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Development and validation of a learning progression for change of seasons, solar and lunar eclipses, and moon phases

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In this paper, we report about the development and validation of a learning progression about the Celestial Motion big idea. Existing curricula, research studies on alternative conceptions about these phenomena, and students' answers to an open questionnaire were the starting point to develop initial learning progressions about change of seasons, solar and lunar eclipses, and Moon phases; then, a two-tier multiple choice questionnaire was designed to validate and improve them. The questionnaire was submitted to about 300 secondary students of different school levels (14 to 18 years old). Item response analysis and curve integral method were used to revise the hypothesized learning progressions. Findings support that spatial reasoning is a key cognitive factor for building an explanatory framework for the Celestial Motion big idea, but also suggest that causal reasoning based on physics mechanisms underlying the phenomena, as light flux laws or energy transfers, may significantly impact a students' understanding. As an implication of the study, we propose that the teaching of the three discussed astronomy phenomena should follow a single teaching-learning path along the following sequence: (i) emphasize from the beginning the geometrical aspects of the Sun-Moon-Earth system motion; (ii) clarify consequences of the motion of the Sun-Moon-Earth system, as the changing solar radiation flow on the surface of Earth during the revolution around the Sun; (iii) help students moving between different reference systems (Earth and space observer's perspective) to understand how Earth's rotation and revolution can change the appearance of the Sun and Moon. Instructional and methodological implications are also briefly discussed.

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I. INTRODUCTION

Research in science education increasingly advocates the use of a learning progression approach to describe and interpret how students develop their understanding of a given concept across school levels [1–4]. In a developmental view of learning, students learn a given science content starting from their intuitive ideas and progress through subsequent cognitive *levels* of a more sophisticated understanding of the topic [5–8]. Learning progressions are usually built around "big ideas" in science [9,10], namely, "core" concepts that help students connect different phenomena, empirical laws, and explanatory models [11]. Across school levels, students' initial ideas are *"progressively refined, elaborated, and extended"* [2] towards a more complete understanding. In physics, examples of big ideas are motion and force or energy [12,13]. Literature suggests that learning progressions support the acquisition of key skills in science and the understanding of how to use a given concept in different contexts. For example, the energy concept explains either the motion of the pointlike masses or the functioning of advanced technological systems.

Recently, there has been an increasing interest in the science education research community to develop learning progressions about Celestial Motion [14–19]. This big idea provides an explanatory framework for a wide range of astronomical phenomena—the daily apparent pattern of the Sun, Moon phases, seasonal changes, eclipses—observed from the perspective of Earth. Moreover, Celestial Motion familiarizes the students with observations and interpretations of evidence relying on interactions between celestial objects [20].

For this study, we chose three of the above phenomena central to this big idea: change of seasons, lunar and solar eclipses, and Moon phases. There are at least three reasons that guided our choice.

The first is that three phenomena allow further study of other big ideas in physics, such as the properties of light. For instance, Moon phases and lunar or solar eclipses can be exploited as contexts for the teaching of rectilinear propagation of light. Similarly, discussing the different

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temperatures experienced during the different seasons can familiarize students with energy transfer through electromagnetic radiation. Finally, Gauss flux law can be introduced as a model of how sunray flow varies at a fixed time of the year over the entire Earth surface leaning towards the Sun; or at a fixed place on the surface as Earth completes its revolution around the Sun.

Second, teaching about the motion of celestial objects is an opportunity to engage students in argumentation. For instance, explaining Moon phases requires that the students connect different frames of reference and relate what an observer on Earth sees (evidence) to the motion of the Sun-Earth-Moon system (explanatory framework) [21].

Third, when studying Celestial Motion, students may also appreciate that astronomical topics are relevant to their lives. For instance, explaining change of seasons gives students the opportunity to discuss global warming, a relevant socio-scientific issue [22], using scientific-based arguments (the factors affecting the temperature of a place on Earth's surface or the mechanisms underlying energy transfers between radiation and environment).

However, research in science education has shown that students have many difficulties in developing a correct understanding of important aspects of Celestial Motion (see reviews in Refs. [23,24]). One of the main issues emerging from the literature is that instructional strategies often focus on different aspects of this big idea; hence, students view seasons, eclipses, and Moon phases as separate and are often unable to develop a coherent explanatory framework. Our main aim is to develop a single learning progression that integrates the three chosen phenomena, to show potential connections between the three phenomena, and to describe students' global understanding of related astronomical phenomena. Validation of such a learning progression might inform researchers' knowledge of how students could develop a more coherent understanding of the Celestial Motion big idea.

As learning progressions include also "the thinking and learning which students might engage" [11], the issue of what cognitive abilities are involved in the progress across subsequent levels of a unifying learning progression about Celestial Motion arises [9,11]. In a recent study [19], it has been suggested that progression about daily motion of the Sun, Moon, and stars, and the phases of the Moon might be shaped by students' spatial thinking. However, as discussed above, understanding the chosen phenomena requires students to develop also a conceptual understanding of underlying physics topics. Engaging students in conceptual learning is improved when students develop causal reasoning [5,6]. Therefore, the second aim of this study was to find evidence about the role of spatial thinking and causal reasoning in the progressive development of a coherent learning about Celestial Motion.

To fulfill the above aims, we built on previous efforts to (i) first, hypothesize three *different* learning progressions for the seasonal changes, Moon phases, and eclipses phenomena; (ii) then, empirically validate the learning progressions and search for evidence to identify *cluster* levels that resume common features of the original learning progressions; (iii) and, eventually, build up the new learning progression characterized by the cluster levels.

Given the aims of the study, a new suitable instrument and analysis method was designed.

Thus, the following research questions guided the study:

RQ1a: To what extent do the initial hypothesized learning progressions describe students' understanding of the cause of seasons, solar and lunar eclipses, and Moon phases across different school levels?
RQ1b: What are the cognitive variables involved in a single learning progression aimed at describing students' understanding of the three phenomena?
RQ2: To what extent are the developed measurement instrument and method suitable for assessing students' understanding of the addressed phenomena with respect to the hypothesized learning progressions?

II. THEORETICAL FRAMEWORK

A. Learning progressions

Learning progressions have been defined as *"descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time"* [25]. Such a description is made through specific *progress indicators*, which refer to what the students know at a given *level*. The entry level is often called *lower anchor*, which typically features students' naïve or incorrect ideas. *Intermediate levels* feature increasingly complex reasoning and implications as well as incomplete explanations. The upper anchor is the correct scientific explanation of the target concept [3,9]. Basically, learning progressions aim at relating curriculum development to empirical evidence about students' conceptual understanding [26]. Hence, learning progressions, as hypothetical models of students' understanding, should be validated [20,27]. This is done by a research-based cycle: an initial learning progression is developed from existing literature or from a didactic reduction of the big idea. Then, data are collected to inspect the alignment with the actual students' achievements: if the alignment is poor, the measurement instrument and the initial learning progression need to be revised. In doing so, empirical evidences gathered about the different levels of conceptual understanding are used to tune the initial learning progression with the instrument. The cycle ends when alignment between actual and hypothesized outcomes becomes sufficiently satisfactory [13]. Different methodologies have been adopted by authors to validate hypothesized learning progressions. Neumann and colleagues [13] constructed a multiple choice questionnaire about energy and used Rasch analysis to compare students' achievements across different school levels against a hypothesized learning progression. Shea and Duncan [28] used qualitative data as interview and written artifacts of middle school students, engaged in a two-year specific instructional context to validate and revise a learning progression about genetics.

Three studies concern change of seasons. Willard and Roseman [14] proposed a learning progression organized around three ideas: (i) patterns of temperature variations during the year across Earth; (ii) how light warms the objects; (iii) motion of Earth. The rationale of the progression is to relate (i) the change in temperature to the different exposition to sunlight, (ii) the amount of warming to the intensity of light, and (iii) the different amount of sunlight received by Earth's regions to Earth's motion along its orbit. No validation of the learning progression is provided. This learning progression is interesting because it hypothesizes that students progress towards a justification of the change of seasons through a more sophisticated understanding of how sunlight flux influences temperature changes on Earth.

Sneider and colleagues [15] described a hypothetical learning progression which starts from (i) the knowledge of Earth's shape and day-to-night cycle, then (ii) focuses on the effects of seasonal changes from "Earth perspective" (temperature changes, path of the Sun observed in winter and summer), and (iii) arrives at a description of seasons from the "space perspective", with emphasis on the tilt of the axis, the orbit around the Sun and climate zones. Plummer and Maynard [16] validated a learning progression organized into five levels: (i) naïve ideas; (ii) knowledge of Earth's orbit, scale of the Sun-Moon-Earth system, the Sun's apparent motion and its influence on seasons; (iii) knowledge of observational features of the seasons; (iv–v) knowledge of how length of day, altitude of the Sun, and tilt of Earth may explain temperature at different locations on Earth. Both latter learning progressions aim at building a qualitative explanatory framework, including how the tilt of Earth's axis and revolution around the Sun may influence sunlight flux and hence temperature on the Earth's surface.

In her work about the phases of the Moon [19], Plummer proposed a learning progression which starts from (i) the observational knowledge about Moon phases (shape and time evolution), then (ii) describes the Moon's orbit and angle of observation to explain patterns of change in lunar phases, and, finally (iii), includes the Sun illumination and alignment of the Sun-Earth-Moon system into the explanatory framework. As in the work about seasons, the rationale is that students should connect Earth observations with a space-based perspective. Plummer reports a validation of the learning progression showing how students exposed to different instructional contexts moved across hypothesized levels.

Finally, in the work about the motion of the Sun and of the Moon as seen from Earth's perspective [17,18], Plummer and Krajcik described the levels of students' understanding along four conceptual patterns: (i) the Sun's path slowly changes in length and altitude across the seasons; (ii) the Moon moves across the sky in a path similar to that of the Sun; (iii) the path of stars remains the same but appear to an observer on Earth to move nightly; (iv) the appearance of the Moon changes slowly in a cycle during a month. This learning progression represents a first attempt to lump together different aspects of the Celestial motion "big idea", showing connections and relationships among the target phenomena at different levels (Earth and space viewpoint).

As stated in the introduction, the above learning progressions were taken into account in the design of the three initial learning progressions about seasons, eclipses, and Moon phases, especially in the definition of the progress indicators of the upper anchors.

B. Students' ideas about astronomical phenomena

A common practice in the development of learning progressions is to take into account students' alternative conceptions about the addressed topic [29]. Astronomy education research has thoroughly investigated students' ideas about the three phenomena discussed in this paper. We drew on such literature to construct our first version of three learning progressions about the chosen topics and design the research instrument. In particular, the lower anchor level and the intermediate levels were informed by students' accounts reported in the literature.

Concerning change of seasons, there are numerous alternative ideas that emerged in studies with students (from primary school to university) [30–34] as well as teachers [35,36]. One of the most common ideas is the "distance misconception", namely, that seasons are due to a change in the distance between the Sun and Earth. Examples of reasoning strategies based on this idea are (i) the axis' tilt brings some of Earth's regions closer to the Sun during the summer [31]; (ii) in summer, when Earth is further from the Sun, it slows down and hence it receives more energy for more time from the Sun. In other cases, students' explanations of the cause of seasons are incomplete [32]. For instance, students may correctly claim that Earth's axis is inclined but could not relate the different inclination of sunrays over Earth's surface to the tilt of the axis; or, students may be not aware that the axis during the revolution always points in the same direction, hence they may relate the change of seasons to the flip and flop of the axis [36]. Other nonscientific explanations about seasons emerged from studies with primary school students [30]: (i) the winter on Earth is due to other planets that "subtract" heat to the Sun or to clouds that prevent heat from reaching Earth's surface; (ii) the Sun rotates around Earth and hence it warms in different ways the different regions of Earth.

As far as Moon phases and solar and lunar eclipses are concerned, students' difficulties are mainly related to spatial thinking and to the need to put together pieces of information from the motions of three celestial objects (Sun, Earth, and Moon). Studies with primary school students [30,37–39] showed that Moon phases are often confused with eclipses, leading to the idea that these phenomena are due to the shadow of Earth or other objects falling on the Moon ("shadow misconception"). More specifically, incorrect explanations based on this idea are (i) the Moon is obscured by a cloud or by the Sun; (ii) as Earth rotates around its axis; different regions see different phases of the Moon. Nonscientific explanations about Moon phases emerged also in studies with university students [40–44], primary [45–48], and prospective teachers [49,50]. These studies mainly show that the persistence of incorrect ideas about this phenomenon may be related to a lack of knowledge about (i) the scale of the Moon-Earth system and (ii) the relationship between the Moon's rotation and its revolution motion around Earth.

The literature results basically informed the lower anchor of the three initial learning progressions about seasons, eclipses, and Moon phases. However, students' reasoning strategies reported in the above studies were analyzed and also used to define the intermediate levels of the progressions.

C. Cognitive abilities affecting learning about astronomical phenomena

From the above review about learning progressions and students' difficulties in astronomy, it can be inferred that to develop explanations about Celestial Motion students should connect Earth and space perspective and scientifically interpret everyday experiences and observations about familiar phenomena such as seasons, eclipses, and Moon phases. Such a complex amalgam requires the activation of high level cognitive processes. Abilities associated with such processes may become important indicators for the progression of learning in this content area.

In this study, we define "cognitive abilities" as those abilities that concern cognitive tasks, where a cognitive task is any task in which the correct processing of mental information is critical for a successful performance [51]. A first cognitive ability that seems to be relevant for understanding Celestial Motion is *spatial thinking*, because this big idea involves also the notion of scale, proportion and pattern [19,52,53]. Spatial thinking has been defined in a variety of ways. A document of the National Research Council [54], for instance, relates spatial thinking to *"understanding the meaning of space and using the properties of space as a vehicle for structuring problems, for finding answers, and for expressing solutions"* (p. 3), hence as *"a way of thinking about spaces, orientations, rotations, movements and perspective"* [52]. A more specific view defines spatial thinking as the ability of performing abstract manipulations of mental images or their parts [55,56] and to draw 3D information from 2D representations [57].

Focusing on astronomy, spatial thinking may help the visualization of celestial objects and their motions in relation to Earth's motion. In particular, the capability of mentally rotating an object may help to visualize Moon and Earth orbits, thus improving learners' explanations of such phenomena as eclipse and Moon phases. Similarly, to correctly describe phenomena in different reference frames (Earth and space based) may help to explain the apparent motion of Sun and Moon phases. Finally, spatial reasoning may be useful to qualitatively relate changes of solar flux on Earth's surface to the inclination of the axis and revolution around the Sun [16].

While spatial thinking has been considered as an important predictor for the success in science [58–61], some studies in physics found no significant correlation between spatial skills and conceptual understanding in force and motion [62], and between the capability of mentally rotating objects and the success in introductory electricity and magnetism [63]. Kozhenivkov and colleagues [55], for instance, found that when students interpreted kinematics problems after physics instruction, spatial thinking was no longer a predictor of their performance. Given the nature of the tasks used in that study, such evidence suggests that explanations or problems that require a more sophisticated reasoning involve different cognitive abilities. As the authors themselves hint, a first different cognitive ability probably at play was *causal reasoning*. Literature suggests that to reason causally is central to understand the physical world [64,65] because it is at the basis of the modeling process [66].

Moreover, causal reasoning is important when solving physics problems that involve qualitative descriptions of physical processes, because these kinds of tasks require one to explain causal relationships between variables. Hence, as many research studies [67–69] proved the importance of developing qualitative explanations for the learning process, to increase causal reasoning may result also in better conceptual knowledge.

In astronomy, causal reasoning may help students to achieve a more quantitative understanding of the changes of the solar flux during seasons by relating the "energy" received by Earth and the different conditions under which solar light hits Earth's surface [70]. Similarly, consequences of rectilinear propagation of light may be exploited by students to justify the appearance of Moon phases and conditions for lunar and solar eclipses.

From the above discussion, we hypothesize that to integrate causal reasoning with spatial thinking may help students progress from qualitative to more quantitative explanatory models about Celestial Motion.

III. METHODS

A. Development of the initial learning progressions

As already mentioned, in order to answer our research questions we first developed three different initial learning progressions based on (i) research studies in astronomy education, (ii) Italian secondary school science curriculum, and (iii) answers to an open questionnaire we administered to 189 secondary school students (of ages ranging from 13 to 18 years old) in the preliminary phase of our research. More details are reported in Ref. [71].

In Italy, astronomy topics are taught at secondary schools (14–18 years old). The National Indications from the Ministry of Education [72] suggest for the first two years (14–15 years old) of the biology, chemistry, and earth sciences subjects *"to deepen the explanatory framework of the Motions of Earth"*. To have a more precise idea of how these guidelines are implemented, we looked at common textbooks [73]. The proposed teaching sequence is (i) the solar system; (ii) the motions of Earth, including seasons; (iii) the motions of the Moon, including phases and eclipses; (iv) time measurement and its relation with Earth's motion. Some of these topics are again taught, in more detail, in the last year of secondary school (18 years). Quantitative considerations about Celestial Motion are added between the third and fifth year (16–18 years) in the mathematics and physics subjects *"With the study of Newtonian gravitation and of the Kepler's laws, the student may deepen the knowledge about cosmological systems… The teacher should use a suitable mathematical formalism that is accessible to students, bringing to front the fundamental concepts"*. Other aspects related to seasons (influence on temperature's environment, electromagnetic radiation flow) are also addressed.

Thus, while not explicitly organized around "big ideas", the Italian National Indications framework implicitly assumes a progression from qualitative explanations towards more quantitative models of natural phenomena.

The initial learning progressions for seasonal changes, eclipses, and Moon phases are reported in Table I.

B. Instrument development and functioning

In order to validate the hypothesized learning progressions, we chose a quantitative approach and developed a questionnaire in an attempt to generalize our results to educational contexts similar to the Italian one. A qualitative approach could also have been used to gain more details about students' interpretation of the target phenomena. In that case, our results would have been limited by a small sample size.

In designing our instrument, we decided to use a slightly modified two-tier structure. Traditional two-tier tests consist of a first tier with a content question, usually multiple choice, and a second tier in which the student is asked to give a justification of the answer given in the first tier [74]. The second tier may be open or multiple choice [75]. For this study we modified this basic structure: we put in the first tier three true or false statements concerning simple facts that the students should know in order to answer the question in the second tier.

The set of the first tier statements was constructed taking into account literature results and students' justifications to the open questionnaire (which informed also the initial learning progressions). The remaining items contained statements that featured images about the discussed phenomena. The images were selected from another study we conducted in the preliminary phase with twenty secondary school students. Details are reported in Ref. [76].

The questions in the second tier were adapted from existing instruments [42,44]. Each question asked for an explanation of the target phenomena among four answer choices, only one true, which corresponded to the progress indicator of a specific level of the hypothesized learning progression. Hence, in our instrument, the levels of the initial learning progressions correspond to different questions concerning the same phenomenon. The wrong answer choices featured explanations based on naïve ideas drawn from the students' answers to the open questionnaire and correspond to the lower anchors of the progressions.

By investigating the correlation between students' answers to the first and second tier we wanted to check if a wrong answer in the second tier was based on the lack of knowledge of basic facts or, conversely, whether the knowledge of basic facts was sufficient to choose a correct explanation of the phenomenon.

Overall, the questionnaire featured 12 two-tier items, for a total of 12 multiple choice questions and 36 true or false

TABLE I. Initial learning progression about change of seasons, eclipses, and Moon phases.

Phenomenon	Level	Progress indicator: The students know that
Seasons	1	Seasons are due to inclination of solar rays that changes during the year
	2	Level 1 + the revolution of Earth around the Sun
	3	Level 2 + tilt of Earth's axis
	Upper anchor	Level 3 + Earth's axis constant direction in space
Eclipses	1	Sun and Moon eclipses are due to alignment between the Sun, Moon, and Earth
	2	Level 1 + alignment happens in a 3D space
	Upper anchor	Level 2 + relative inclination of Moon and Earth orbits' planes
Moon phases	1	Moon phases are due to revolution of the Moon around Earth
	2	Level 1 + periodicity of the phases
	3	Level 2 + Sun illumination
	Upper anchor	Level 3 + relative positions of Earth, Moon, and the Sun

statements. The total score was 30 points: a student received 0.5 points for each correct true or false statement, 1 point for each multiple choice question answered correctly. The complete questionnaire is reported in the Appendix, where questions 1–16 concern seasons change, 17–32 Moon phases, and 33–48 lunar and solar eclipses. For the class submission, the questions were randomly distributed and five versions, each with a different order of questions, were generated. We lumped together all three target topics in the same questionnaire because we aimed at identifying reasoning strategies common to the three related topics and at building a new progression. Moreover, the submission of three different questionnaires was judged to be time consuming and hence not feasible with a large sample.

The questionnaire's internal reliability was investigated by means of classical test theory (Cronbach's alpha, difficulty, discrimination, and point biserial indices). As the reliability of these indices is strongly influenced by the sample, to quantitatively assess the hypothesized vs actual sequence of the learning levels for each phenomenon we also used item response (IR) theory [77,78]. A first analysis was carried out by means of the one-parameter logistic or Rasch model. The model relates the probability of correctly answering an item to the difference between a person's ability and an item's difficulty [79,80]. The Rasch analysis was carried out using a dichotomous model in ConstructMap software, generating a Wright map of the questionnaire. The dichotomous model was chosen so as to make the analysis independent of the scoring of true-false questions. Agreement of the data with the model and one dimensionality of the instrument was checked by means of infit and outfit statistics. Relationships between the first and second tier were investigated by looking, for each item, at the correlation between the average difficulty (in logits) of the three true or false statements in the first tier and the difficulty (in logits) of the corresponding multiple choice question.

During the analysis, however, we realized that item grouping from the Wright map was not sufficient to fully establish the alignment between the data and the hypothesized learning progression. From the Wright map one can estimate the probability of a student correctly answering a single question [80], not their overall understanding of the target construct, which can be articulated on more than one question. The map, in fact, does not allow analysis of the distracters, which are usually related, as in our case, to known erroneous student conceptions. For instance, a student could answer correctly to a question which corresponds to the upper anchor of the learning progression but wrongly choose distracters in other questions corresponding to the intermediate levels of the progression. To address this issue, we could have chosen a Rasch partial credit model, giving different partial scores to each answer choice. However, in our initial learning progression, intermediate levels between naïve ideas and the upper anchor featured incomplete yet correct explanations, whereas the answer choices featured incorrect explanations.

Hence, as intermediate levels correspond to different questions concerning the same content, to complete the analysis, we constructed from the raw data the IR curve (IRC) for the multiple choice questions. An IRC relates the number of students at each level of ability, measured in standard deviations, to each alternative of a question. Analysis of an IRC provides insights about the difficulty and discrimination of a given answer choice. In our case, inasmuch as each correct answer choice corresponds to a level of the hypothesized learning progressions, the analysis of the IRC provides information about the students' distribution across the intermediate levels of the learning progression. Moreover, incorrect answer choices of all the questions are related to explanations of the target phenomena based on naïve or transitional ideas; hence, using the IR analysis, we can obtain more precise insights into about how students of different ability deal with misconceptions. Our analysis consisted of calculating the *integral* of an IRC f, generally defined as

$$I_i^{\mathrm{IRC}} \equiv \int_{-n\sigma}^{+n\sigma} f_i^{\mathrm{IRC}}; \qquad f \in [0,1]; \tag{1}$$

where σ is the standard deviation of students' scores, n indicates within how many standard deviations the students' scores are distributed (usually 2, 2.5, or 3) and i is an index that varies between 1 and the number of answer choices of a given question plus 1, to include the not given answers. In our case i varies between 1 and 5. In general, integrals of IRC are correlated to the percentage of students picking the corresponding answer choice (Fig. 1). The integral defined in Eq. (1) approximates the average probability for students to pick the ith answer choice of a question because one can prove that

$$\frac{1}{2n\sigma}\sum_i I_i^{\mathrm{IRC}} = 1. \tag{2}$$

Note that the integral is not estimated from the model but numerically calculated from raw data.

The first advantage of using the integral of the IRC is to easily rank levels of the learning progression. In particular, levels near the upper anchor of the learning progression should have lower values of the integral of the corresponding IRC.

The second advantage is that levels of the three phenomena with similar integral values can be grouped into *cluster levels*, because they present the same degree of difficulty for the students. If the progress indicators of these cluster

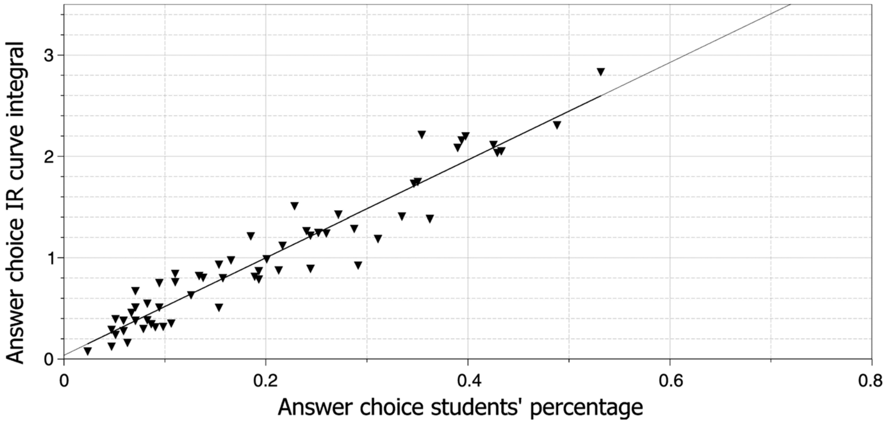

FIG. 1. Correlation between the IRC integral of an answer choice and the percentage of students who picked it. Data in the plot are from the present study. The solid line shows a best fit to the data. The slope is 4.8 ± 0.2, which approximates the range of student' scores measured in standard deviations.

levels resume common features of the original progress indicators, then a single learning progression that completely describes students' reasoning about the addressed phenomena can be hypothesized and assessed. To this aim, IRC for each cluster level can be obtained by averaging the percentage of students corresponding to the original levels.

Finally, the integral of the IRC of the cluster levels can be used to assess the sequence of the levels of the resulting learning progression.

C. Sample

The two-tier questionnaire was submitted to 300 Italian secondary school students at the beginning (14 years old) and at the end of secondary school (18 years old). The assumption for the sample choice was that the involved students should have concluded their learning path about the target phenomena as envisioned by the National Curriculum Indications.

All the students had hence already studied the target topics using only curriculum-based materials (mainly textbook-based instruction, no specific teaching materials were given). The students were from the same school and had the same teachers (biology, chemistry and earth sciences; mathematics and physics) to limit as much as possible the influence of the context. One hour was given to complete the questionnaire in an anonymous form.

IV. FINDINGS

A. Overall results

Out of the 300 collected questionnaires, only 254 were considered valid: 114 of first class students, 140 of fifth class students. We had to throw out from the analysis 46 questionnaires because they missed information about the class attended by the students. With the adopted scoring system, the mean score was 16.4 ± 3.9, which indicates that on average only 55% of the students' answers were correct. Specific scores for the three phenomena and the two groups of students (1st and 5th class) are reported in Table II.

Cronbach's alpha for all the items (true-false and multiple choice) was 0.76, which can be considered satisfactory. However, the Cronbach's alpha for only the solely multiple choice questions was 0.50. This low value does not imply that these questions were not valid—it could reflect the fact that our sample was quite homogenous in its knowledge about the target concepts. Clearly the true or false questions increased the variance of the total score and hence of the alpha value.

Difficulty, discrimination, and point biserial indices for all 48 questions are reported in Table III. Multiple choice questions are indicated in bold face. The average values of these indices are 0.59, 0.31, and 0.27, respectively. All the

TABLE II. Basic statistics of the questionnaire.

	Total		Seasons		Phases		Eclipses	
Class	1st	5th	1st	5th	1st	5th	1st	5th
Mean	14, 55	17, 98	4, 89	6, 06	4, 45	6, 00	5, 21	5, 91
Standard error	0, 29	0, 32	0, 13	0, 13	0, 15	0, 17	0, 13	0, 12
Median	14, 5	17, 5	5	6	4, 5	5, 5	5, 5	6
Standard deviation	3, 14	3, 79	1, 42	1, 53	1, 57	2, 01	1, 44	1, 43
Range	17	16	7	6, 5	8, 5	8	7, 5	7, 5

TABLE III. Psychometric indices of the questionnaire. Multiple choice questions are indicated in bold face.

Item	Difficulty (25%)	Discrimination	Point Bi-Serial	Item	Difficulty (25%)	Discrimination	Point Bi-Serial
Q1	0, 76	0, 46	0, 43	Q25	0, 65	0, 41	0, 35
Q2	0, 80	0, 30	0, 31	Q26	0, 61	0, 42	0, 36
Q3	0, 80	0, 36	0, 37	Q27	0, 76	0, 37	0, 36
Q4	**0, 24**	**0, 12**	**0, 12**	**Q28**	**0, 39**	**0, 41**	**0, 34**
Q5	0, 80	0, 27	0, 25	Q29	0, 67	0, 39	0, 35
Q6	0, 43	0, 01	0, 02	Q30	0, 73	0, 40	0, 32
Q7	0, 42	0, 02	0, 02	Q31	0, 73	0, 22	0, 19
Q8	**0, 44**	**0, 46**	**0, 36**	**Q32**	**0, 11**	**0, 30**	**0, 37**
Q9	0, 70	0, 31	0, 29	Q33	0, 81	0, 42	0, 41
Q10	0, 83	0, 27	0, 27	Q34	0, 80	0, 38	0, 36
Q11	0, 43	0, 19	0, 18	Q35	0, 71	0, 30	0, 25
Q12	**0, 49**	**0, 59**	**0, 44**	**Q36**	**0, 40**	**0, 18**	**0, 12**
Q13	0, 81	0, 32	0, 31	Q37	0, 56	0, 44	0, 34
Q14	0, 62	0, 26	0, 23	Q38	0, 61	0, 14	0, 10
Q15	0, 85	0, 12	0, 12	Q39	0, 32	−0, 02	−0, 01
Q16	**0, 23**	**0, 31**	**0, 31**	**Q40**	**0, 54**	**0, 56**	**0, 40**
Q17	0, 65	0, 54	0, 37	Q41	0, 54	0, 25	0, 24
Q18	0, 71	0, 29	0, 29	Q42	0, 47	0, 04	0, 03
Q19	0, 63	0, 32	0, 29	Q43	0, 81	0, 20	0, 22
Q20	**0, 35**	**0, 62**	**0, 51**	**Q44**	**0, 43**	**0, 33**	**0, 17**
Q21	0, 74	0, 37	0, 36	Q45	0, 78	0, 39	0, 31
Q22	0, 63	0, 26	0, 22	Q46	0, 60	0, 02	−0, 02
Q23	0, 56	0, 46	0, 36	Q47	0, 59	0, 20	0, 17
Q24	**0, 40**	**0, 53**	**0, 46**	**Q48**	**0, 44**	**0, 45**	**0, 34**

questions have an acceptable difficulty index (between 0.2 and 0.8) except question Q32, which concerned how Moon phases are seen from different places on Earth. As far as discrimination and point biserial indices, we notice different results for multiple choice and true-false questions. Only two of the multiple choice questions (one about seasons, the other about lunar and solar eclipses) have an index lower than 0.2, which indicates that the item was difficult for both high and low achievers. Eight true-false questions had indices lower than 0.2—four concerned seasons, the other eclipses. Plausibly, also these low discriminating questions led to a lower than expected value of reliability for the questionnaire.

When looking at the questions, we realized that the seasons' questions concerned statements about the influence of the environment on the temperature of a place on Earth. Plausibly, although part of the curricular instruction about seasons, this topic was not part of school teaching. The eclipses questions contained common textbook images, which plausibly resulted to be too complex for the students of our sample.

B. Item response analysis

A Wright map of the questionnaire is reported in Fig 2. Each x represents 3 students, each row is 0, 255 logits.

The map suggests that the persons' abilities are well distributed over the range of the questions' difficulties; except for one item (Q32: *Which is the Moon phase seen by a Canadian when, in Italy, you can see the Moon at its first quarter?*). The average ability estimate is 0.44 logits (SE = 0.03). Hence, the questionnaire was suitable for the students of the sample. No misfitting items were found. The infit and outfit mean square values were between 0.8 and 1.2 for all the questions, within the acceptable range 0.7–1.3 [79]. Values of 1.4 would have indicated 40% more variability than predicted by the Rasch model. Participants' responses were also consistent with Rasch model expected randomness: the average infit mean square was 1.0 (SD = 0.10) while the mean outfit was 0.99 (SD = 0.04). Person separation reliability, which represents the distribution of the participants' abilities across the

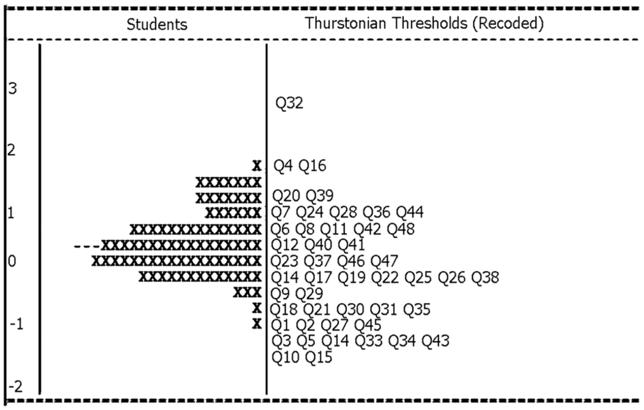

FIG. 2. Wright map of the questionnaire used in the study.

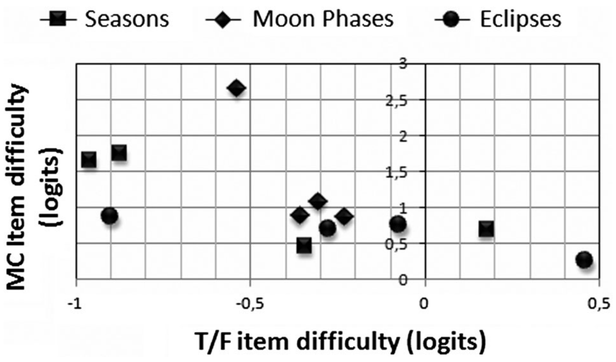

FIG. 3. Relationship between the mean difficulty of the first and second tier of the questionnaire.

questionnaire, was moderate (0.66), likely due to some items that were difficult for both high and low ability students. Overall, such results suggest an adequate fit of the Rasch model to our data and support the validity of lumping in the same questionnaire the three related topics.

The mean difficulty of the second tier (multiple choice questions) as a function of the mean difficulty of the first tier (true-false questions) for the 12 items of the questionnaire is reported in Fig. 3.

The difficulties of the two tiers are weakly correlated ($r = -0.61$, significant at 0.05 level) as all multiple choice questions were significantly more difficult with respect to (w.r.t.) true-false ones [as measured by a *t test*, $t(46) = -6.424$, $p < 10^{-4}$]. This result, common to all the three target phenomena, implies that students of our sample knew most of the facts at the basis of the target phenomena, but they were mostly not able to use them when choosing a possible explanation.

IRC for the change of seasons are shown in Fig. 4. As the minimum raw score was 7 and the maximum score 26, the students' scores fall into approximately ±2.5 standard deviations. The four curves refer to the correct answer choices of the four multiple choice questions about this phenomenon—Q4 about Earth's motion along the orbit (*The main factor for which summer and winter alternate is…?*), Q8 about solar ray inclination (*The reason for which in Italy during summer is hotter than in winter is that during summer …?*), Q12 about axis' tilt and Earth's motion along the orbit (*"What causes the changes in the inclination of solar rays on the Earth surface during the year?"*), and Q16 about the constant direction in space of the axis (*Which of the following statements best explains the phenomenon of the different seasons?*). The other two curves refer to incorrect answer choices of *all* the four questions, namely, those related to an Earth-Sun distance-based explanation and to the idea that Earth's axis changes direction or inclination. The six curves have a quasi-increasing trend and provide useful information. In particular, a qualitative analysis shows that only about 40% of the low ability students correctly think that the Sun-Earth distance does not influence seasons' change, while, as expected, this percentage increases up to 80% for high ability students.

Rather surprisingly, the percentage of high ability students who think that the inclination of Earth's axis does not change during the year is not significantly higher than the corresponding percentage of low ability students. This result suggests that students may correctly claim that the tilt of the axis influences seasons' change but may be confused about why and how such tilt causes seasons [16]. In particular, students found difficult to relate the "energy" received by Earth and the different conditions under which solar light hits Earth's surface [70].

Furthermore, our method may give some insights about the students' difficulty. We note that the curve related to the correct answer choice of Q12 (*The revolution of the Earth around the Sun and the inclination of the Earth's axis with respect to orbit's plane*) has an integral value that is higher than the curve related to the incorrect answer choices about the direction and inclination of Earth's axis. The meaning of this finding is that few high-ability students chose the correct answer choice of Q12 and did *not* chose wrong answer choices related to Earth's axis in the other three

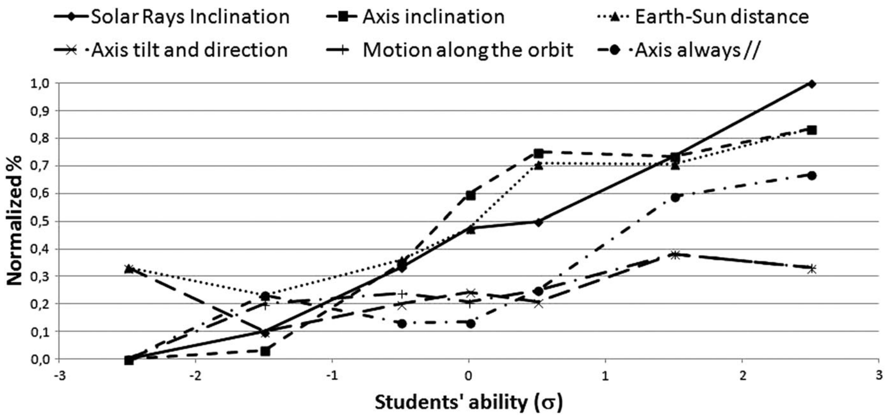

FIG. 4. Item response curves for seasons' change items.

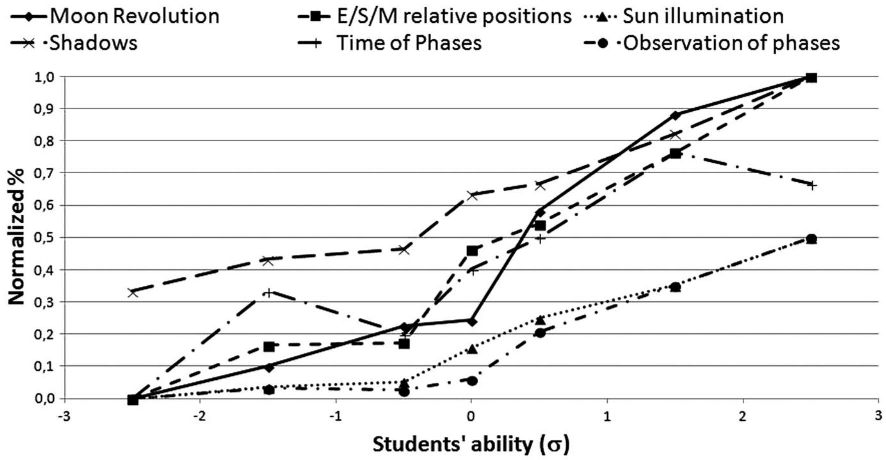

FIG. 5. Item response curves for Moon phases items.

questions. This trend supports the evidence that even high ability students were not able to relate seasons' change to both the axis constant tilt *and* Earth's motion along the orbit.

The curves for Moon phases and eclipses are shown in Figs. 5 and 6. The analysis of the curves for the Moon phases shows that, as expected, the shadow misconception disappears as the student's ability increases. However, only 50% of high ability students were able to recognize the role of the Sun's illumination in the phenomenon, and, as a consequence, that the same phase of the Moon is visible from the locations on Earth that can see the satellite at that time.

Finally, about 40% of low ability students were able to recognize the alignment of the Sun, Moon, and Earth as the condition needed for an eclipse to happen. Most of the high ability students (80%) were able to indicate the reasons for the periodicity of the phenomenon, but only 67% were able to explain why eclipses are seen from a small portion of Earth's surface.

C. Revision of the initial learning progressions

The IRC integrals for the change of seasons are reported in Table IV. Values of the integrals should be divided by 5 to get the probability of picking the correct answer choice (s). The obtained values do not confirm the hypothesized level sequence of the learning progression (see Table I).

While the distance misconception has the greatest value of IRC integral (2.562) as expected, the axis variable tilt misconception and the role of revolution motion along the orbit (Level 1) have the smallest values of the integral (1.244 and 1.220). Similarly, the value of the integral corresponding to level 3 is greater than that of level 2. Hence, such analysis led us to modify and refine the hypothesized learning progression about seasons' change, as reported in Table V. For the sake of coherence, we changed also the progress indicators formulation. Our findings suggest that the most difficult concept for the students to grasp in understanding the mechanism underlying change of seasons is to bring together the notion of the tilted axis with its constant direction in space and Earth's revolution around the Sun.

Changes made to the learning progressions for eclipses and Moon phases were less significant. For the Sun and Moon eclipses, we included in the upper anchor of the revised version also the knowledge that, due to the scale of the Sun-Moon-Earth system and the conditions for the alignment of the Sun, Moon, and Earth orbits' planes,

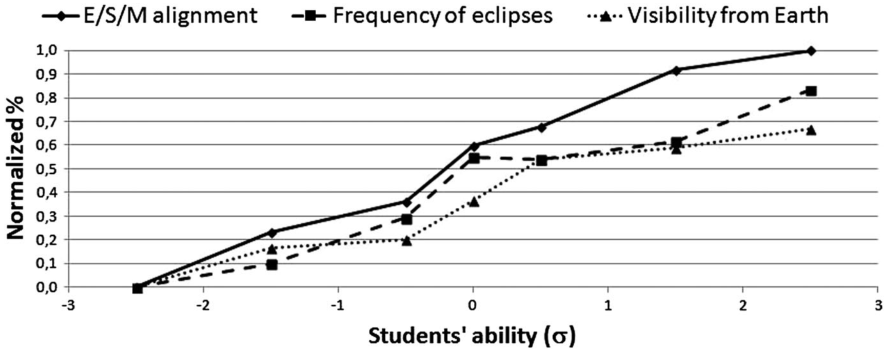

FIG. 6. Item response curves for eclipses items.

TABLE IV. Values of IRC integrals for learning progression about seasons' change.

Level	Progress indicator	IRC integral
Naïve idea	Changing distance between Sun and Earth influences seasons' change	2.562
Naïve idea	Earth's axis change inclination w.r.t. orbit's plane and direction in space	1.244
1	Seasons are due to inclination of solar rays that changes during the year	2.198
2	Level 1 + the revolution of Earth around the Sun	1.220
3	Level 2 + tilt of Earth's axis	2.307
Upper anchor	Level 3 + Earth's axis constant direction in space	1.509

eclipses do not happen frequently and are visible only from a small portion of Earth's surface. For the Moon phases, we note that the dependence of the phases on the relative positions of Earth, Sun, and Moon was easily recognized by the students and hence we moved this condition down to level 1 of the learning progression. However, we added to the upper anchor the knowledge that the same phase is visible from Earth locations that can see the Moon, which is a consequence of illumination conditions of the Moon surface.

D. Cluster levels

To construct the cluster levels as defined in Sec. III, we performed the analysis of the IRC integral also for the questions addressing Moon phases and solar or lunar eclipses. Overall results for the three phenomena are reported in Table VI.

First of all, we note that the distribution of values of the IRC integrals clearly reflects the different results obtained by students in answering the questions about the three topics. For instance, levels near the upper anchor of the learning progression about solar and lunar eclipses are easier than the corresponding levels of the Moon phases and seasons' change.

Second, we note that the progress indicators of the original learning progression levels, grouped according to their IRC integral values, have the following common features (see Table VI):

(i) Levels with a value of the integral greater than 2.5, which corresponds to a probability of more than 50% to be picked by students, concern explanations of the target phenomena based on *naïve ideas*, as the "distance" or the "shadow" misconception (lower anchor);

(ii) Levels with an integral values between 2 and 2.5 (probability from 40% to 50%) concern explanations of the three phenomena based on causal reasoning as, for instance, the tilt of Earth's axis causes different locations on Earth's surface to receive a different amount of sunlight flux (seasons); the revolution of the Moon around Earth causes changes in the lighted portion of the Moon's surface (Moon phases);

(iii) Levels with an integral value between 1.5 and 2 (probability from 30% to 40%) concern simple implications that students can include in their reasoning starting from the above explanations. In this case, students use both causal and spatial reasoning to relate different variables that describe the phenomenon. For instance, different amounts of sunlight reaches locations on the surface of Earth during the year because Earth's axis is inclined and does not change its direction in space during the revolution of Earth around the Sun (seasons); the alignment of Earth, Sun, and Moon depends on the relative inclination between the Moon and Earth orbits' planes; hence, Moon and solar eclipses do not happen frequently (eclipses); because the Moon orbits with a given period around Earth, the observed phases of the Moon are a periodical phenomenon (Moon phases);

(iv) Finally, levels with integral values lower than 1.5 (probability less than 30%) require more sophisticated implications based on both causal and spatial reasoning about the three phenomena. At this level, for instance, students are able to combine Earth's axis inclination, constant direction, and revolution motion to justify the different amount of sunlight that reaches Earth's surface (seasons); explain that temperature at a given location depends on the sunlight flux received and on the environment (seasons); recognize that the same Moon phase is visible from Earth locations that can see it at a certain time because the satellite's appearance from Earth's perspective depends on the Sun illumination and on the relative positions between the Sun,

TABLE V. Modified learning progression about change of seasons.

Level	Progress indicator
1	Seasons are due to Earth's axis inclination w.r.t. the orbit's plane
2	Level 1 + the inclination of solar rays changes during the year
3	Level 2 + constant direction in space of Earth's axis
Upper anchor	Level 3 + revolution of Earth around the Sun and constant tilt of Earth's axis w.r.t. orbit's plane

TABLE VI. Construction of the cluster levels for the seasons, Moon phases, and solar and lunar eclipses.

	Progress indicators		
Value of IRC integral I	Seasons	Moon phases	Solar or Lunar eclipses
$I > 2.5$	Changing distance between Sun and Earth influences seasons' change	Moon phases are due to Earth's shadow or of other planets	Eclipses are due to celestial bodies between Sun, Moon and Earth
$2 < I < 2.5$	(i) Seasons are due to Earth's axis inclination w.r.t. orbit's plane (ii) Being Earth's axis inclined, also the inclination of solar rays changes during the year	(i) Moon phases are due to Moon revolution (ii) Moon phases depend on the relative positions between Earth (E), Sun (S) and Moon (M)	Eclipses happen when Sun, Moon and Earth are aligned
$1.5 < I < 2$	The different inclination of sunrays is also due to the constant direction in space of Earth's axis	Revolution of Moon and the relative positions between E, S and M determine a given periodicity of the Moon phases	As the S-M-E alignment happens in a 3D space, eclipses depend also on the relative inclination between Moon and Earth orbit's planes; hence, they do not happen frequently
$1 < I < 1.5$	(i) As the axis always points in the same direction, it does not change inclination with respect to orbit's plane (ii) The different inclination of sunrays is due to the Earth that has changed position along its orbit		As eclipses depend also on the distance between Moon, Earth and Sun and on the relative dimensions of the three bodies, the solar eclipses are visible only from a small portion of the Earth and the lunar eclipses from the Earth hemisphere where it is night.
$I < 1$		(i) The relative positions between E, S and M determine how the Moon surface is illuminated (ii) Being illumination of Moon surface dependent on the relative positions between E, S and M, the same phase is visible from all the Earth	

Moon, and Earth (Moon phases); justify why solar eclipses are visible from a small portion of Earth using the spatial scale and proportions of the Sun-Moon-Earth system.

These clustered progress indicators completely define the levels of a new learning progression, which tie the three phenomena (Table VII).

The IRC of the cluster levels are reported in Fig. 7.

The curves were obtained by averaging, for each level of ability, the values of the students' percentage in the original levels. The integral analysis (see Table VII) supports the proposed sequence of the clustered levels of the learning progression common to the three phenomena.

TABLE VII. Learning progression about Celestial Motion.

Level	Progress indicator	IRC integral
Lower anchor	Explanations based on naïve ideas: Lack or insufficient knowledge about Earth-Sun distance, and about the motion of the Moon around the Earth and the Sun.	3.291
1	Explanations from basic facts: Knowledge of plane geometry conditions, and of E-S-M positions and motion.	2.361
2	Explanations with simple implications from basic facts: Knowledge of Earth's surface illumination conditions, and of the frequency of Moon phases and eclipses phenomena.	2.130
Upper anchor	Explanations showing more complex reasoning: Knowledge of 3D geometrical features of the Sun, Moon, and Earth motion, and of how change of the observer's perspective may change the description of the phenomena.	1.265

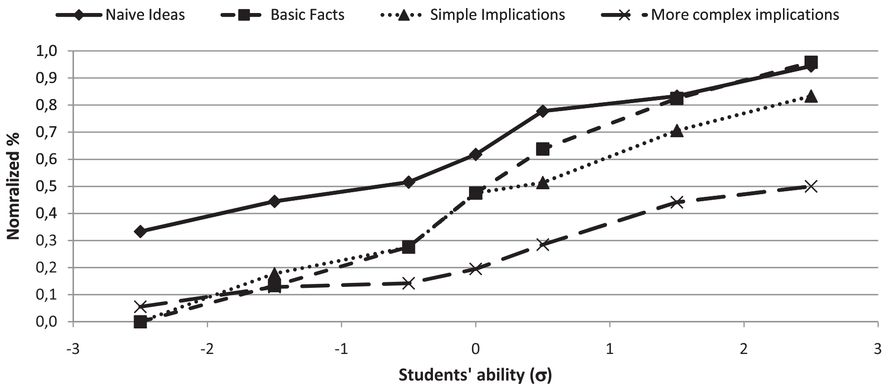

FIG. 7. IRC for cluster levels of the learning progression about change of seasons, Moon phases, and solar or lunar eclipses.

V. CONCLUSIONS

The first aim (RQ1a) of the study was to provide details of an initial cycle of empirical validation and subsequent revision of three learning progressions about basic aspects of the Celestial Motion big idea—seasons, phases, eclipses.

Differently from the previous studies, we chose to validate the initial learning progressions focusing on the Italian curricular instruction about the chosen topics, as done by Neumann and colleagues [13]. The main reason was that this study is the first effort of its kind carried out in Italy; hence, at this stage of the research, we were interested in investigating outcomes of astronomy teaching as it happens in classrooms.

First of all, coherently with most of the existing literature, our study supports that students' conceptions about the target astronomy phenomena improve with school instruction. Plausibly, the students of the fifth classes in our sample had been exposed to a more quantitative teaching about the three phenomena, and also to some physics; more complex topics of astronomy (stars' structure, cosmology) are also present in the national curriculum. Hence, the better achievements of older students may be due to additional instruction, although we cannot argue more from our data.

Despite such differences, however, the average percentage of correct answers for students at the end of secondary school does not exceed 60%, a percentage that is coherent with previous similar studies about students of the same school grade in other countries [32,42]. Concerning differences among the three phenomena, we note that for the first classes, questions about Moon phases were the most difficult (4.45 out of 10), while the lowest average score of the fifth class students concerned questions about eclipses (5.91 out of 10). Such results add empirical evidence to the progression put forth in Ref. [20], suggesting that curricular instruction plausibly provides only basic explanations of astronomy phenomena, not focusing on more specific implications of the motion of the Sun-Earth-Moon system.

Second, the initial hypothesized progressions were only partially supported by data. In particular, for change of seasons, we had hypothesized that students would have related the change of inclination of solar rays first to the revolution of Earth and then to the tilt of Earth's axis and finally to the axis' constant direction in space. However, this sequence was not supported by students' answers to the questionnaire, resulting in a progression that relates seasons first to the axis tilt and then combines this notion with the changing positions of Earth along its orbit. A plausible reason may be that to recognize how sunlight flux on Earth's surface changes when Earth is moving along the orbit requires a reasoning which involves at the same time physics and geometrical considerations. Similarly, for Moon phases, we had hypothesized that the upper anchor of the progression would have corresponded to the knowledge that the Moon phases depend on the relative positions of Earth, Moon, and Sun. Contrarily to this hypothesis, we found that also low ability students hint at relationships between Moon phases and the changing position of the satellite in the Sun-Earth-Moon system. However, most of the students were not able to correctly derive the different illumination conditions from the knowledge of Moon motion; moreover, only high ability students correctly recognized that a phase shape is independent of the position on Earth of an observer that can see the Moon. Also in this case, geometrical and scale considerations may play a relevant role in students' making sense of everyday experiences.

Such results suggest that similar cognitive factors may inform students' understanding of the three phenomena (RQ1b). The new learning progression constructed with the method of the IRC integral (Table VII) supports that spatial reasoning is a key dimension for building an explanatory framework for relevant phenomena of the Celestial Motion big idea [16,19,81,82]. However, our analysis adds to the literature showing that at least one other important cognitive variable concurs in building a more complete explanatory framework for the target phenomena, namely, causal reasoning based on the physics underlying the phenomena, as propagation of light, radiation flux laws, and energy transfers. Such a further cognitive variable informs intermediate cluster levels between the naïve ideas and upper anchor. The first level, which concerns a basic explanation of the three phenomena, includes what other authors call "Earth Perspective" [14,15] or "observational knowledge" [16]. Different from previous learning progressions, the focus is on how the students, using basic causal reasoning, may infer a first explanation of the phenomena starting from their observations. The second level, that involves simple implications from the basic facts, includes what is called "Space Perspective" by Sneider, Bar, and Cavanagh [15]. Such a perspective requires the students to use both causal and spatial reasoning to enrich their explanations of the phenomena also involving some physics mechanisms.

The upper anchor is mainly described by the capability of using spatial thinking in a more sophisticated way, as suggested by Plummer in Ref. [19]. Students at this level are able to mentally visualize the motions of Earth, Sun, and Moon, and manipulate them to describe consequences of the changes in the system configuration. However, our findings add that the students at this level can also make inferences about the physical relationships that are relevant for the explanation of the target phenomena using geometrical features of the Sun-Earth-Moon system. An example is the relationship between the change of the sunlight flux on Earth's surface, the temperature change, and the motion of Earth along its orbit.

To the latest concern, we note that, according to some authors [83], spatial thinking is strictly related to the capability of extracting information about the behavior of a physical system from 2D representations (as images are). The analysis of the IRC of the 13 questions that featured one or more images (integral $= 0.9378$, the lowest among the values of the IR curves) suggests that students at the upper level of the learning progression are able to fruitfully interpret images of the phenomena. This is in agreement with the results of the study by Kozhenivkov and colleagues [55], who found that "high-spatial" ability students spent more time in decoding iconic features (arrows, lines, labels, etc.) of the images used in the kinematics problems, while "low-spatial" ability students described graphical representation of objects' motions as pictures, thus not translating visual patterns into conceptual relations [84]. Insofar as the role of image reading has to be studied with more compelling evidence in the next step of the research, our findings, in agreement with previous studies [85–92], suggest that also the capability of reading images may influence how students, during instruction, progress in their learning about Celestial Motion, as it happens also in other areas of science [59,93].

The second aim of the study (RQ2) was to investigate whether the designed questionnaire and analysis method were effective to investigate students' understanding of the target phenomena. The analysis of questionnaire statistics, classical and based on the Rasch model, revealed that the instrument is sufficiently reliable and able to discriminate between low and high ability students. Our analysis led to revise the initial learning progressions and construct the *cluster* levels, which contain common features of the original single-phenomenon progress indicators, thus contributing to the development of a learning progression about the Celestial Motion big idea. Such effort would be important to inform additional research on learning progressions about other big ideas in astronomy and astrophysics, sporadically or not yet completely studied in science education literature, as the properties and formation of stars [94], cosmology [95], or galaxies [96].

The main implication of this study concerns the teaching of the Celestial Motion big idea. In particular, the new learning progression informs a teaching-learning sequence that integrates different aspects of the motion of Earth and the Moon around the Sun in order to construct a more coherent explanatory framework. In particular, the cluster levels (Table VI) may inform teaching aims to be fulfilled with suitable activities.

Instruction starts by eliciting students' ideas about seasons, eclipses, and Moon phases and by illustrating to the students how the geometry (essentially plane trajectories) and the time dependence of the Earth and Moon motions around the Sun influence the three phenomena. Further activities may include quantitative considerations about Earth's orbit or Kepler's laws.

Then, it is possible to introduce some *causal* reasoning to explain the basic physics mechanisms behind the phenomena showing, for instance, (i) for seasons and Moon phases, how the motion of the whole system influences different illumination conditions of Earth or the Moon, or (ii) for seasons, how the composition of environment influences the energy transfers between radiation and the environment itself. Activities that may support students include imagining consequences to seasonal changes if Earth's axis would be not tilted [15] and the study of the yearly temperature changes for different places on Earth [14,16]. In a recent paper by our group [97], drawing from studies in physics education about light [70] and heat and temperature [98] we propose to integrate these activities with quantitative experiments about sunray flux cosine and inverse square distance laws, and about the role of specific heat in thermal interactions. Such activities may help students deepen the qualitative explanatory framework proposed for the middle school level in Refs. [14–26] and explain why (i) inclination of a surface affects the intercepted radiation flow; (ii) at the northern regions of Europe, despite having at summer solstice very long days, the temperature does not increase up to the level of southern Europe; or (iii) the temperature pattern in zones near the sea is different from where there is only soil.

Finally, explanations can be enriched by including 3D demonstrations and virtual modeling [99,100] and a description of the phenomena from Earth and the space perspective to understand how rotation and revolution can change the appearance of the celestial bodies. Throughout the proposed activities, particular emphasis should be put also on correct interpretation of images about the phenomena.

A second implication of this study concerns the development of learning progressions. We found that it was possible to identify a single learning progression combining the levels of three initial progressions of different but related phenomena. The students' progression across the newly defined levels can be effectively described not only by the increasingly sophisticated knowledge and use of explanatory models, but also by a more refined use of cognitive abilities such as spatial thinking and causal reasoning. As a consequence, our findings suggest that the teaching of apparently disconnected phenomena related to a given big idea or core concept may be better coordinated and sequenced, helping students to develop scientific explanations that exploit cross-cutting cognitive abilities. This study shows that issues related to fragmented teaching of contents within the same science discipline can hence be fruitfully addressed using a learning progression research approach, shifting the instructional focus from isolated facts towards a more coherent selection and reorganization of different aspects of the target core concepts.

VI. LIMITATIONS OF THE STUDY

This study has two main limitations: First, we cannot claim that students would necessarily progress from the "naïve ideas" level to the upper anchor exactly across the identified cluster levels. This limitation is mainly due to the instrument used: although built on previous open-ended tasks (including interviews), we could have gained more insights about students' reasoning strategies with postsubmission interviews. However, the cluster levels we identified in this study may represent a useful basis to describe also alternative successful learning progressions.

Second, our findings may be dependent on the national educational context. The new learning progression better fits with the Italian school system, where students usually start a more systematic study of astronomy at secondary school (14 years old) and integrate what is taught in the chemistry, biology, and earth science subjects later with physics lessons. Hence, in our educational context, the proposed learning progression may help to systematically align the astronomy and physics curriculum, instruction, and assessment. However, the questionnaire can be useful to extend our research also to other countries to investigate the extent to which the proposed learning progression depends on the country-specific science curriculum.

ACKNOWLEDGMENTS

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APPENDIX: QUESTIONNAIRE USED IN THE STUDY

(True statements are in bold face)

Indicate, for each of the following statements, if it is true or false

Q1 The Sun produces more energy during summer than during winter

Q2 **When a surface is lighted up by a light source, the energy absorbed by the surface is maximum when light hits the surface perpendicularly**

Q3 **Solar rays' incidence on the Earth's surface changes during the year**

Q4 The main factor for which summer and winter alternate is (please indicate the correct one):

(i) The distance between Sun and Earth changes during the year, so the incidence of solar rays on the Earth's surface varies

(ii) The inclination of the Earth's axis with respect to the orbit plane changes during the year, therefore the incidence of the solar rays on the Earth surface varies

(iii) Earth's axis direction in space changes during the year therefore the incidence of the solar rays on the Earth's surface varies

(iv) **Earth's position along its orbit changes during the year, therefore the incidence of the solar rays on the Earth's surface varies**

Indicate, for each of the following statements, if it is true or false

Q5 Earth's surface absorbs energy from the Sun

Q6 In a certain place of the Earth the temperature depends on energy transfers with the environment

Q7 In a certain place of the Earth the absorbed energy depends on the atmosphere's thickness

Q8 The reason for which in Italy during summer is hotter than in winter is that during summer …? (please indicate the correct one):

(i) the Earth is closer to the Sun and the day lasts more than in winter

(ii) the inclination of the Earth's axis changes

(iii) **solar rays are less inclined and the day is longer**

(iv) the Sun produces more energy

Indicate, for each of the following statements, if it is true or false

Q9 Earth's axis precesses during the year

Q10 Earth's axis is inclined with respect to the Earth's orbit plane

Q11 Earth's axis remains parallel to itself during the year

Q12 Some students answer to the question: “What causes the changes in the inclination of solar rays on the Earth surface during the year?” with the following answers. Who is right? (please indicate the correct one):

(i) The revolution of the Earth around the Sun and the change of the Earth-Sun distance
(ii) **The revolution of the Earth around the Sun and the inclination of the Earth’s axis with respect to orbit’s plane**
(iii) The inclination of the Earth’s axis with respect to the orbit’s plane and its oscillation
(iv) The change of the Earth-Sun distance and the fact that the Earth axis is perpendicular to the orbit plane

Indicate, for each of the following statements, if it is true or false

Q13 Earth’s motion around the Sun is a periodic motion on a closed orbit

Q14 Earth’s orbit around the Sun is a very eccentric ellipse

Q15 Season periodicity is due to the revolution of the Earth around the Sun

Q16 Which of the following statements best explains the phenomenon of the different seasons? (please indicate the correct one)

(i) During the revolution, the distance between the Earth and the Sun changes so, in a certain places of the Earth, solar rays do not always have the same incidence on the surface
(ii) During the revolution, the direction of the Earth’s axis changes so, in a certain place of the Earth, solar rays do not always have the same incidence on the surface
(iii) **During the revolution, Earth’s axis remains parallel to itself so, in a certain place of the Earth, solar rays do not always have the same incidence on the surface**
(iv) During revolution, Earth’s axis is always perpendicular to the orbit plane so, in a certain place of the Earth, solar rays do not always have the same incidence on the surface

Indicate, for each of the following statements, if it is true or false

Q17 The Moon rotates on itself for about the same time it takes to rotate around the Earth

Q18 The period of revolution of the Moon around the Earth is about one month

Q19 The Moon rotates around the Earth and the Sun

Q20 Which is the cause of the different Moon phases? (please indicate the correct one)

(i) **The revolution of the Moon around the Earth and how solar rays hit Moon’s surface**
(ii) The revolution of the Moon around the Earth and the revolution of the Earth around the Sun
(iii) Earth’s motion and how solar rays are reflected by Moon surface
(iv) The shadow of clouds and planets between the Earth and the Moon and the revolution of the Earth around the Sun

Indicate, for each of the following statements, if it is true or false

Q21 The *New Moon* phase occurs approximately every two weeks

Q22 During a Sun eclipse, Moon is in the *New Moon* phase

Q23 Referring to the picture (Fig. 8), the phase of *New Moon* occurs when the Moon is in the position E and the sunlight comes from the left

Q24 During the *New Moon* phase, the Moon is not visible by an observer on the Earth. This happens because (please indicate the correct one):

(i) The Moon is between the Earth and a celestial body that prevents the sunlight from lighting up the Moon
(ii) With respect to the Earth, the Moon is on the same side of the Sun, whose light covers the weak light of the Moon
(iii) Earth’s shadow covers the Moon, obscuring it
(iv) **With respect to the Earth, the Moon is on the same side of the Sun that lights up Moon hidden face**

Indicate, for each of the following statements, if it is true or false

Q25 The Moon completes its phases in lesser time than that necessary to complete its revolution around the Earth

Q26 The Moon completes its phases in a time approximately equal to that necessary to complete its revolution around the Earth

Q27 The Moon completes its phases in more time than that necessary to complete its revolution around the Earth

Q28 An evening you observed that the Moon appeared as in the (Fig. 9)

How much time will pass before you could see it as shown in the (Fig. 10)? (please indicate the correct one):

(i) About one day
(ii) **About one week**
(iii) About two weeks
(iv) About one month

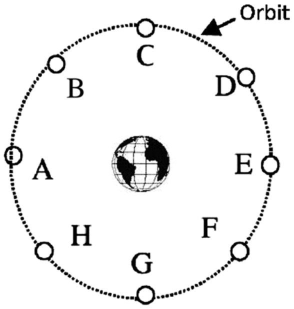


FIG. 8. Phases of the Moon.

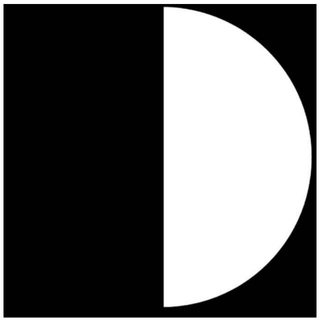


FIG. 9. First quarter—I.

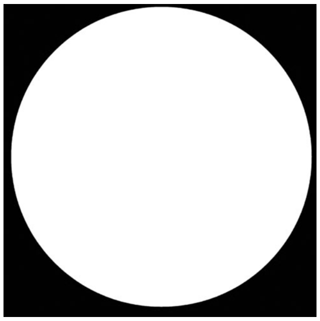


FIG. 10. Full Moon.

Referring to the picture (Fig. 11), indicate, for each of the following statements, if it is true or false

Q29 The time required to the Moon to move counter-clockwise from position A to position B is of approximately two weeks

Q30 When the Moon is in the position A it appears as in the (Fig. 12)

Q31 When the Moon is in the position B it appears as in the (Fig. 13)

Q32 Which is the Moon phase seen by a Canadian when, in Italy, you can see the Moon at its first quarter? (please indicate the correct one):

(i) **The same because we are in the same day**
(ii) A different one because the lighting of the Sun changes depending on where we are on the Earth's surface
(iii) The same because we are in the same hemisphere

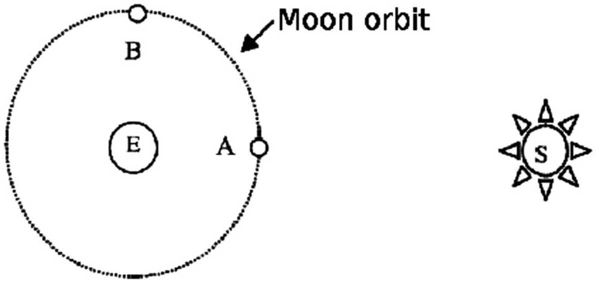


FIG. 11. Moon orbit.

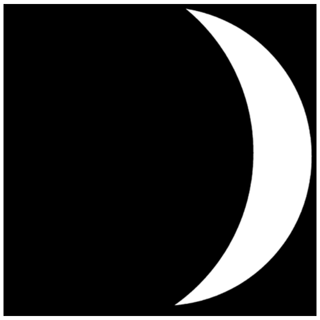


FIG. 12. Waxing crescent.

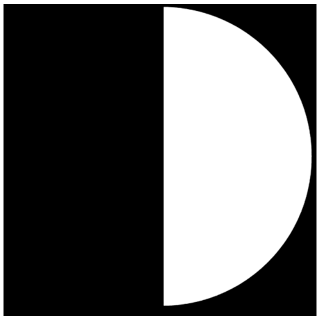


FIG. 13. First quarter—II.

(iv) A different one because the enlightened portion of the visible Moon face changes depending on where we are on the Earth's surface

Indicate, for each of the following statements, if it is true or false

Q33 The Moon orbit's plane is inclined with respect to the Earth's orbit plane

Q34 The Moon orbit's plane is perpendicular to the Earth's orbit plane

Q35 The Moon's orbit intersects the Earth's one

Q36 Which is the cause of a total Moon eclipse? (please indicate the correct one)

(i) **The alignment of the Earth, the Sun and the Moon**
(ii) The Earth's shadow
(iii) The Sun that obscures the Moon
(iv) The inclination of Moon's orbit plane with respect to the Earth's one

Referring to the picture (Fig. 14), indicate, for each of the following statements, if it is true or false

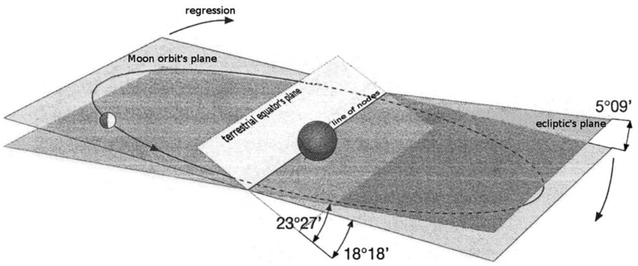
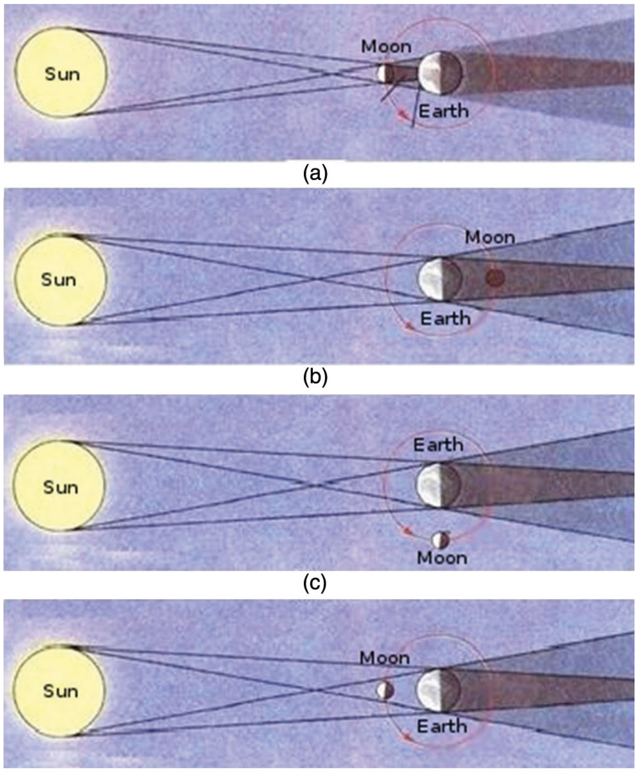


FIG. 14. Line of nodes.



(a)

(b)

(c)

(d)

FIG. 15. Solar and lunar eclipses—I.

Q37 Moon orbit's plane is inclined by 18°18′ with respect to the ecliptic's plane

Q38 The ecliptic is inclined by 5°09′ with respect to the Earth equator

Q39 The line of nodes is inclined by 23°27′ with respect to the ecliptic's plane

Q40 Why solar and lunar eclipses do not occur every months? (please indicate the correct one)

(i) Moon orbit's plane is inclined with respect to the Earth equator's plane
(ii) **The Sun, the Earth and the Moon are aligned only when they are along the line of nodes and this does not occur every month**
(iii) The distance between the Moon and the Earth and the Sun and the Earth is approximately constant
(iv) Revolution periods of the Moon around the Earth and of the Earth around the Sun are generally different and are the same only during certain months

Referring to the picture (Fig. 15), indicate, for each of the following statements, if it is true or false

Q41 In a) and d) it is shown the necessary condition for a total solar eclipse to occur

Q42 In c) and d) there are not the conditions for a solar or lunar eclipse to occur

Q43 In b) it is shown the necessary condition for a lunar eclipse to occur

Q44. Which is the cause of a solar eclipse? (please indicate the correct one)

(i) **The alignment of the Earth, the Sun and the Moon in the ecliptic's plane**
(ii) The Moon crosses the cone of shadow cast by the Earth
(iii) Moon's orbit intersects Earth's orbit around the Sun (the ecliptic)
(iv) A planet is aligned between the Earth and the Sun

Referring to the picture (Fig. 16), indicate, for each of the following statements, if it is true or false

Q45 You can see a total lunar eclipse only if you are in a not lighted up Earth's place

Q46 You can see a total solar eclipse only if you are in a lighted up Earth's place

Q47 You can see an annular solar eclipse only if you are in a not lighted up Earth's place

Q48. A total solar eclipse visible from Italy

(i) is visible also from Brazil if it is daytime
(ii) **is not visible from Brazil because the shadow cone cast by the Moon on the Earth is small**
(iii) is visible also from Brazil if the Moon is full
(iv) probably it is visible from Brazil because in Brazil it is night

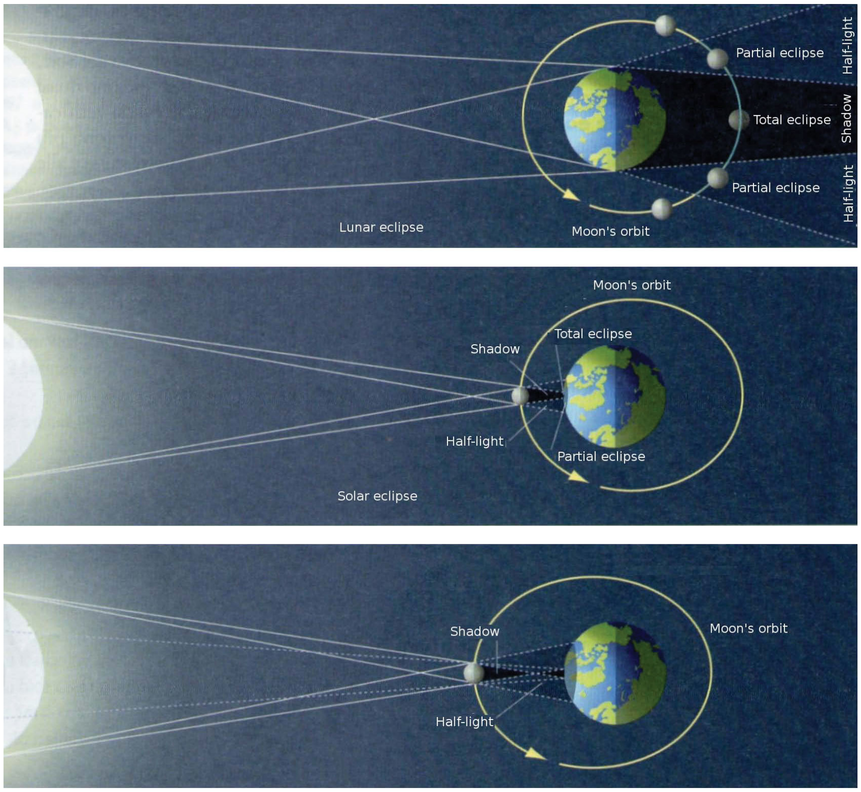


FIG. 16. Solar and lunar eclipses—II.

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