

VEGA: Adaptive Learning in Astronomy through Symbiotic Artificial Intelligence

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Abstract

The increasing availability of astronomical data and public interest in Near-Earth Objects (NEOs) has highlighted the need for accessible, adaptive, and educational tools that support exploration and learning in this complex scientific domain. This paper presents VEGA (Visual Exploration and Graphical Analysis of Asteroids), an interactive system that leverages Symbiotic Artificial Intelligence (SAI) to enable a personalized and transparent learning experience in astronomy. Grounded in SAI principles—such as explainability, fairness, and human-in-the-loop interaction—the proposed system integrates generative AI, reinforcement learning, and user modeling to deliver tailored educational content related to asteroids and NEOs. VEGA allows non-expert and expert users to explore real-time NASA data, generate customized learning materials and quizzes via Large Language Models (LLMs), and iteratively improve content through a dynamic versioning mechanism. The paper introduces a modular framework for adaptive learning based on five co-evolving components, illustrating how SAI can foster trust and cognitive augmentation in science education. This approach not only enhances public awareness of astronomical phenomena but also serves as a testbed for the application of human-centered AI in low-risk yet high-impact domains.

Keywords

Symbiotic AI, Asteroids, Astronomy, Near-Earth Objects (NEO), Personalized Educational Content, AI-assisted Learning

1. Introduction

Between late 2024 and 2025, there was considerable discussion about the asteroid 2024 YR4, which exhibited several fluctuations in the probability of a possible future impact with Earth. This phenomenon, which has captured considerable media attention, along with other events not covered in this paper, has fueled interest in the so-called *Potentially Hazardous Asteroids (PHAs)*, encouraging research and scientific information from enthusiasts and academics regarding these celestial bodies, classified as Near Earth Objects (NEOs). However, access to this information was complex for the non-specialized range of users, as it was often necessary to have advanced technical skills to install specific applications along with their dependencies, or to make queries via NASA APIs. As a result, there is a lack of reliable and accessible tools for obtaining real-time information.

The lack of dynamic visual tools further hampers pattern recognition and comparative analysis and do not consider the application of Symbiotic-AI (SAI) to create collaborative partnerships between human expertise and Artificial Intelligence (AI) [1]. SAI systems are designed to learn from and adapt to individual users, providing personalized support and fostering a strong human-AI bond [2].

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The concept of Symbiotic AI (SAI) introduces Embodied Symbiotic Learning, where AI partners with humans in real-time, developing a theory of mind and shared communication norms [3]. This approach allows for greater task flexibility and environmental resilience compared to traditional AI systems. In medical applications, SAI systems demonstrate potential for improving healthcare outcomes [4]. However, the development of SAI raises ethical concerns and regulatory challenges, necessitating frameworks like the EU's AI Act to ensure responsible implementation [1, 5].

Therefore, it is necessary to investigate human-AI symbiosis for creative work and real-time neural link integrations for enhanced cognitive abilities, providing foundational frameworks applicable to astronomical research contexts. Research should focus on:

- Real-time adaptive learning systems that evolve based on astronomer feedback.
- Transparent AI decision-making processes that maintain human agency in discovery.
- Multi-modal interaction interfaces that leverage both human intuition and AI pattern recognition.
- Ethical frameworks for AI-assisted scientific discovery attribution.

With this in mind, the paper presents **VEGA** (Visual Exploration and Graphical Analysis of Asteroids), an interactive platform designed for both consultation and science dissemination. The design and implementation of a system that, according to the principles of SAI, applies generative AI to a highly complex domain such as astronomy, while promoting accessibility, personalization and educational quality.

One of its main features is the creation of an educational module for the delivery of content related to astronomy. The content is dynamically generated on end-user request through a Large Language Model (LLM), which also takes care of the creation of an associated quiz. The module also allows for content to be exported in PDF format and for custom versions to be generated through corrective or in-depth feedback. Given the automatic generative nature of the module and its educational goal, it was chosen to embed the system within the framework of SAI, which not only provides functionality but also enhances the interaction between user and AI, reinforcing perceived trustworthiness through principles such as transparency.

The remainder of the paper is organized as follows. Section 2 reports relevant works concerning AI and SAI in astronomy, whereas Section 2 presents the SAI principles and Section 3 the application of principles to personalized learning in astronomy. Section 4 shows the system design and the results of the development, and conclusions are provided in Section 5.

2. Related Works

The integration of AI into astronomical research has revolutionized the way scientists observe, analyze, and interpret cosmic phenomena. However, the growing complexity of AI systems and the vastness of astronomical data require a paradigm shift: from traditional tool-based automation towards a SAI approach, where human and machine collaborate as partners in the scientific process. SAI emphasizes mutual augmentation—AI supports human cognition, while humans guide and refine AI learning with domain expertise. In astronomy, this collaboration is particularly crucial due to the interpretative nature of tasks such as anomaly detection, classification of celestial objects, and hypothesis generation from observational data. Rather than replacing astronomers, SAI systems assist them in exploring large-scale surveys by filtering relevant patterns, flagging anomalies, and suggesting possible astrophysical interpretations.

Traditional applications of machine learning in astronomy have focused on classification tasks, such as identifying galaxy morphologies, detecting exoplanet candidates, and transient event recognition [6, 7]. These efforts have demonstrated the effectiveness of supervised and unsupervised learning in extracting patterns from high-dimensional data, yet they often treat AI systems as static pipelines with limited interactivity. In contrast, the SAI paradigm introduces a more dynamic model of interaction between astronomers and intelligent systems. This vision is informed by work in Human-Centered AI [8], which advocates for AI systems that are transparent, explainable, and adaptive to user input. In the

astronomical context, tools such as Astronet [9], AstroMLab 1 [10], Cosmosage [11] have demonstrated the feasibility of interactive learning loops, where human feedback informs ongoing model refinement.

For example, Cosmosage [11] is a natural language assistant developed to support a wide range of users in understanding cosmology, from the inexperienced to the experienced. Based on advanced language models, Cosmosage was pre-trained on a large and specialized set of open access academic texts, including articles and textbooks, and then optimized to effectively answer cosmological questions. Instead, in [12] the authors evaluate the quality of learning in e-Learning platforms using Structural Equation Modeling (SEM) analysis, relying on a structured questionnaire consisting of 30 questions.

As outlined in the theory of feedback intervention proposed by Kluger and DeNisi (1996) [13], performance outcomes tend to improve when feedback is directed toward learning-related activities. In contrast, when attention is diverted to more peripheral elements, feedback can have a counterproductive effect. Consistent with the **Cognitive Load Theory**, technologies such as ChatGPT offer immediate, task-oriented feedback, facilitating the activation of complex cognitive processes such as analysis, evaluation, and creation, characteristic of higher-order thinking. These works suggest that SAI is not merely a technical upgrade, but a methodological evolution that aligns with the collaborative nature of scientific inquiry.

The integration of AI into software engineering raises critical issues, especially regarding explainability. To address this, the Human-Centered AI (HCAI) paradigm emphasizes user involvement, transparency, and system accountability. A specialized branch, **Symbiotic AI**, promotes ongoing human-AI collaboration while safeguarding human autonomy.

Some of the main requirements that guide the creation of SAI systems are: *Transparency* achieved through making models explainable and interpretable, allowing users to understand and oversee system decisions [14, 15]; *Fairness* which ensures accurate information and the prevention of discrimination or bias throughout the AI lifecycle [16]; *Level of Automation* requires balancing human control with algorithmic autonomy [17]; *Protection* that takes into account privacy and security [18, 19].

3. Application of Symbiotic AI Principles to Personalized Learning in Astronomy

Adopting the main requirements of SAI to the design of educational systems makes it possible to overcome the critical issues of traditional digital learning environments by fostering continuous, co-evolving interaction that respects user autonomy. The framework described in this paper is divided into five functional modules, each of which embodies specific SAI requirements defined in the previous section.

1. **User Modeling.** The first module, addressing user modeling, contributes directly to the principle of **fairness**, since the analysis of cognitive preferences, thematic interests, and behaviors allows for personalized content delivery, *reducing the risk of discrimination or educational misalignment*. At the same time, the collection of behavioral data must be handled according to **privacy** and **security** criteria, ensuring the protection of learner identity, complying with Article 5 of the GDPR. In particular, the triad CIA (Confidentiality, Integrity, Availability) must be respected.
2. **Symbiotic AI Engine (Co-Adaptive Engine).** The core of the system is the co-adaptive engine, in which the generative capabilities of LLMs, the adaptivity of Reinforcement Learning, and the operational transparency offered by Explainable AI converge. This module is designed in accordance with the principle of **transparency**, particularly the dimensions of **explainability** and **interpretability**, which enable the user to understand the motivations behind the system's decisions.
3. **Personalization of Astronomical Content.** Personalization of astronomical content takes the form of a synergistic application of the principles of **trustworthiness** and **robustness**. The dynamic generation of educational materials consistent with the user's profile, *concept maps, interactive simulations, and adaptive quizzes*, enables not only effective learning, but also resilience

to variations in skill levels or user behaviors. The **reliability** of the system is further enhanced by its ability to adapt under unplanned conditions, such as different cognitive loads or changes in interaction patterns.

4. **Symbiotic Human-AI Interface.** The design of the symbiotic human- AI interface reflects the principle of **automation** level, balancing the role of AI with maintaining human control. The natural, multimodal interaction promotes inclusiveness (invoking the principle of **fairness**) and enables active user participation while respecting the user’s decision-making autonomy. Interactive features, such as the ability to ask questions, receive explanations, or correct generated content, are a concrete application of the **human-on-the-loop paradigm**.
5. **Continuous and Co-Evolutionary Assessment.** Finally, the continuous and co-evolutionary evaluation module operates in line with the principles of **trustworthiness**, adopting tools for monitoring system effectiveness and learning progression. The inclusion of the user in the evaluation cycle, with the ability to correct or supplement AI responses, creates a mechanism for mutual trust and improvement, consistent with the vision of a cognitive symbiosis between human and machine.

Figure 1 shows the connections of these modules with the principles of symbiotic AI.

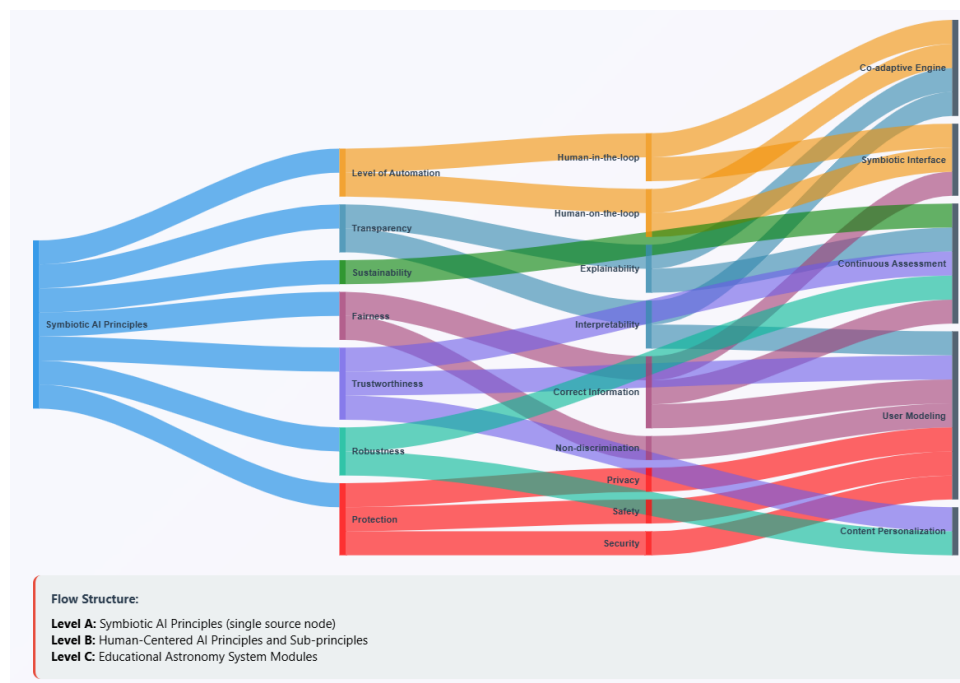


Figure 1: Mapping of Symbiotic AI Principles and Their Sub-Dimensions to System Modules for Personalized Astronomy Learning

3.1. Framework Architecture

The architecture of the framework is designed around a continuous and adaptive exchange of information between five main components. The **User Modeling** module retrieves learner data from the DBMS and updates it when the user profile evolves. This model is accessed by the **Co-Adaptive Engine**, which requests user knowledge to tailor its content generation strategies and may propose updates to the user model based on observed behavior. The engine’s output is passed to the **Content Personalization** module, which transforms it into structured learning content, such as quizzes or simulations. To ensure relevance, it also interacts with **User Modeling** to align content with the learner’s current profile. This personalized content is delivered through the **Symbiotic Human-AI Interface**, which not only presents the material but also allows the user to submit feedback or request new content. That

feedback is routed to the Continuous and Co-Evolutionary Assessment module, which evaluates performance and learning progression. Based on this, it triggers updates to the User model, closing the loop and enabling the system to evolve alongside the learner.

Each component contributes to a coherent flow of data and actions, supporting explainability, user autonomy, and personalization in line with SAI principles. The considered framework architecture for the delivery of educational content aligned with the principles of SAI is shown below.

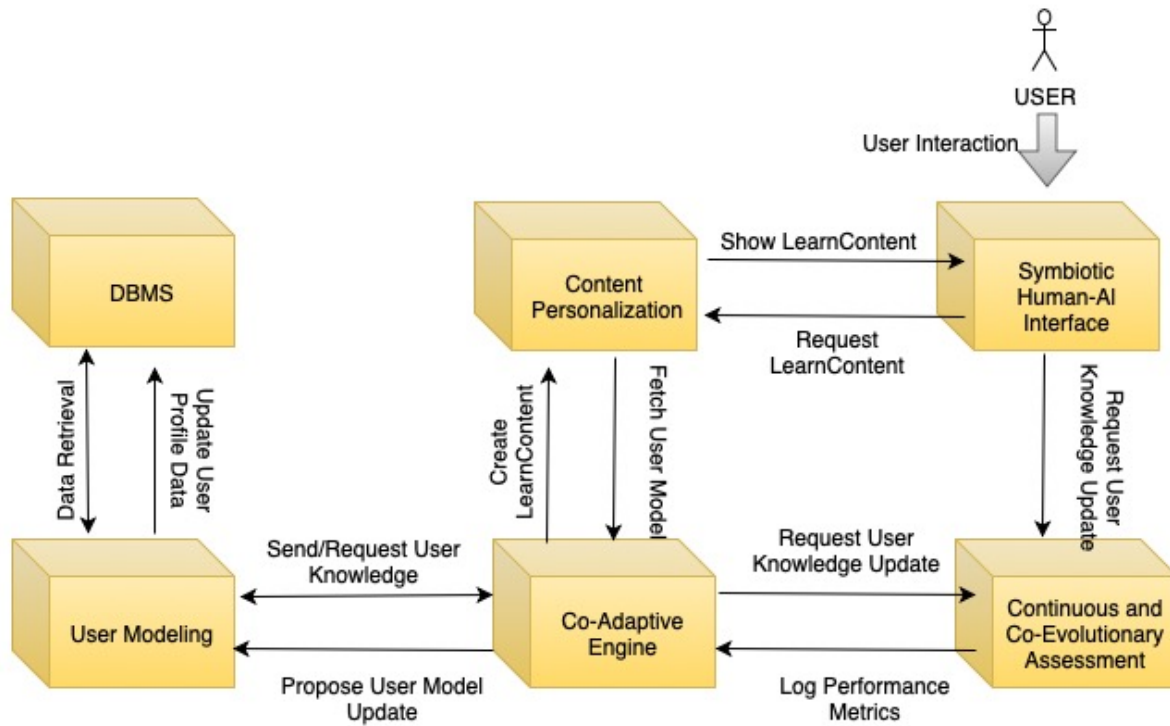


Figure 2: Component-Based Architecture of the Personalized Astronomy Learning System Aligned with Symbiotic Human-Centered AI Principles

4. VEGA - Visual Exploration and Graphical Analysis of Asteroids

The system design was informed by requirements collected from two user groups: non-experts (such as astronomy enthusiasts and beginners) and experts (including astrophysicists, researchers, astronomers, and academic professionals). VEGA was designed according to the principles of Symbiotic Human-Centered AI defined in the article [20], using MVC (Model-View-Controller) architecture and a white-box DBMS for managing educational content and LLMs. Data from the NASA API are not stored locally, ensuring lightweight and real-time updating. Figure 3 shows an example of asteroid search. Instead, Figure 4 and Figure 5 show, respectively, the details of the search results for a single asteroid based on NASA data, or a list of results that meet the search criteria.

In addition, VEGA allows a user to request educational content via natural language: the LLM generates both text and associated quizzes, showing the prompt used to increase the transparency of the system. A disclaimer is present to comply with the principle of Correct Information because of the possibility of hallucinations by an LLM. Content is generated in an inclusive format in order to avoid discrimination.

The scientific domain of reference (astronomy) significantly reduces the risk of implicit bias, and the absence of references to human subjects almost completely mitigates the risk of discrimination. Despite this, an explicit instruction aimed at respecting the principle of Non-Discrimination was included within the prompts at the design stage. The system implements a hierarchical versioning mechanism:



Figure 3: VEGA: Search for Asteroids

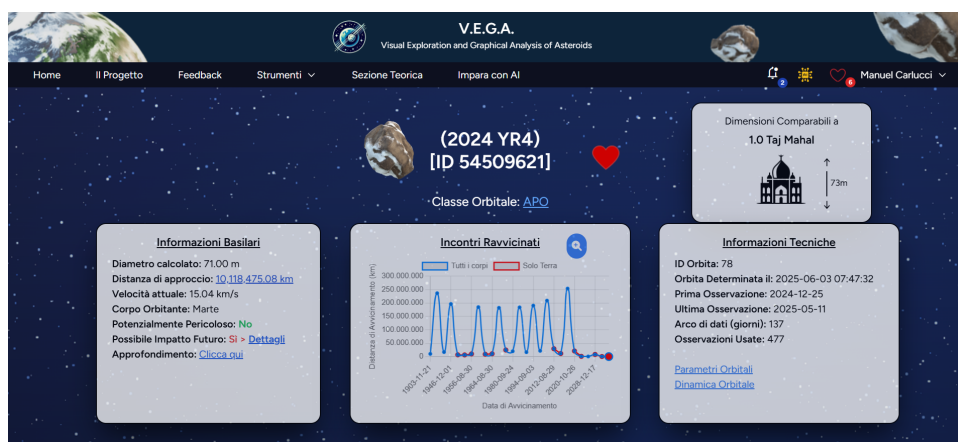


Figure 4: VEGA: Search for Asteroids - Single Result

Asteroid #	Diametro #	Data di Approccio #	Distanza (km) #	Velocità (km/s) #	Magnitudine #	Dettaglio
170903 (2004 WS2)	Non Disponibile	1900-Jan-01 00:38	13.855.307.38 km	16.74	18.20	Clicca qui
(2018 BM3)	Non Disponibile	1900-Jan-01 22:41	11.418.275.67 km	16.92	21.99	Clicca qui
(2001 XX4)	Non Disponibile	1900-Jan-02 14:36	20.207.213.43 km	13.16	22.10	Clicca qui
417217 (2005 YS)	Non Disponibile	1900-Jan-03 02:44	15.367.419.68 km	19.14	19.52	Clicca qui
(2022 YB4)	Non Disponibile	1900-Jan-04 08:37	63.265.178.58 km	4.00	21.80	Clicca qui

Figure 5: VEGA: Search for Asteroids - Multiple Result

each user feedback generates a new version of the content, possibly accompanied by a new quiz. This approach adopts a human-on-the-loop logic, suitable for the low-risk domain. Consequently, the process generates a tree structure among versions, as each subversion can in turn be further refined.

From a technical point of view, content is managed in tables such as LearnContent and rendered in easily readable Markdown HTML format addressing the principle of explainability. The system adopts the principles of privacy-by-design (no sensitive data collected and forwarded to LLM or profiling)

and security-by-design, thanks to the mechanisms of the Laravel framework. This choice is fully consistent with the data minimization principle established in Article 5 of the GDPR. A mechanism for exporting content in PDF format has also been implemented. Figure 6 shows an example of automatically generated theoretical content, accompanied by the versioning mechanism that allows the evolution of changes over time to be tracked.



Figure 6: View of the automatically generated theoretical content with versioning

The development involved the integration of several public APIs from NASA¹, mainly CAD, NeoWS, Fireball, and Sentry. Failover and fallback strategies were adopted to ensure the reliability of real-time data access and to ensure consistency between sources referring to past and future astronomical events.

5. Conclusion

Adaptive learning through SAI can bring its advantages in the field of astronomy. This research presents a framework structured on five main components, designed to integrate the principles of SAI. A first example of a concrete application of this framework is a specific feature of the VEGA system, which has been designed and developed. Although VEGA does not yet implement all of the framework's components in their entirety, further development toward fully integrating them is planned. However, it is important to note that even in its current version VEGA fully complies with all the basic principles of SAI outlined above. The development of a module for the delivery of educational content based on these principles is therefore an original contribution. In particular, the possibility for the end user to provide corrective or in-depth feedback reinforces the symbiotic dimension of the system, enabling a continuous versioning process of the generated content.

Currently, the testing phase of the system is still ongoing. Looking ahead, the symbiotic component of the system is planned to be strengthened by modeling end-user knowledge, making it dynamic based on interactions with the system itself. Another possible development concerns the expansion of how acquired skills are assessed: in addition to the multiple-choice quiz, automatic correction of open-ended answers through AI systems could be introduced. Lastly, it would be useful to implement a tool that allows the user to test knowledge related to multiple selected teaching modules, thus evaluating learning on distributed content in an integrated form.

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¹<https://api.nasa.gov/>

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Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

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