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Teaching Astronomy in Specialized Schools as A Means of Developing Students' Scientific Thinking and Research Skills: An Inquiry-Based Methodological Model

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Abstract

Background: Uzbekistan's first participation in PISA (2022) showed a mean science score of 355 points against an OECD average of 485, which highlights the need to strengthen students' scientific reasoning rather than factual recall. Astronomy, often described as a "gateway science", offers authentic phenomena that students can observe, measure and explain, yet its potential for developing research skills in Uzbek specialized schools has not been described systematically. Purpose: The study aims to substantiate the pedagogical significance of astronomy teaching in specialized schools for developing students' scientific thinking and research skills and to propose a methodological model for organizing student research. Methods: A theoretical-methodological design was used, combining analysis of national and international literature, analysis of international assessment data, pedagogical modelling, and the computational design of research tasks based on real astronomical data for Kokand (40.53° N, 70.94° E) generated with the PyEphem library and NASA planetary data. Results: An inquiry-based model linking five inquiry phases (orientation, conceptualisation, investigation, conclusion, discussion) to astronomy activities and six assessable research skills is proposed; a matrix mapping nine astronomy topics to these skills, three data-based research tasks (the noon altitude of the Sun, the lunar phase cycle, Kepler's third law) and a four-level criterion-based assessment rubric are presented. Conclusion: Astronomy lessons organised as a sequence of small investigations with real data and explicit assessment criteria can systematically develop students' scientific thinking. The model is ready for empirical validation in a pedagogical experiment.

Keywords: Astronomy education; specialized schools; scientific thinking; research skills; inquiry-based learning; assessment rubric; secondary education.

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1. Introduction

One of the key objectives of modern education systems is not merely to provide students with ready-made knowledge, but to develop their ability to think independently, analyse problems, evaluate scientific evidence and justify their conclusions. International frameworks for science education describe this goal as engaging students in the practices of science: asking questions, developing and using models, planning and carrying out investigations, analysing and interpreting data, and constructing explanations based on evidence

(National Research Council [NRC], 2012). In this view, scientific knowledge and scientific thinking are developed together, through activity rather than through memorisation.

For Uzbekistan this goal has acquired particular urgency. In 2022 the country took part in the Programme for International Student Assessment (PISA) for the first time. Fifteen-year-old students scored 364 points in mathematics, 336 in reading and 355 in science, compared with OECD averages of 472, 476 and 485 points respectively (OECD, 2023). The gap in science is therefore 130 points (Figure 1). Since PISA science items assess the ability to explain phenomena scientifically, evaluate and design scientific enquiry, and interpret data and evidence, the result indicates that the development of scientific reasoning, and not only of subject knowledge, should become a priority of school science teaching.

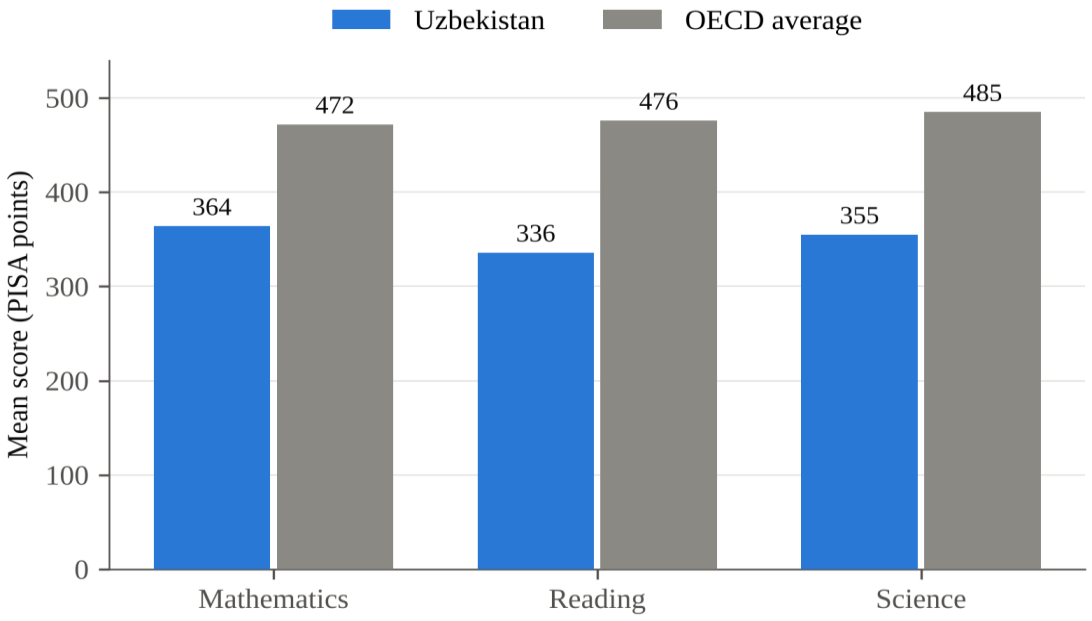


Figure 1. Mean PISA 2022 scores of 15-year-old students in Uzbekistan compared with the OECD average

Source: compiled by the author from OECD (2023).

Specialized schools play a special role in addressing this task. In Uzbekistan, the Agency of Specialized Educational Institutions was established by Presidential Decree No. 5815 of 9 September 2019 with the mandate of identifying and educating gifted young people and introducing advanced teaching methods and pedagogical technologies into the educational process of Presidential, creative and specialized schools (Agency of Specialized Educational Institutions, n.d.). The organisation of the educational process in such schools aims to develop students' individual abilities, interest in academic subjects and intellectual potential, which creates favourable conditions for research-oriented teaching.

Astronomy offers considerable opportunities for fostering scientific thinking. By studying the structure of the universe, the motion of celestial bodies, the Solar System, stars, galaxies and the physical processes occurring in space, students learn to explain natural phenomena through cause-and-effect relationships. Crucially, many astronomical phenomena (the daily and annual motion of the Sun, the phases of the Moon, the motion of planets) can be observed directly by every student, without laboratory equipment, which makes astronomy a natural field for authentic, data-based inquiry (Salimpour et al., 2021). In the process of learning astronomy, students therefore acquire not only theoretical knowledge but also the essential elements of scientific inquiry: observation, data collection, calculation, comparison, modelling and interpretation of results.

Uzbek methodological research has addressed the content of school astronomy (Mamadazimov, 1994; Mamadazimov & Rizayev, 2016), the integration of physics and astronomy (Mamadazimov, 1996), problem-

solving methods (Nurmamatov, 2020) and the use of modern research results in teaching (Tillaboyev, 2021a, 2021b). However, the question of how astronomy lessons in specialized schools can be organised so as to develop students' research skills systematically, and how these skills can be assessed, has not been sufficiently addressed. This constitutes the research gap of the present study.

The purpose of the article is to substantiate the pedagogical significance of teaching astronomy in specialized schools for developing students' scientific thinking and research skills, and to propose an inquiry-based methodological model for organising and assessing students' research activities. The study addresses three research questions:

RQ1. Which components of scientific thinking and research skills can be developed through the content of school astronomy?

RQ2. How can astronomy lessons be organised as a sequence of inquiry phases using real astronomical data?

RQ3. Which criteria and performance levels can be used to assess students' research skills in astronomy lessons?

2. Literature Review

2.1. Scientific thinking and inquiry-based learning

Scientific thinking is a cognitive process based on observing events and phenomena, identifying relationships between them, analysing evidence, testing hypotheses and drawing logical conclusions. In a comprehensive review of developmental research, Zimmerman (2007) shows that scientific thinking includes both domain-specific knowledge and domain-general skills such as hypothesis generation, experimentation, evidence evaluation and inference, and that these skills develop through instruction and practice rather than spontaneously. Students who demonstrate scientific thinking do not simply accept information; they seek to understand its meaning, evaluate its reliability and comprehend its scientific foundations.

Inquiry-based learning is the most widely used pedagogical approach for developing these skills. A synthesis of 138 studies conducted between 1984 and 2002 found a clear positive trend in favour of inquiry-based instructional practices, particularly instruction that emphasises students' active thinking and drawing conclusions from data (Minner et al., 2010). Pedaste et al. (2015), after a systematic review of 32 articles describing inquiry phases, synthesised them into a framework of five general phases: orientation, conceptualisation (questioning and hypothesis generation), investigation (exploration, experimentation, data interpretation), conclusion and discussion (communication and reflection). This framework is used in the present study as the basis of the proposed model.

2.2. Astronomy as a context for developing research skills

Astronomy education research has accumulated substantial evidence about students' learning difficulties. Reviews of the field identify recurring "big ideas" that students find difficult: the Earth's shape and gravity, the day–night cycle, the seasons, the phases of the Moon, the Solar System, and the scale of the universe (Bailey & Slater, 2003; Lelliott & Rollnick, 2010). Many misconceptions, for example the belief that seasons are caused by changes in the Earth–Sun distance, or that the phases of the Moon are caused by the Earth's shadow, persist even after formal instruction. Plummer (2014) argues that progress in astronomy learning is closely linked to spatial thinking, that is, to the ability to coordinate the Earth-based view of the sky with a heliocentric model; developing this ability requires that students actively connect observations with models.

At the same time, astronomy is present in virtually all school curricula. An analysis of 52 curricula from 37 countries (OECD members, China, South Africa and the International Baccalaureate) found that astronomy-related topics appear in at least one grade in every curriculum examined, and that concepts such as the Earth, Sun, Moon and stars are among the most frequent keywords (Salimpour et al., 2021). Large-scale projects in which secondary students use real robotic telescopes have shown that inquiry-based design can make authentic astronomical research accessible at school level (Fitzgerald et al., 2015). Modern astronomy textbooks likewise present the subject as a science in which knowledge is built by connecting observations with physical models (Chaisson & McMillan, 2016).

In Uzbekistan, the methodological foundations of astronomy teaching were laid by Mamadazimov (1994, 1996), who emphasised an integrative approach to teaching physics and astronomy. Subsequent studies examined the problems of astronomy teaching in the

continuing education system (Mamadazimov & Rizayev, 2016), methods of solving problems on the celestial sphere (Nurmamatov, 2020), the conceptual foundations of modern teaching technologies (Nurmamatov, n.d.), the methodology of teaching astronomy (Qodirov, 2019), the use of modern scientific results in teaching (Tillaboyev, 2021a, 2021b) and innovative pedagogical technologies in the continuing education system (Xolmurodov, 2024). These studies focus mainly on content and teaching methods; the systematic development and assessment of research skills in specialized schools remains less explored.

3. Methods

The study employed a theoretical-methodological design. No intervention was carried out with students at this stage; the aim was to develop and substantiate a model that can subsequently be tested empirically. The following methods were used:

– **Analysis of literature** – national and international publications on scientific thinking, inquiry-based learning and astronomy education (1994–2024) were analysed to identify the components of research skills and the conditions for developing them;

– **Analysis of international assessment data** – the PISA 2022 results for Uzbekistan (OECD, 2023) were used to characterise the current state of students' scientific literacy;

– **Pedagogical modelling** – the five-phase inquiry framework of Pedaste et al. (2015) was adapted to the content of school astronomy, and a matrix linking astronomy topics to research skills was constructed;

– **Computational design of research tasks** – to ensure that the proposed tasks rest on real data, the noon altitude of the Sun, the length of daylight and the illuminated fraction of the Moon were calculated for Kokand (40.53° N, 70.94° E, 409 m above sea level; local time UTC+5) for 2026 using the PyEphem astronomical library, version 4.2.1 (Rhodes, 2011). Sunrise and sunset were defined for the upper limb of the Sun with a standard refraction of 34′. Orbital data for the planets were taken from the NASA Planetary Fact Sheet (Williams, n.d.);

– **Criterion-based design of assessment** – assessment criteria were derived from the inquiry phases and described at four performance levels.

4. Results

4.1. An inquiry-based model for developing research skills in astronomy lessons

Based on the analysis, an inquiry-based model was developed (Figure 2). Each lesson or project is organised as a cycle of five phases. In every phase the student performs a specific astronomy activity, and each activity corresponds to a research skill that can be observed and assessed. The cycle is closed by reflection: if the data do not support the hypothesis, the student returns to the orientation or conceptualisation phase and revises the question, the hypothesis or the method.

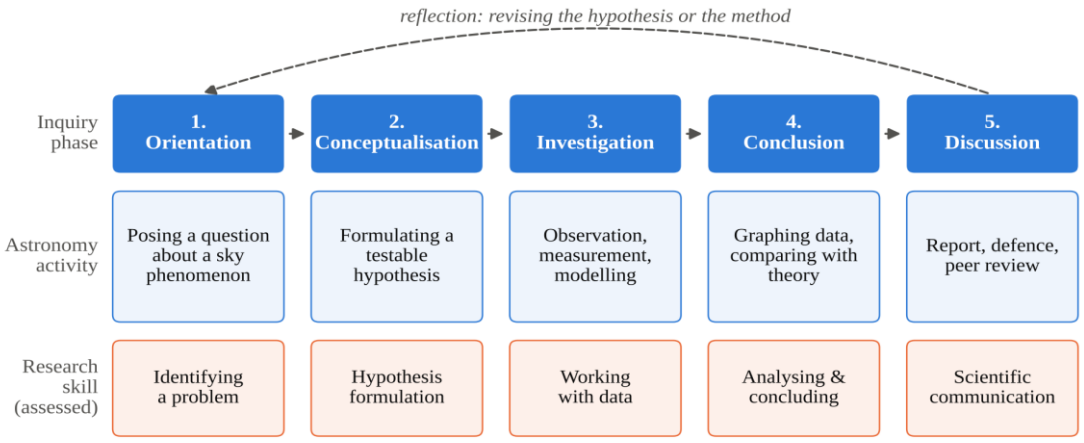


Figure 2. Inquiry-based model for developing research skills in astronomy lessons

Source: developed by the author on the basis of Pedaste et al. (2015).

The model addresses RQ1 by specifying six research skills that astronomy can develop: (1) identifying a problem, (2) formulating a hypothesis, (3) working with data, (4) analysing information, (5) drawing evidence-based conclusions and (6) scientific communication. In the model, skills 4 and 5 are both developed in the conclusion phase.

4.2. Correspondence between astronomy content and research skills

Not every topic contributes equally to every skill. Table 1 shows the result of mapping nine topics of the school astronomy course onto the six research skills. The mapping was carried out by analysing which types of student activity each topic naturally supports: direct observation, measurement, calculation, comparison of objects or modelling.

Table 1. Correspondence between astronomy topics and the research skills they primarily develop

Topic	Problem	Hypo-thesis	Data	Analysis	Conclu-sion	Commu-nication
Apparent daily motion of the Sun; the gnomon	●	○	●	●	○	○
Change of seasons	●	●	○	●	●	○
Phases of the Moon	○	●	●	●	●	○
Solar and lunar eclipses	●	●	○	○	●	●
Celestial sphere and coordinates	○	○	●	●	○	○
Kepler's laws and planetary motion	○	●	●	●	●	○
Comparative study of the planets	●	○	●	●	○	●
Stars: brightness, colour, temperature	○	●	●	●	●	○
Galaxies and the scale of the universe	●	○	○	●	○	●

Note: ● – the topic provides the main context for developing the skill; ○ – the topic supports the skill. Developed by the author.

The table shows that topics based on direct observation (the Sun, the Moon) are especially suitable for developing the skills of working with data, whereas topics that involve explaining a phenomenon (seasons, eclipses, Kepler's laws) are particularly suitable for formulating and testing hypotheses. Topics dealing with the planets and the scale of the universe provide rich material for comparison, classification and scientific communication. A teacher can therefore plan a course so that every skill is practised several times in different contexts.

4.3. Research tasks based on real astronomical data

To address RQ2, three research tasks were designed for specialized school students. Each task follows the five phases of the model and uses real data that students can

either obtain by their own observations or verify against calculated values.

Task 1. Why does the noon Sun rise higher in summer? Orientation: students notice that the shadow of a vertical stick (gnomon) at noon is much shorter in June than in December. Conceptualisation: they formulate the hypothesis that the noon altitude of the Sun depends on the season and can be predicted by the formula $h = 90° - \varphi + \delta$, where φ is the latitude of the place and δ is the declination of the Sun. Investigation: once a week students measure the length of the noon shadow L of a gnomon of height H and calculate $h = \arctan(H/L)$. Conclusion: they compare their measurements with the calculated curve (Figure 3) and with the theoretical values (Table 2). Discussion: students explain why the change of seasons is caused by the tilt of the Earth's axis rather than by the Earth–Sun distance, a common misconception (Lelliott & Rollnick, 2010).

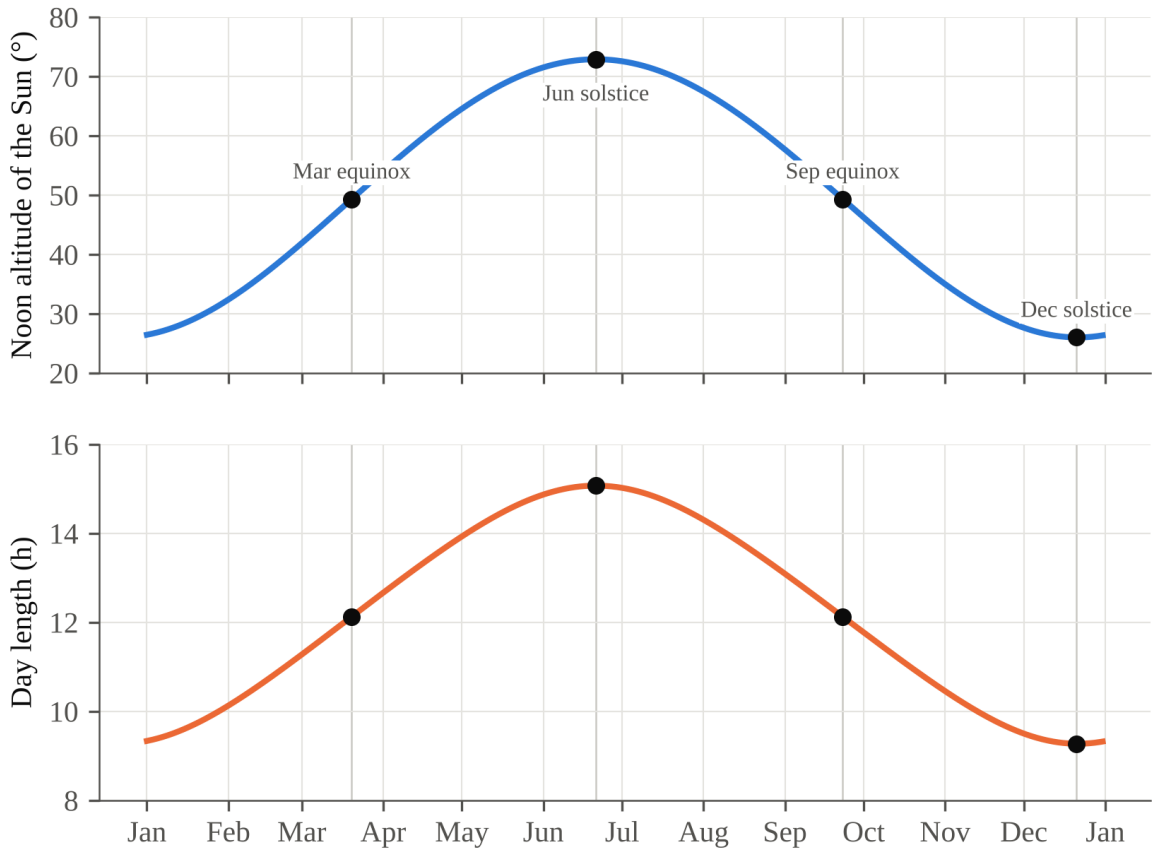


Figure 3. Noon altitude of the Sun (top) and length of daylight (bottom) in Kokand during 2026

Source: calculated by the author with PyEphem 4.2.1 (Rhodes, 2011) for 40.53° N, 70.94° E.

Table 2. Noon altitude of the Sun and length of daylight in Kokand on characteristic dates of 2026

Date	δ of the Sun	Theoretical $h = 90° - \varphi + \delta$	Calculated h	Day length
20 March (equinox)	0°	49.5°	49.3°	12 h 08 min
21 June (solstice)	+23.4°	72.9°	72.9°	15 h 04 min
23 September (equinox)	0°	49.5°	49.4°	12 h 08 min

Date	δ of the Sun	Theoretical h = 90° − φ + δ	Calculated h	Day length
21 December (solstice)	−23.4°	26.0°	26.0°	9 h 16 min

Note: φ = 40.53° N. Calculated values were obtained with PyEphem 4.2.1; small differences from the theoretical values arise because the Sun's declination on the given calendar date is not exactly 0° or ±23.4°.

The data show that in the course of the year the noon altitude of the Sun in Kokand changes from 26° to 72.9°, that is, by almost 47° (twice the tilt of the Earth's axis), while the length of daylight changes from 9 h 16 min to 15 h 04 min. By comparing their own gnomon measurements with these values, students learn to evaluate measurement error and to test a quantitative hypothesis, which are central components of scientific thinking (Zimmerman, 2007).

Task 2. What causes the phases of the Moon? Orientation: students record the appearance of the Moon every clear evening for one month and sketch it in an observation journal. Conceptualisation: two competing hypotheses are discussed: (a) the phases are caused by the Earth's shadow; (b) the phases depend on the relative positions of the Sun, Earth and Moon. Investigation: students estimate the illuminated fraction of the lunar disc and record the angular distance between the Moon and the Sun; in class they model the phases with a lamp and a ball. Conclusion: the observations are compared with the calculated curve (Figure 4). The Moon is full when it is opposite the Sun, not when the Earth's shadow falls on it; hypothesis (a) is therefore rejected. Discussion: students determine the length of the synodic month from their data; in the period shown in Figure 4 it is 29.74 days.

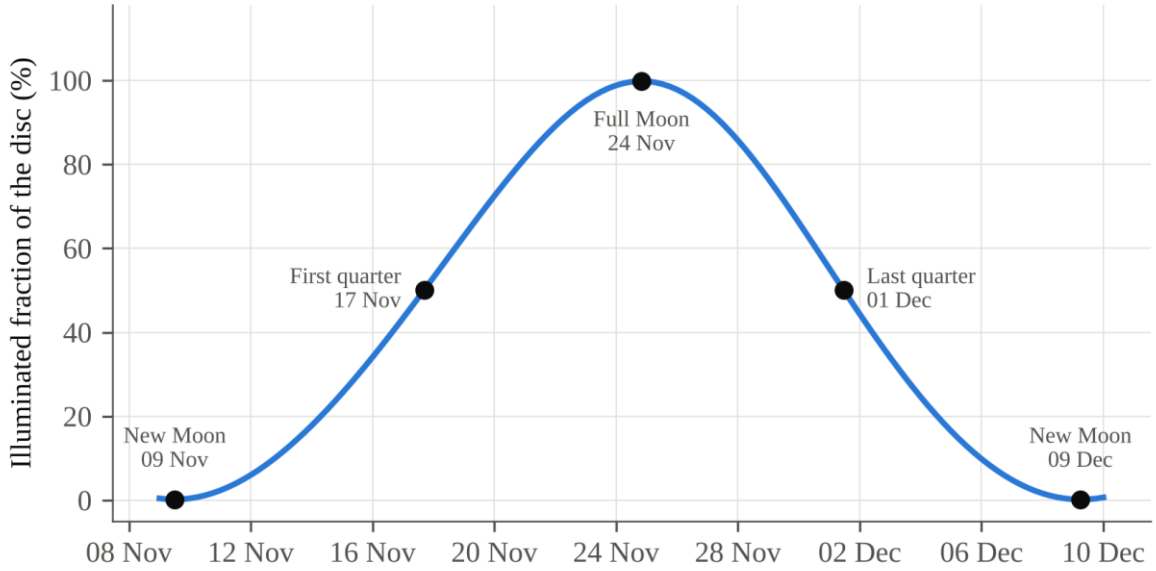


Figure 4. Illuminated fraction of the lunar disc during the lunation of November–December 2026 (Kokand local time, UTC+5)

Source: calculated by the author with PyEphem 4.2.1 (Rhodes, 2011).

Task 3. Is there a law connecting a planet's distance from the Sun with its period? Orientation: students are given a table of the semi-major axes a and orbital periods T of the planets (Table 3). Conceptualisation: they notice that distant planets have much longer periods and hypothesise a power-law relationship $T = k \cdot a^n$. Investigation: students plot the data on logarithmic axes (Figure 5) and determine the slope of the line. Conclusion: the slope obtained from the real data is 1.500, i.e. $n \approx 3/2$, and the ratio T^2/a^3 is equal to 1.00 for all planets to within 0.2% (Table 3). Students thereby independently "rediscover" Kepler's third law.

Discussion: they discuss why the ratio is the same for all planets and what it would be for the moons of Jupiter, which leads to the concept of the mass of the central body.

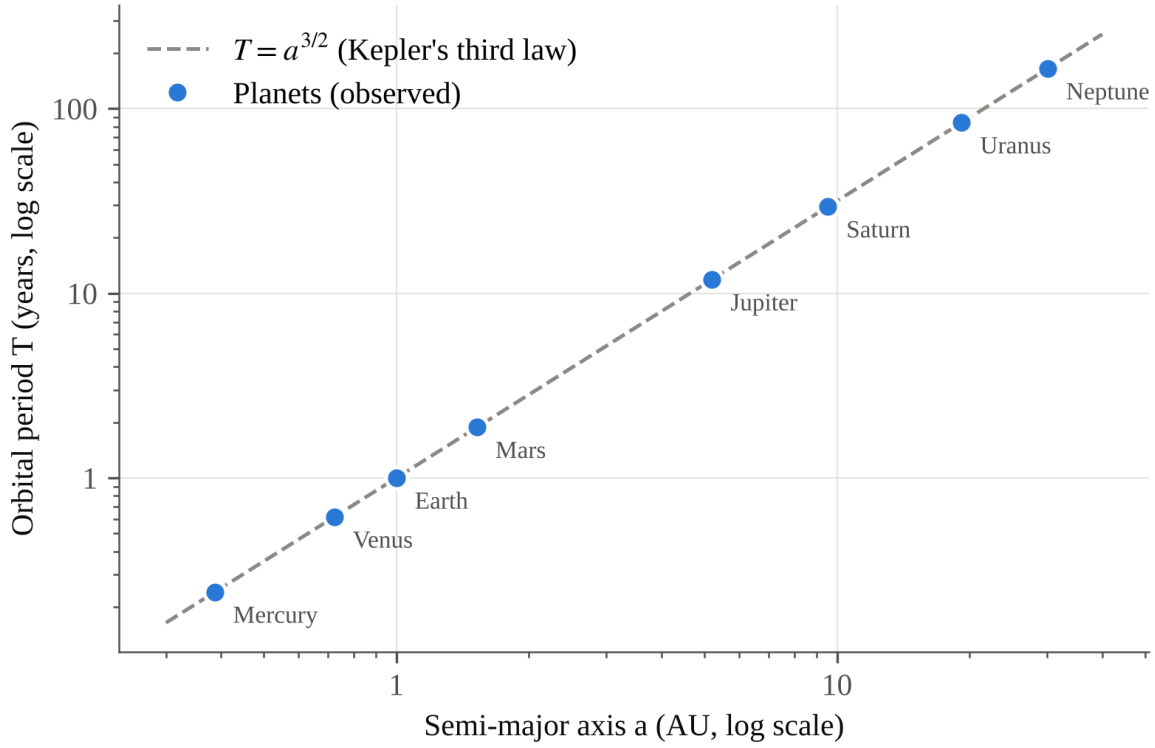


Figure 5. Orbital period versus semi-major axis of the planets of the Solar System (logarithmic scales)

Source: plotted by the author using data from the NASA Planetary Fact Sheet (Williams, n.d.).

Table 3. Orbital data of the planets used in Task 3

Planet	a, AU	T, years	T^2 / a^3
Mercury	0.387	0.241	1.002
Venus	0.723	0.615	1.001
Earth	1.000	1.000	1.000
Mars	1.524	1.881	1.000
Jupiter	5.203	11.86	0.999
Saturn	9.537	29.46	1.001
Uranus	19.19	84.01	0.999
Neptune	30.07	164.8	0.999

Note: a and T from the NASA Planetary Fact Sheet (Williams, n.d.); T^2/a^3 calculated by the author.

4.4. Criterion-based assessment of research skills

To address RQ3, assessment in astronomy lessons should not be limited to determining how well students remember facts. It should also evaluate their scientific reasoning, ability to work with information, capacity to test hypotheses and competence in presenting evidence-based conclusions. Table 4 presents a rubric with six criteria, each described at four levels of performance. The rubric can be used to assess projects, observation journals, practical assignments, graphs and oral presentations.

Table 4. Rubric for assessing students' research skills in astronomy lessons

Criterion	Level 1 – Initial	Level 2 – Developing	Level 3 – Proficient	Level 4 – Advanced
Identifying a problem	Repeats a question given by the teacher	Formulates a question, but it is vague or not researchable	Formulates a clear, researchable question about a phenomenon	Formulates an original question and justifies its significance
Formulating a hypothesis	Gives a guess without justification	Proposes an assumption based on everyday experience	Proposes a testable hypothesis based on scientific knowledge	Proposes competing hypotheses and states how each can be tested
Working with data	Records data incompletely or inaccurately	Records data, but without units or regular intervals	Records complete, systematic data in tables or a journal	Evaluates the reliability of data and estimates measurement error
Analysing information	Describes individual data points	Notices a general trend	Identifies relationships using graphs and comparisons	Describes the relationship quantitatively (formula, slope, ratio)
Drawing conclusions	Conclusion is not connected to the data	Conclusion is partly supported by the data	Conclusion is supported by evidence and evaluates the hypothesis	Discusses the limitations of the conclusion and alternative explanations
Scientific communication	Presents results incoherently	Presents results, but has difficulty answering questions	Presents results clearly with graphs and answers questions	Defends the results with arguments and discusses alternative viewpoints

Note: developed by the author. Levels may be converted to points (1–4 per criterion; maximum 24 points).

Assessment should take into account not only the final result but also the consistency of the research process, the reliability of the data and the validity of the conclusions. Providing students with the rubric before they begin an assignment helps them plan their activities, evaluate their own results and independently identify areas for improvement.

5. Discussion

The results support the view that astronomy has a particular value for developing scientific thinking. Unlike many school science topics, astronomical phenomena are accessible to every student without special equipment, and observation is the primary method of astronomy itself. This allows students to experience the full research cycle, from question to communicated conclusion, which is consistent with the practices described in international science education frameworks (NRC, 2012) and with the five-phase inquiry cycle (Pedaste et al., 2015).

The proposed tasks are deliberately built around phenomena that are known to generate persistent misconceptions: the seasons and the phases of the Moon (Bailey & Slater, 2003; Lelliott & Rollnick, 2010). In each task, students formulate competing hypotheses and test them against data, so that the misconception is not simply corrected by the teacher but rejected by the student on the basis of evidence. Combining observations from the Earth with physical models (a lamp and a ball, a gnomon) supports the coordination of Earth-based and space-based perspectives that Plummer (2014) identifies as the key dimension of progress in astronomy learning.

The use of real calculated data is a distinctive feature of the model. Students' own measurements in school conditions are inevitably imprecise; comparing them with accurate ephemeris data teaches students to estimate error, to distinguish between a systematic trend and random variation, and to judge whether a deviation refutes a hypothesis. The Kepler task illustrates how a classical law can be "rediscovered" from tabular data, which reflects the historical path of science and develops quantitative reasoning. Similar approaches using real telescope data have been successfully implemented in large-scale school projects (Fitzgerald et al., 2015). Free software for calculating ephemerides and plotting data also corresponds to the learning preferences of today's students, who learn most effectively when they act as partners of the teacher in solving real problems with digital tools (Prensky, 2010).

For Uzbekistan, the significance of the model is connected with the results of PISA 2022 (OECD, 2023). The science competencies assessed by PISA (explaining phenomena scientifically, evaluating and designing scientific enquiry, interpreting data and evidence) correspond directly to the research skills in the proposed model. Specialized schools, which concentrate motivated and capable students and are expected to introduce advanced pedagogical technologies, are an appropriate environment for piloting such approaches before they are extended to general secondary schools.

Limitations. The study is theoretical and methodological. The effectiveness of the model has not yet been verified experimentally, and the topic–skill matrix (Table 1) reflects the author's expert analysis rather than empirical measurement. Future research should include a pedagogical experiment with experimental and control groups in specialized schools, pre- and post-testing of research skills using the rubric in Table 4, and an assessment of the rubric's inter-rater reliability.

6. Conclusion

Teaching astronomy in specialized schools offers considerable pedagogical opportunities for developing students' scientific thinking and research skills. By studying astronomical phenomena, students engage in important scientific activities such as observation, comparison, analysis, hypothesis formulation and drawing evidence-based conclusions. The study leads to the following conclusions.

First, six research skills can be systematically developed through the content of school astronomy: identifying a problem, formulating a hypothesis, working with data, analysing information, drawing conclusions and scientific communication; different topics provide the main context for different skills (RQ1).

Second, astronomy lessons can be organised as a cycle of five inquiry phases (orientation, conceptualisation, investigation, conclusion and discussion) in which every phase is linked to a specific astronomy activity. Research tasks based on real data, such as the noon altitude of the Sun, the phases of the Moon and Kepler's third law, allow students to test hypotheses quantitatively and to overcome common misconceptions on the basis of evidence (RQ2).

Third, students' research skills can be assessed with a criterion-based rubric that describes each skill at four levels; making the criteria known to students in advance supports self-assessment and planning (RQ3).

Fourth, the effective organisation of students' research activities requires consistent methodological guidance at every stage, from identifying a problem to presenting the results.

In general, enriching astronomy teaching with research-oriented approaches can broaden the scientific outlook of students in specialized schools, increase their interest in natural phenomena and help them develop the skills necessary for future scientific inquiry. The next stage of the research will be the experimental validation of the proposed model.

DECLARATIONS

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Conflict of interest. The author declares no conflict of interest.

Ethics statement. Not applicable: the study did not involve human participants or the collection of personal data.

Data availability. The astronomical data used in Figures 3–5 and Tables 2–3 can be reproduced with the open-source PyEphem library and the NASA Planetary Fact Sheet; the calculation script is available from the author on request.

Use of AI tools. ChatGPT(OpenAI) was used to assist with language editing and improving the clarity of the manuscript. The author reviewed the final version and takes full responsibility for the content of the article.

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