyshev, Slava G., et al. *Science opportunities with solar sailing smallsats,* [Planetary and space Science, Volume 235, 1 Oct 2023](https://www.sciencedirect.com/science/article/abs/pii/S0032063323001137).