Geographic Information Systems for Space Science Education: A Review

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Abstract

The field of science education is changing, focusing greater importance on developing students' critical thinking and analytical skills beyond mere rote memorization. Among these essential skills, spatial thinking is gaining recognition as a fundamental component of scientific literacy. Geographic Information Systems (GIS) offer a powerful avenue to cultivate spatial acumen across science curricula, particularly in exploring celestial phenomena. This paper examines the integration of GIS in science education, with particular focus on extra-Earth explorations. Through a comprehensive analysis of GIS applications in astronomy and planetary science education, we illuminate the pedagogical opportunities, implementation challenges, and promising practices across educational settings. The integration of GIS into science curriculum supports interdisciplinary learning, fosters spatial thinking skills crucial for STEM careers, and provides authentic contexts for problem-based learning. This review provides example activities and lesson ideas for incorporating GIS-based instruction into science education.*

Keywords: Geographic Information Systems, Space Science Education, Astronomy Education, Planetary Science, Spatial Thinking

1 Introduction

The landscape of science education is continually evolving, with an increasing emphasis on equipping students with skills that extend beyond rote memorization to encompass critical thinking and analytical capabilities. Among these essential skills, spatial thinking is gaining recognition as a fundamental component of scientific literacy, moving beyond its traditional association with geography (Bednarz, 2019). This acknowledgment reflects a broader understanding that many scientific disciplines, including those focused on celestial phenomena, inherently involve spatial relationships and distributions.

The integration of Geographic Information Systems (GIS) into the science curriculum offers a powerful avenue to cultivate this spatial acumen. GIS, a sophisticated toolset for visualizing, analyzing, and interpreting spatial data, transcends the boundaries of terrestrial studies, offering profound utility in the exploration of the cosmos (DiBiase, 2008). The burgeoning availability of spatial data pertaining to planets, moons, and other celestial bodies, gathered through numerous space missions and observatories, presents an unprecedented opportunity for educators to bring the wonders of extra-Earth exploration into the classroom in a dynamic and engaging manner (Kingsley, Oliver, & Van Kranendonk, 2017).

In the Canadian educational context, these opportunities align with broader curricular goals emphasizing scientific literacy and technological competence (Moorman & Garbutt, 2018). Canadian science education frameworks increasingly recognize that by leveraging GIS, science lessons about the sky and planets can be transformed from passive reception of information to active, inquiry-driven investigations that mirror the methodologies employed by contemporary planetary scientists and astronomers.

Similarly, the Ukrainian educational landscape presents unique opportunities and challenges for GIS integration in science education. Ukraine's educational system is undergoing significant transformation driven by European integration goals, educational reforms, and the need to modernize geography and science education to meet contemporary demands (Dronova, Maruniak, Rudenko, & Topchiyev, 2023;

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Malchykova & Mezentsev, 2022). Ukrainian universities have been incorporating GIS into geography and environmental science programs, with institutions like Kryvyi Rih State Pedagogical University emphasizing both theoretical and practical applications through platforms like ArcGIS Online (Kholoshyn, Bondarenko, Hanchuk, & Shmeltser, 2019; Molikevych, Bohadorova, Kovalova, & Okhremenko, 2019). The interdisciplinary approach to GIS education extends beyond geography to fields such as environmental sciences, computer sciences, and engineering, reflecting a broader recognition of spatial technologies' importance in modern education (Iatsyshyn et al., 2020). Despite challenges including limited resources, lack of Ukrainian-language content in GIS platforms, and the ongoing impact of geopolitical tensions, Ukrainian educators have demonstrated innovation in adapting GIS technologies for both in-person and distance learning contexts (Kholoshyn et al., 2019; Stepanyuk et al., 2024).

This review paper examines the integration of Geographic Information Systems in science education with a specific focus on extra-Earth explorations. Through a comprehensive analysis of current literature and educational practices, we address fundamental questions about the nature of spatial thinking in science, the core concepts and applications of GIS in astronomy and planetary science education, and the unique challenges and opportunities presented by diverse educational landscapes. The paper is organized as follows: Section 2 explores the theoretical foundations of spatial thinking in science education, examining both its fundamental nature and its connection to applied physics principles, while also considering how spatial skills develop through formal education and everyday experiences like driving and navigation. Section 3 provides an overview of GIS core concepts and applications, including fundamental data types and analysis methods, specific applications in astronomy and planetary science education, and the evolution of educational GIS tools. Section 4 analyzes GIS integration in Canadian and Ukrainian science education contexts, examining educational policies, current implementation practices, and the unique challenges and opportunities in each setting. Section 5 presents practical frameworks for integrating GIS into the teaching of extra-Earth explorations, including pedagogical approaches, example activities and lesson ideas, and extended student research projects. Section 6 outlines essential resources and implementation strategies, covering GIS tools and data sources, teacher professional development approaches, and context-specific implementation strategies for different educational settings. Section 7 evaluates the educational benefits and impact of GIS integration, including enhanced student engagement, development of STEM career skills, and support for educational equity. Finally, Section 8 addresses implementation barriers and future directions, proposing research priorities and pathways for advancing GIS integration in space science education. This comprehensive structure provides educators, researchers, and policymakers with both theoretical understanding and practical guidance for implementing GIS-enhanced space science education.

2 Spatial Thinking in Science Education

2.1 The Nature of Spatial Thinking

Spatial thinking encompasses a set of cognitive skills that enable individuals to mentally manipulate, organize, and reason about the physical arrangement of objects, their locations, and directional relationships in both concrete and abstract spaces (Uttal, Miller, & Newcombe, 2013). These skills include visualizing three-dimensional structures from different perspectives, understanding spatial relationships, and making inferences about space through patterns and representations.

Spatial thinking intersects fundamentally with applied physics – the branch of physics that focuses on practical applications of physical principles to solve real-world problems. Applied physics serves as a bridge between theoretical concepts and practical applications, leveraging extensive modeling and forecasting capabilities to analyze physical processes (Marascu, Mihailescu, & Barna, 2023). This intersection is particularly relevant in astronomy and planetary science education, where students must understand physical phenomena such as gravitational fields, orbital mechanics, electromagnetic radiation, and planetary dynamics while simultaneously visualizing their spatial manifestations.

McNeal and Petcovic (2020) emphasize that spatial thinking is not a singular ability but rather a collection of skills that can be developed through education and experience. These skills include mental rotation, spatial perception, spatial visualization, and spatial orientation. In astronomy education, these spatial skills must be integrated with an understanding of applied physics concepts – for example, visualizing how gravitational forces shape planetary orbits requires both spatial reasoning and comprehension of Newtonian mechanics.

The cultivation of these integrated abilities has significant implications for success in science, technology, engineering, and mathematics (STEM) fields (Gagnier, Holochwost, & Fisher, 2022). Applied physics principles are essential for interpreting astronomical phenomena, from understanding how light from distant stars reaches Earth to comprehending the physical processes that shape planetary surfaces (Durante, Prezado, & Patera, 2019).

In the context of science education, spatial thinking facilitates students' understanding of complex scientific concepts and phenomena that occur across multiple scales, from the subatomic to the cosmic (Uttal, McKee, Simms, Hegarty, & Newcombe, 2024). When examining celestial bodies and astronomical phenomena, students must navigate vastly different scales and dimensions while applying physical principles, making both spatial reasoning and applied physics understanding particularly crucial (Gilbert et al., 2013).

2.2 The Role of Spatial Thinking in STEM Learning

Research consistently demonstrates that spatial thinking abilities correlate strongly with achievement and persistence in STEM disciplines (Uttal et al., 2013; Zhu et al., 2023). A meta-analysis by Uttal et al. (2013) revealed that spatial skills are malleable and can be improved through targeted training, with transfer effects to STEM learning outcomes.

Spatial thinking and reasoning skills are also developed through everyday life experiences that are often overlooked in formal educational contexts. For instance, when individuals "gain access to the car keys", they engage in complex spatial reasoning that requires and develops spatial awareness for decision making (Tinella, Lopez, Caffò, Grattagliano, & Bosco, 2020). This phenomenon, sometimes referred to as "spatial independence", encompasses various spatial competencies including spatial orientation (understanding and navigating the environment), spatial memory (remembering locations and routes), and mental rotation (mentally manipulating spatial information for navigation) (Nori, Palmiero, Bocchi, Giannini, & Piccardi, 2020; Sandamas & Foreman, 2015).

Research on driving and spatial cognition reveals that active navigation – whether driving a vehicle or actively exploring an environment – develops stronger spatial skills compared to passive observation (Sandamas & Foreman, 2015). Nori et al. (2020) found that drivers who prefer survey strategies (forming mental maps from a bird's-eye view) demonstrate better spatial decision-making abilities and are less likely to commit driving errors. This real-world application of spatial thinking illustrates how spatial skills developed in one context can transfer to other domains, including STEM learning.

Within the Canadian educational context, Huynh and Sharpe (2009) conducted research with 104 geography students in Waterloo, Ontario, finding that spatial reasoning skills develop progressively through educational levels. Their study demonstrated that Grade 9 students averaged significantly lower spatial reasoning scores compared to university students, highlighting the developmental trajectory of these skills through both formal education and life experiences.

The implications for science education are profound, particularly in astronomy and planetary science, where concepts inherently involve complex spatial relationships (Li, 2023). Just as drivers must integrate spatial information with real-time decision-making, students studying celestial mechanics must visualize and reason about three-dimensional orbital paths, planetary rotations, and the relative positions of celestial bodies. As Mulligan, Woolcott, Mitchelmore, and Davis (2018) argue, developing spatial reasoning provides new pathways for mathematics learning, and by extension, for science learning that involves mathematical concepts and representations.

These spatial skills, whether developed through formal education, everyday activities like driving, or targeted interventions, form a foundation for success in STEM fields. The concept of spatial independence – the ability to autonomously navigate and make spatial decisions – parallels the kind of independent spatial reasoning required in advanced scientific thinking (Green, 2018). This suggests that educators should recognize and build upon the spatial experiences students bring from their daily lives, including navigation and wayfinding activities, to enhance their understanding of abstract scientific concepts.

Figure 1 illustrates the multidimensional nature of spatial thinking and its integration with scientific concepts. This framework emphasizes that spatial thinking in science education involves not only basic spatial skills but also their application to complex scientific phenomena, particularly in fields like astronomy and planetary science.

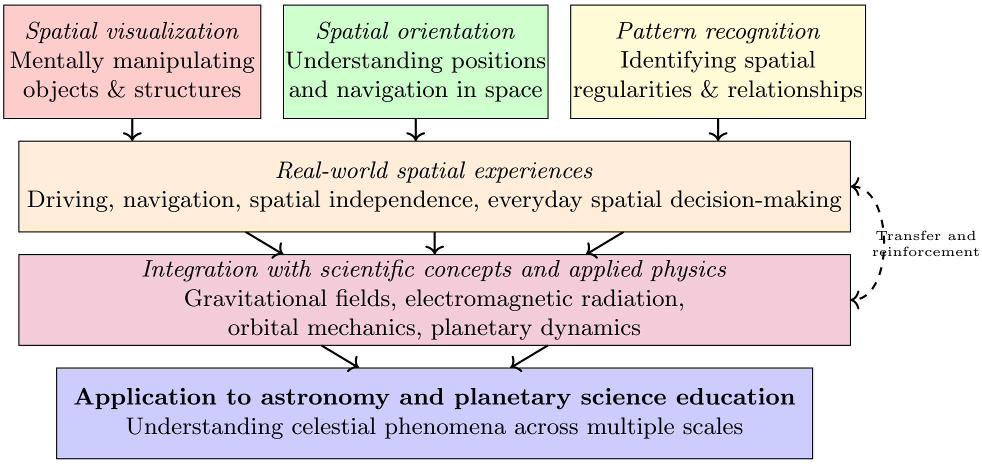

Fig. 1 Conceptual framework for spatial thinking dimensions in science education.

3 Geographic Information Systems: Core Concepts and Applications

3.1 Fundamentals of GIS for Science Education

Geographic Information Systems represent a powerful set of tools for managing, analyzing, and visualizing spatial data. At its core, GIS deals with two primary types of spatial data: raster (grid-based data like satellite imagery) and vector (point, line, and polygon features representing discrete objects) (Mísařová, Svobodová, Mašterová, & Novotná, 2024). In science education contexts, understanding these data types and their applications provides students with a foundation for spatial analysis across various scientific domains.

A crucial aspect of working with spatial data, especially in the context of planetary science, is the understanding of coordinate systems. While Earth utilizes latitude and longitude, planetary bodies have their own unique coordinate systems defined by their rotational axes and prime meridians (Dahal, Hall, Morrison, Lamble, & Luna, 2011). Consequently, mapping these celestial bodies requires specialized map projections that accurately represent their spherical surfaces on a two-dimensional plane.

The organization of spatial data in GIS often involves layers, where different datasets representing various attributes of a celestial body (e.g., topography, mineral composition, geological units) are stacked upon each other. This layering allows for the analysis of spatial relationships and correlations between different features (Patiño & Pérez, 2024). Furthermore, GIS provides a suite of spatial analysis tools that enable quantitative examination of these features, including measuring distances, areas, and other spatial properties of planets and moons.

Canadian educators have recognized the value of these fundamental GIS concepts in enhancing science education. As Huynh and Sharpe (2009) note in their Waterloo-based study, "The ability to reason about spatial relations, including the identification of spatial patterns and spatial associations, is important to geographic problem solving using a GIS".

3.2 GIS Applications in Astronomy and Planetary Science Education

The practical applications of GIS are deeply embedded in contemporary planetary science and astronomy. Notably, space agencies like NASA extensively utilize GIS for mission planning, data analysis, and the creation of compelling visualizations that enhance scientific understanding and public engagement (Balram, Dragicevic, & Meredith, 2003).

The educational applications of GIS in astronomy and planetary science are diverse and engaging. Table 1 outlines key application areas with specific examples and their educational relevance.

Table 1 GIS applications in astronomy and planetary science education

Application area	Specific examples	Educational relevance
Mission planning	Mars rover path planning; identifying safe landing zones	Develops critical thinking and problem-solving skills; Integrates engineering design principles
Topographic analysis	Mapping lunar crater depths; creating digital elevation models of Mars	Enhances understanding of geological processes; Develops quantitative analysis skills
Landing site selection	Analyzing terrain slope for potential Mars landing sites	Connects multiple variables (safety, scientific interest, resource availability); Fosters systems thinking
Resource identification	Mapping potential lunar ice deposits	Addresses real-world challenges of space exploration; Integrates chemistry, physics, and geology
Eclipse prediction	Predicting the path of totality for a solar eclipse	Connects astronomy with Earth-based geography; Demonstrates practical applications of orbital mechanics
Planetary geology	Mapping geological units on the Moon and Mars	Builds comparative analysis skills; Enhances understanding of geological processes beyond Earth
Mineral composition analysis	Identifying regions with specific minerals on planetary surfaces	Integrates spectroscopy concepts; Connects to astrobiology and search for life

These applications align with educational initiatives that emphasize interdisciplinary approaches to science education. The incorporation of GIS analysis into astronomy education provides authentic contexts for students to engage with STEM concepts while developing valuable technological skills (Moorman & Garbutt, 2018).

3.3 Evolution of GIS Tools for Educational Use

The landscape of GIS software suitable for educational use has evolved significantly over the past decade, transforming from specialized desktop applications to accessible web-based platforms. Steiniger and Hunter (2013) provided a comprehensive overview of free and open-source GIS software available in 2012, identifying eight mature desktop GIS projects and numerous specialized tools. While their review is now over a decade old and may not reflect recent innovations such as cloud-based GIS and mobile applications, it provides important historical context for understanding the evolution of educational GIS tools.

According to Steiniger and Hunter (2013), the major desktop GIS projects at that time included GRASS GIS, QGIS, OpenJUMP, gvSIG, SAGA, MapWindow GIS, ILWIS, and uDig. These systems varied in their functionality, with some focusing on raster analysis (GRASS, SAGA), others on user-friendly interfaces (QGIS, MapWindow), and some on specific domains like remote sensing (ILWIS). The authors noted that the transition from "early adopters" to "early majority" stage was already underway, with certain FOSS4G software products competing effectively with proprietary solutions.

Since 2013, the GIS landscape for education has transformed dramatically with the emergence of web-based platforms that lower technical barriers. ArcGIS Online, a cloud-based GIS platform, now offers a user-friendly interface with access to numerous planetary datasets and analysis tools, making it ideal for introducing GIS concepts in educational settings (Oda, Herman, & Hasan, 2020). Its accessibility eliminates the need for software installation and provides consistent functionality across different devices and operating systems.

QGIS has emerged as the leading open-source desktop GIS for education, having evolved significantly from its status in the Steiniger review. It now provides robust analytical capabilities, supports a wide variety of data formats including those used in planetary science, and offers extensive documentation and educational resources (Ciolli et al., 2017; Lacaze, Dudek, & Picard, 2018). The development of educational plugins and simplified interfaces has made QGIS particularly suitable for secondary and post-secondary education.

For specialized planetary science applications, NASA's JMARS (Java Mission-planning and Analysis for Remote Sensing) provides access to an extensive archive of planetary imagery and tools specifically designed for planetary research (Stieff, 2011). While not mentioned in earlier reviews, JMARS represents the growing category of domain-specific GIS tools that bridge research and education.

Recent innovations not captured in the 2012 review include the integration of GIS with virtual and augmented reality technologies, mobile GIS applications that enable field data collection, and the incorporation of machine learning capabilities into educational GIS platforms. Ricketts, Salsbury, Bevan, and Brown (2018) discuss the use of immersive visualization environments to engage students in hands-on learning about biomolecular structures, an approach that has parallels in planetary science visualization. Similarly, Spencer, Christie, Pakakis, and Rankin (2012) describe the development of serious games for astronomy education at the Victorian Space Science

Education Centre, demonstrating how gamification can enhance student engagement with complex space science concepts.

The shift toward Software as a Service models and cloud computing has fundamentally changed how educational institutions access and deploy GIS tools. This evolution addresses many of the challenges identified by Steiniger and Hunter (2013), including installation complexity, cross-platform compatibility, and the need for powerful local hardware. Contemporary educational GIS tools emphasize collaboration, real-time data sharing, and integration with learning management systems – features that were nascent or absent in 2012.

The evolution of these tools reflects a broader trend toward making sophisticated spatial analysis more accessible to students across different educational levels, a development that has particular relevance for Canadian educators working in diverse and often geographically dispersed contexts.

4 GIS Integration in Canadian and Ukrainian Science Education

4.1 GIS Integration in Canadian Science Education

The Canadian educational landscape, characterized by provincial jurisdiction over education, presents a diverse array of approaches to science education and the integration of spatial technologies. While there is no single national curriculum, several provincial frameworks have begun to recognize the importance of spatial thinking and GIS in science education.

Moorman and Garbutt (2018) note that across Canadian provinces, global understanding is a common theme in geography curricula, particularly in early grades. This emphasis on global and spatial awareness creates a foundation for the integration of GIS tools in science education. However, they also observe that "the most recent mandatory curricula emphasize numeracy, literacy, and historical perspectives, increasingly at the expense of current global and geographical views and topics, despite mutual relevancy".

Despite these challenges, several Canadian initiatives support the integration of spatial thinking and GIS across the curriculum. For example, the Canadian Space Agency's educational outreach programs emphasize the use of spatial data and technologies in understanding Earth and space science concepts (Balram et al., 2003). Similarly, provincial science curricula increasingly reference spatial analysis and technology integration as core competencies for 21st-century learning.

The implementation of GIS in Canadian science classrooms reflects varying levels of sophistication across educational stages. Huynh and Sharpe (2009) conducted a comprehensive study with 104 geography students from four distinct educational levels in Waterloo, Ontario: Grade 9 students (ages 13-14), first-year university undergraduates, third and fourth-year geography majors, and graduate students (ages 22-32). Their research revealed a clear developmental progression in spatial reasoning abilities, with Grade 9 students averaging 7.5 out of 30 on a spatial reasoning scale, while graduate students averaged 20.6.

More importantly, the study demonstrated that these different educational cohorts employed fundamentally different GIS problem-solving strategies. Students with lower spatial reasoning scores predominantly used basic visualization tools (zoom and measure functions) or simple buffer operations, while those with higher scores applied sophisticated combinations of buffers, intersections, and spatial queries. This finding suggests that GIS implementation must be tailored to students' developmental stages, with simpler visualization-based activities for younger students gradually progressing to more complex analytical tasks as spatial reasoning abilities mature. The research underscores the importance of scaffolding GIS instruction across educational levels rather than applying a one-size-fits-all approach.

In a comprehensive study of spatial thinking in education, Bednarz (2019) proposed that geography education can close gender-based achievement gaps through explicit instruction in spatial thinking. This finding has significant implications for science education in Canada, where achieving gender equity in STEM fields remains a priority.

The practical implementation of GIS in Canadian classrooms often involves collaborative projects that connect students with real-world applications. For example, initiatives like the "Mapping Mars" project described by Gilbert et al. (2013) engage students in analyzing Martian surface features using Google Earth, demonstrating how accessible technologies can support sophisticated spatial analysis in educational settings.

Canada's vast geography and diverse population present both challenges and opportunities for implementing GIS in science education. The significant distances between communities, particularly in northern regions, make digital tools for spatial analysis particularly valuable for connecting students to scientific data and concepts that might otherwise be inaccessible.

As illustrated in Figure 2, the challenges facing Canadian educators include geographic dispersion, variable digital infrastructure, limited teacher training in GIS, and provincial curriculum variations. However, these challenges are balanced by opportunities such as Canada's strong geomatics industry, institutional expertise in spatial technologies, a growing educational technology sector, and the potential for cross-curricular applications.

N. Trautmann and MaKinster (2014) emphasize the importance of professional development in supporting teachers' integration of geospatial technologies. In the Canadian context, initiatives like the GIS Ahead project have demonstrated the effectiveness of flexibly adaptive models of professional development that respond to teachers' specific contexts and needs.

The increasing availability of web-based GIS tools presents particular opportunities for Canadian educators. As Jo, Hong, and Verma (2016) demonstrated, web-based GIS activities can significantly enhance students' spatial thinking skills, making these technologies particularly valuable in contexts where specialized software may be difficult to install or maintain.

4.2 GIS Integration in Ukrainian Science Education

The integration of GIS in Ukrainian science education reflects a complex interplay of educational reform, technological advancement, and geopolitical factors. Ukraine's

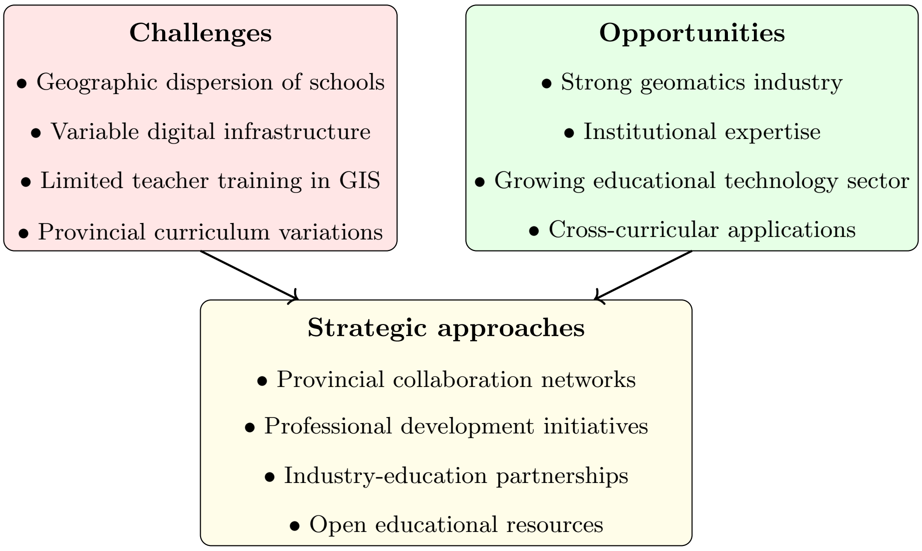

Fig. 2 Challenges, opportunities, and strategic approaches for GIS integration in Canadian science education.

education system has been actively modernizing its approach to spatial technologies as part of broader European integration efforts and national educational reforms (Zharinova, Zharinov, & Rybalko, 2024).

Ukrainian universities have made significant progress in incorporating GIS into their curricula. Institutions such as Kherson State University have developed comprehensive educational and professional training programs for geographers that integrate GIS across multiple specialties: Earth Sciences, Geography, and Secondary Education (Molikevych et al., 2019). These programs emphasize both classroom instruction and fieldwork components, with considerable importance given to online platforms like ArcGIS Online for distance learning and practical laboratory work (Kholoshyn et al., 2019).

The interdisciplinary nature of GIS education in Ukraine extends beyond traditional geography departments. As Iatsyshyn et al. (2020) note, GIS competencies are being developed across specialties including Environmental Sciences, Earth Sciences, Computer Sciences, and Environmental Technologies. This broad integration reflects an understanding that spatial analysis skills are increasingly essential across multiple scientific disciplines.

International collaborations have played a crucial role in advancing GIS education in Ukraine. Since 2011, partnerships between Ukrainian universities and institutions such as the Institute of Applied Photogrammetry and Geoinformatics in Germany have enriched GIS education by introducing advanced technologies like terrestrial laser scanning and 3D data acquisition (Kravchenko, Luhmann, & Shults, 2016; Luhmann, 2021). These collaborations have facilitated technology transfer, curriculum reform, and the development of e-learning approaches that have proven particularly valuable given recent challenges.

At the secondary level, GIS integration aims to enhance geographical literacy, spatial thinking, and students' ability to analyze human-environment interactions (Malchykova & Mezentsev, 2022). The approach emphasizes "teaching with GIS" rather than merely "teaching about GIS", involving the use of GIS tools to solve real-world problems and making learning more relevant and practical (Jakab, Ševčík, & Grežo, 2017).

However, the implementation faces significant challenges. The reduction of compulsory geography education and its inclusion in integrated courses has led to decreased public demand for geographical expertise (Malchykova & Mezentsev, 2022). Additionally, there is limited emphasis on the methodological component of geoinformatics in educational programs, presenting barriers to effective GIS integration (Krylova, Pachev, Poliakova, Schkoda, & Zhiryakov, 2020).

As illustrated in Figure 3, Ukrainian educators face several distinct challenges in implementing GIS, including resource constraints such as limited access to proprietary software and the need for both open-source (QGIS, uDIG) and commercial (ArcGIS) solutions (Iatsyshyn et al., 2020), language barriers due to the lack of Ukrainian-language content in major GIS platforms (Kholoshyn et al., 2019), infrastructure limitations characterized by variable internet connectivity and computing resources across different regions, and geopolitical impacts as the ongoing conflict has disrupted educational infrastructure and necessitated rapid adaptation to distance learning modalities (Stepanyuk et al., 2024).

Despite these challenges, Ukrainian educators have demonstrated remarkable innovation. The development of cloud-based GIS approaches has enabled continued education even in challenging circumstances, with platforms like ArcGIS Online providing round-the-clock access and the ability to work with GIS packages in the cloud (Kholoshyn et al., 2019). The emphasis on developing "geoinformation competence" rather than merely technical skills reflects a sophisticated understanding of the role of spatial technologies in modern education (Molikevych et al., 2019).

The future of GIS integration in Ukrainian science education is closely tied to broader educational reforms and European integration efforts. The development of the National Electronic Scientific Information System (URIS) aims to enhance the visibility of Ukrainian research and support the country's integration into the European Research Area (Zharinova et al., 2024). This infrastructure development, combined with continued international collaboration and the resilience demonstrated by Ukrainian educators, suggests potential for significant advancement in GIS-enhanced science education despite current challenges.

5 Integrating GIS in the Teaching of Extra-Earth Explorations

5.1 Pedagogical Approaches and Frameworks

The integration of GIS into science education focused on extra-Earth explorations requires thoughtful consideration of pedagogical approaches that leverage the unique

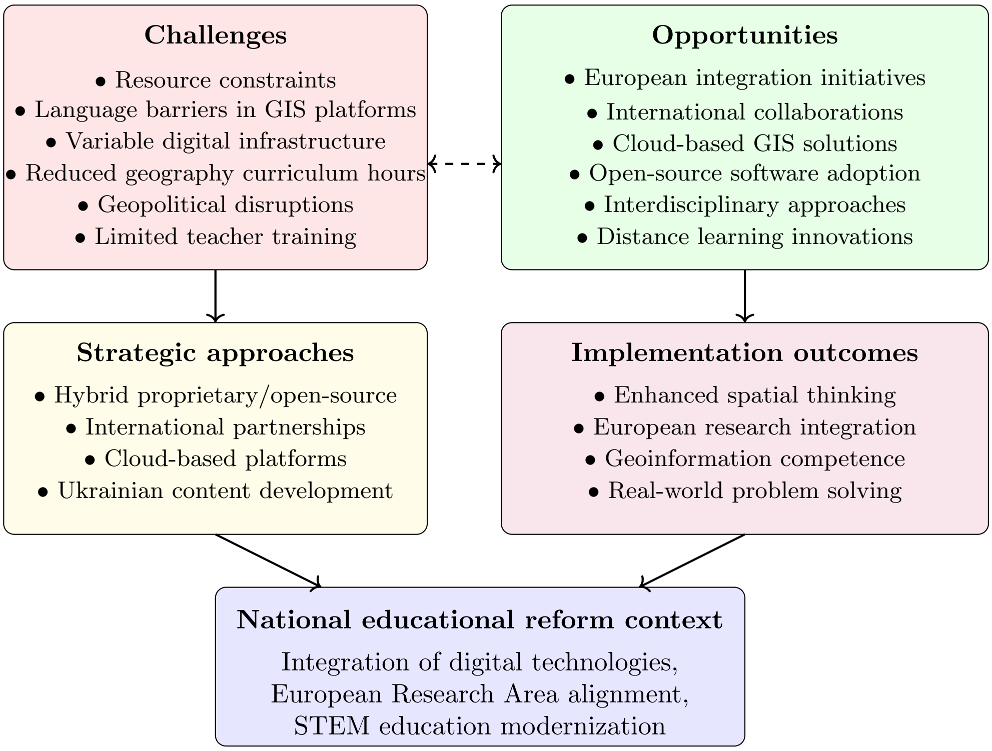

Fig. 3 Challenges, opportunities, and strategic approaches for GIS integration in Ukrainian science education.

capabilities of spatial technologies while addressing curricular objectives. Several frameworks offer guidance for this integration.

The Technological Pedagogical Content Knowledge (TPACK) framework, as applied by Oda et al. (2020), provides a useful lens for understanding how teachers can effectively integrate GIS into their instruction. This framework emphasizes the importance of connecting technological knowledge (how to use GIS tools), pedagogical knowledge (effective teaching strategies), and content knowledge (astronomy and planetary science concepts).

Inquiry-based approaches have shown particular promise for integrating GIS into science education. Rodríguez-Triana, Prieto, and Pishtari (2021) analyzed the content of digitally-authored inquiry designs, finding that well-structured inquiry activities scaffold learning while promoting engagement and collaboration. For astronomy and planetary science education, inquiry-based approaches using GIS allow students to explore authentic questions about celestial bodies and phenomena.

Problem-based learning (PBL) represents another effective approach for integrating GIS into extra-Earth explorations. As Dias (2004) argues, one of the most effective ways of learning technical skills is through problem-solving exercises. In the context of astronomy education, this might involve tasking students with identifying suitable landing sites for a hypothetical Mars mission or analyzing the distribution of specific geological features on the lunar surface.

5.2 Essential GIS Tools and Resources for Educators

To effectively integrate GIS into science lessons about extra-Earth exploration, educators can use a range of essential resources and tools. Several software platforms stand out for their suitability in educational settings.

ArcGIS Online, a web-based GIS platform, offers a user-friendly interface and provides access to numerous planetary datasets and analysis tools, making it an ideal starting point for introducing GIS concepts (Oda et al., 2020). Its accessibility and ease of use lower the barrier to entry for both teachers and students. The Esri Canada GIS Education Program provides Canadian schools with access to ArcGIS Online and educational resources, making this platform relevant in the Canadian context (Balram et al., 2003).

QGIS, a free and open-source desktop GIS software, presents a more robust analytical environment and supports a wide variety of data formats, including those commonly used in planetary science, offering a cost-effective option for schools (Golob, 2017). This platform is valuable in Ukrainian contexts where educational budgets may be limited or where open-source solutions are preferred.

For those seeking specialized capabilities, JMARS (Java Mission-planning and Analysis for Remote Sensing), developed by NASA, provides access to an extensive archive of planetary imagery and data, along with tools specifically designed for planetary science research (Stieff, 2011).

Access to reliable data sources is paramount. The USGS Astrogeology Science Center serves as a premier provider of GIS-ready spatial information about planets, moons, and other objects in our solar system, offering maps, imagery, and valuable tutorials. NASA Earthdata provides a vast repository of Earth science data, which can be invaluable for comparative planetology studies, allowing students to draw parallels between Earth and other celestial bodies.

5.3 Example Activities and Lesson Ideas

Building on these pedagogical frameworks, Table 2 presents several engaging lesson ideas and activities that integrate GIS into the teaching of extra-Earth explorations. These activities are designed to be adaptable across different grade levels and technological contexts, making them suitable for the diverse educational landscape.

These activities align with the pedagogical approaches discussed earlier, emphasizing inquiry, problem-solving, and authentic applications of spatial analysis. They also connect to various aspects of provincial science curricula across Canada, making them adaptable to different educational contexts.

5.4 Student Research Projects and Extended Investigations

Beyond structured lessons, GIS provides a fertile ground for inspiring engaging student research projects in space science. These extended investigations allow students

Table 2 GIS-based activities for extra-Earth explorations

Activity title	Description	Learning objectives	Data sources	GIS tools
Mapping lunar craters	Students map, measure, and analyze the distribution and size of craters on the Moon using lunar imagery and data.	Apply spatial analysis techniques; understand the Moon's impact history	NASA LRO data; USGS Astrogeology data	ArcGIS Online; QGIS
Exploring martian topography	Students create topographic maps of Mars, identify key geological features, and analyze their scale	Develop sense of scale; understand geological processes shaping Mars and Mars Reconnaissance Orbiter data; USGS data	ArcGIS Online; QGIS	
Tracking a meteor shower	Students map the radiant point and distribution of observed meteors, investigating connections to cometary debris trails	Connect celestial mechanics with spatial data analysis	American Meteor Society data	ArcGIS Online; QGIS
Visualizing exoplanet discoveries	Students map locations and characteristics of discovered exoplanets relative to our solar system	Introduce exoplanet research; explore diversity of planetary systems	NASA Exoplanet Archive	ArcGIS Online; QGIS
Modeling solar eclipse visibility	Students map the path of totality and partial eclipse zones, determining visibility from different locations	Understand eclipse geometry; develop spatial reasoning skills	NASA eclipse data; Esri GIS data	ArcGIS Online; QGIS

to develop deeper understanding of both scientific concepts and spatial analysis techniques.

Table 3 outlines several potential student research projects that leverage GIS for exploring extra-Earth phenomena. These projects encourage independent inquiry while developing valuable research and analytical skills.

These research projects offer opportunities for students to engage with authentic scientific questions using spatial analysis tools. They connect to broader curricular goals related to scientific inquiry, technological literacy, and environmental awareness.

6 Implementation Strategies

6.1 Teacher Professional Development Approaches

Effective integration of GIS into astronomy and planetary science education requires comprehensive teacher professional development. N.M. Trautmann and MaKinster (2010) describe a flexibly adaptive model of professional development that enables

Table 3 GIS-based student research projects in extra-Earth explorations

Project title	Description	Project elements	Educational value
Lunar ice mining potential	Identify potential locations for lunar ice mining by layering and analyzing data on topography, hydrogen abundance, and slope	Define criteria for suitable mining locations; analyze data layers in GIS; Present findings on a map	Engages with current topics in space exploration; applies GIS for real-world problem-solving
Analyzing martian gullies	Investigate the formation of gullies on Mars by mapping their distribution, orientation, and relationship to other surface features	Formulate hypotheses about gully origin; analyze spatial patterns using GIS; support arguments with evidence	Develops critical thinking about geological processes; uses spatial data for scientific reasoning
Mapping impact craters	Compare and contrast impact crater characteristics on different planetary bodies	Research impactor populations and surface conditions; analyze crater data in GIS; explain differences in crater characteristics	Fosters comparative planetology; enhances understanding of impact events in shaping planetary surfaces
Light pollution and observatories	Analyze the impact of light pollution on astronomical observations	Create maps showing light pollution gradients and observatory locations; discuss implications for research	Connects environmental issues with astronomy; highlights spatial planning for science
Changes in planetary ice caps	Study changes in polar ice caps on Mars or other icy bodies over time	Digitize ice cap boundaries from different time periods; calculate area changes; correlate with climate patterns	Introduces planetary climate change; applies remote sensing for monitoring environmental changes

secondary science teachers to incorporate geospatial applications into their classrooms. This model emphasizes intensive summer training, ongoing technological and curricular support, and the promotion of a supportive learning community.

Both in the Canadian and Ukrainian contexts, professional development initiatives must address the unique challenges of geographic dispersion and variable technological infrastructure. Online professional learning communities, webinars, and asynchronous training modules can help overcome these challenges, providing teachers with access to expertise and resources regardless of their location.

Oda et al. (2020) emphasize the importance of the TPACK framework in designing professional development for teachers using GIS. Their research with middle and high school teachers found that professional development designed through this framework helped teachers acquire relevant skills and knowledge for integrating GIS with instruction.

6.2 Implementation Strategies for Different Educational Contexts

The implementation of GIS in science education must be tailored to different educational contexts, particularly given the diversity of schools across urban, suburban, rural, and remote settings. Figure 4 presents a framework for adapting GIS implementation strategies across these contexts.

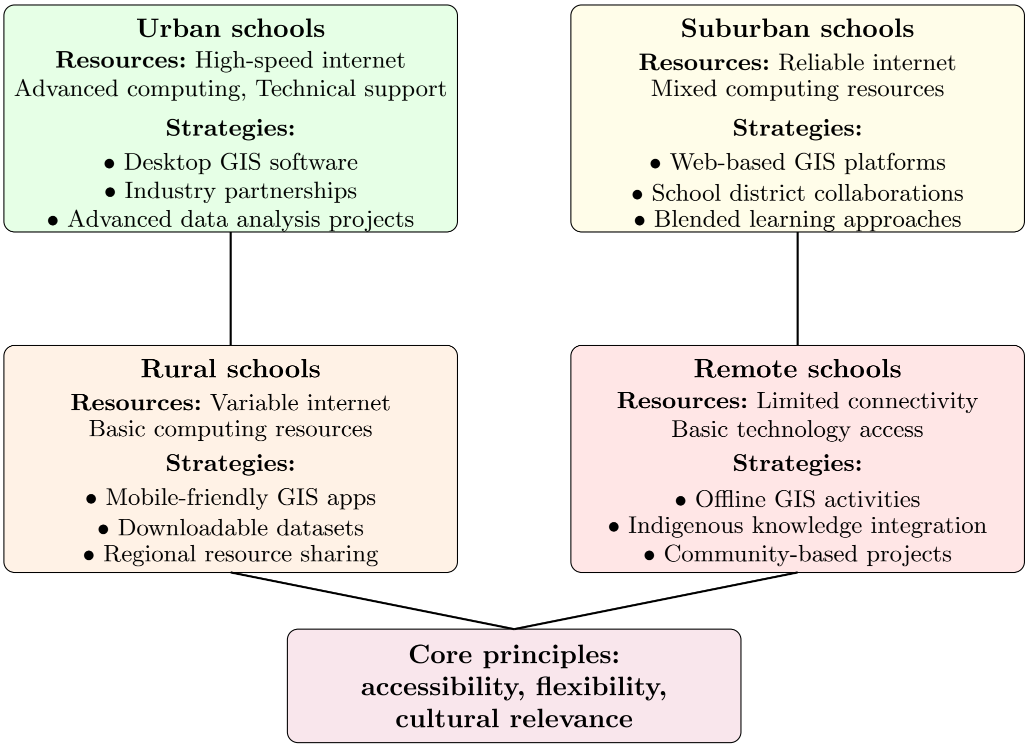

Fig. 4 Strategies for implementing GIS in astronomy education across different educational contexts.

This framework recognizes that implementation strategies must be adapted to the resources and constraints of different educational settings. In urban schools with robust technological infrastructure, sophisticated desktop GIS software and advanced data analysis projects may be feasible. In contrast, remote schools with limited connectivity may need to focus on offline GIS activities and the integration of indigenous knowledge with spatial concepts.

Across all contexts, however, certain core principles remain essential: accessibility, flexibility, and cultural relevance. These principles ensure that GIS integration respects and responds to the diverse needs and perspectives of Canadian and Ukrainian students and communities.

7 Educational Benefits and Impact

7.1 Enhancing Student Engagement and Understanding

The integration of GIS into science education focused on extra-Earth exploration yields numerous benefits for student learning. One of the most significant is the enhanced student engagement that results from working with interactive maps and real-world (or real-planet) data, which can significantly boost interest and motivation in science lessons (Kingsley et al., 2017).

The novelty of exploring celestial bodies through advanced technology can capture students' imaginations and make the learning process more enjoyable. Unlike traditional, often passive methods of teaching about space, GIS offers an active, visual, and highly interactive way for students to engage with the subject matter.

Research by Stieff (2011) on the use of molecular simulations embedded in inquiry activities demonstrates how visualization tools can improve representational competence, a finding that has parallels in astronomy education. When students can visualize and manipulate spatial data related to celestial bodies, they develop a deeper understanding of the underlying scientific concepts.

In the Canadian context, where engaging indigenous students in science education remains a priority, GIS offers opportunities to connect Western scientific approaches with indigenous ways of knowing. As Balram et al. (2003) suggest, GIS can be used to integrate diverse stakeholder knowledge for spatial awareness and understanding, an approach that respects and incorporates multiple knowledge systems.

7.2 Developing Essential Skills for STEM Careers

GIS integration in science education also fosters the development of crucial spatial thinking skills, including the ability to visualize, interpret, and analyze spatial relationships, a competency that is increasingly vital in science and numerous other fields (Uttal et al., 2013).

Working directly with planetary maps and associated data within a GIS environment directly promotes the development of spatial literacy and reasoning. Students learn to understand complex coordinate systems, the intricacies of map projections, the significance of scale, and the spatial distribution of features on distant celestial bodies.

This visual and analytical engagement can lead to a deeper understanding of complex scientific concepts. Visualizing and analyzing spatial data related to space can help students grasp abstract ideas such as the mechanics of planetary orbits, the nature of gravitational fields, or the geological processes that sculpt planetary surfaces (McNeal & Petcovic, 2020).

For Canadian students, these skills have particular relevance in a country with a strong geomatics industry and growing space sector. As Moorman and Garbutt (2018) note, there is demand for students with the ability to organize and manage remote sensing applications, a field where spatial thinking skills are essential.

7.3 Supporting Educational Equity and Inclusion

The integration of GIS into science education also presents opportunities to address educational equity and inclusion. Bednarz (2019) demonstrates that explicit instruction in spatial thinking through geography education can significantly reduce gender-based achievement gaps in STEM fields. The benefits of closing these gender gaps extend far beyond individual achievement. When female students develop strong spatial thinking skills through GIS-enhanced instruction, they gain increased confidence in their ability to pursue STEM careers, particularly in fields like engineering, astronomy, and geosciences where spatial reasoning is fundamental. This enhanced spatial competence translates into improved performance in mathematics and physics courses, subjects that have traditionally shown gender disparities.

Furthermore, closing gender gaps in spatial thinking contributes to broader societal benefits by diversifying the STEM workforce, bringing different perspectives to scientific problem-solving, and providing role models for future generations of female scientists. Research shows that teams with gender diversity produce more innovative solutions and higher-quality research outputs. In the context of space science education, ensuring equitable spatial thinking development means that all students – regardless of gender – can fully participate in humanity's exploration of the cosmos. By using GIS as a tool to develop spatial reasoning in an engaging, technology-rich environment, educators can help dismantle barriers that have historically limited women's participation in spatial sciences.

Similarly, Yaki, Saad, Renuka V, and Zulnaidi (2019) found that integrated STEM approaches benefitted students across different academic abilities, with low-ability students showing the highest mean gains. This suggests that well-designed technology integration can help close achievement gaps and promote equity in science education.

However, as Voithofer and Foley (2007) caution, national discourses about educational technology often support universal and undifferentiated approaches to technology integration. In contrast, they advocate for "sustaining interventions that promote contextual definitions of success and achievement rooted in the values, discourses, and resources of community".

This means designing GIS-based activities that respect and respond to the diverse cultural and linguistic backgrounds of students, including indigenous perspectives and knowledge systems. It also means ensuring that technological resources are distributed equitably across urban, suburban, rural, and remote educational settings.

8 Challenges and Future Directions

8.1 Addressing Implementation Barriers

Despite the considerable benefits, the implementation of GIS in schools for teaching extra-Earth exploration presents certain challenges that need to be addressed thoughtfully. Access to suitable technology, including computers with adequate processing power and the necessary GIS software, even freely available options, can be a significant barrier for some schools, particularly those with limited resources (Bingimlas, 2009).

While the emergence of web-based GIS platforms has undeniably lowered this technological hurdle, reliable internet connectivity and a sufficient number of devices for student use remain crucial prerequisites for effective integration. This challenge is particularly acute in rural and remote communities, where digital infrastructure may be limited.

Another key challenge lies in teacher training and professional development. Many science teachers may not possess the requisite training and practical experience to confidently and effectively integrate GIS into their existing lesson plans (Oda et al., 2020). Providing adequate and ongoing professional development opportunities is therefore essential to equip educators with the necessary skills, pedagogical knowledge, and confidence to utilize GIS effectively in their teaching.

Integrating GIS seamlessly within an already packed science curriculum can also be a considerable challenge for educators (Konstantakatos & Galani, 2023). To overcome this, GIS should be viewed not merely as an add-on but rather as a versatile tool that can enhance and enrich existing curriculum topics, requiring careful planning and a clear alignment with established learning objectives.

8.2 Future Research Directions

The incorporation of GIS in science education presents several promising directions for future research. One key area is the development of more effective assessment strategies for evaluating the impact of GIS-enhanced instruction on students' spatial thinking abilities and science content knowledge. As Kingsley et al. (2017) note, there is limited empirical evidence on the effectiveness of space science outreach and education efforts, highlighting the need for more robust evaluation tools.

Research is also needed to better understand how GIS can be used to support diverse learners in astronomy and planetary science education. This includes investigating how GIS-based activities can be designed to be culturally responsive and inclusive, particularly for indigenous students and other underrepresented groups in STEM.

The emerging field of immersive technologies presents another promising research direction. As Ricketts et al. (2018) suggest, immersive visualization environments offer new opportunities for engaging students in hands-on learning. Investigating how virtual and augmented reality can enhance students' understanding of astronomical phenomena through spatial visualization represents a frontier for educational technology research.

9 Conclusion

Geographic Information Systems hold remarkable potential to revolutionize science education related to the captivating realm of extra-Earth exploration. By fostering spatial thinking, enhancing student engagement, and promoting a deeper understanding of the universe, GIS offers a powerful lens through which students can explore the cosmos.

Both in the Canadian and Ukrainian contexts, this approach aligns with broader educational goals related to scientific literacy, technological competence, and interdisciplinary learning. The varying educational contexts and resources presents both challenges and opportunities for implementing GIS-enhanced astronomy education.

Given the increasing relevance of GIS in cutting-edge space science research, equipping students with these valuable skills today will undoubtedly prepare them for future academic and professional endeavors in STEM fields. To successfully chart a course for these future explorers, educators should prioritize providing adequate teacher training in GIS, starting with accessible software and readily available data resources, and thoughtfully integrating GIS into the existing science curriculum in ways that meaningfully enhance learning outcomes.

Embracing the transformative power of GIS promises to inspire the next generation of space explorers and scientists, igniting their curiosity about the universe and empowering them with the critical skills to make their own discoveries. As we look to the future of science education, the integration of spatial technologies offers a pathway to more engaging, equitable, and effective learning experiences for all students.

Declarations

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On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Ethical approval and Consent to Participate

Not applicable.

Authors' contributions

SOS conceptualized the study, developed the theoretical framework, and drafted the manuscript, including the introduction and foundations of spatial thinking in science education. ISM contributed to the analysis of GIS applications in astronomy and planetary science education. PPN analyzed the integration of GIS in science education and contributed to the educational benefits section. OVB evaluated implementation strategies and resources for educators across different educational contexts. SLM provided expertise on pedagogical approaches and frameworks for GIS integration. All authors reviewed, edited, and approved the final manuscript for submission.

Data availability

No datasets were generated or analyzed during the current study as this paper presents a theoretical framework and literature review on Geographic Information Systems for space science education.

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