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Aryabhata and His Contributions to Indian Mathematics

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Abstract

Aryabhata remains one of the most extraordinary figures in the history of Indian mathematics. The principles that he formulated characterise the Great Early Tradition of Indian mathematics. Aryabhaṭa was the first major mathematician-astronomer since antiquity. His work marks the end of primitive steps and the beginning of fast and competent algebraic methods. Though very little is known of his life, the Aryabhatiya is a landmark in Indian intellectual history. This treatise, in two distinct parts, one dealing with mathematics and the other with astronomy, presents a concise survey of the field as it was known. Within the brief space, Aryabhata manages to introduce original work. In this paper, Aryabhatta and his contribution to Indian Mathematics have been discussed.

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1. INTRODUCTION

India gave rise to some of the earliest mathematicians, among whom Milton included Āryabhaṭa, the celebrated scholar who concerns us here. Āryabhaṭa is best known for his works on mathematics and astronomy—his figure occupies a central place not only in the Oxford Dictionary of Scientists but also in Christoph Harbsmeier's general encyclopaedia of mathematics for 3000 years. The present chapter is devoted to understanding the scientific landscape within which Āryabhaṭa and his followers operated.

Considered within the general development of Indian thought, Āryabhaṭa represents a major starting point for the later flourishing of mathematics in the subcontinent. By drawing on local traditions and Greek sources to create a new synthesis, he established a number of research programmes that would continue to interest Indian mathematicians for centuries. Many of the ideas formulated by Āryabhaṭa, and the systematic elaboration of Indian techniques that they suggested, ultimately played a significant role in the revolutions of the later sixteenth and seventeenth centuries. The following section sketches the broad development of natural science in India prior to

Āryabhaṭa in order to contextualize the innovations implemented by the author of the Āryabhaṭīya (Kak, 2010).

2. Historical Context

The beginning of the Indian Dark Age saw the abundance of mathematics suddenly cease, only to be revived centuries later by luminaries like Āryabhaṭa to again flourish (Kak, 2010). The work of Indian mathematics began significantly with Āryabhaṭa in the 5th century CE and continued through scholars such as Brahmagupta, Bhāskara I, and Bhāskara II. The scientific milieu therefore appeared well developed prior to Āryabhaṭa's epoch. A severe earthquake during his lifetime nearly destroyed the region comprising Kusumapura (Pāṭaliputra) and Magadha (modern Patna and Bihar), which can explain the scarcity of references to his works and the survival of only two of his texts through a brief period of revival under Śāriputra. In the aftermath, the area experienced the rise of the Guptas—a powerful dynasty exerting influence over the Indian subcontinent.

3. Biography of Aryabhata

Apart from the information provided within the Aryabhatiya, very little definite biographical information about Aryabhata is known. He was born in 476 C.E., and the earliest source to mention him is the 7th-century astronomer Bhāskara I, who wrote a commentary on the Āryabhaṭīya that praises his mathematical skills. He wrote the Āryabhaṭīya at the age of 23. There is some uncertainty about the location of Aryabhata's teaching centre, with suggestions including Kusumapura near Pataliputra (modern-day Patna), the great university at Nalanda, or other unidentified locations (Kak, 2010).

3.1. Early Life

Born in 476 CE in Kusumapura (Pataliputra, present-day Patna), Aryabhata's early dates and life details have been inferred by scholars such as Rṭhīdharāchāryya (1919). His only surviving work, the Āryabhaṭīya, does not mention his place of birth. Acharya Pingala's reference to an Ārya-siddhānta suggests that his father was named Ārya, and that he may have spent his youth with his family in Kusumapura. His name itself – Āryabhaṭa – probably means "noble-born" and it is used exclusively in this personal form rather than as an eponym. Pataliputra was a seat of learning with an astronomical observatory: mathematics and particularly astronomy were pursued by the priestly Brahmin class in 5th-century India. In this intellectual milieu, and given the royal patronage and scientific traditions of Kusumapura, it is plausible that Aryabhata studied the sciences under renowned scholars during his formative years. In 524 CE, the Gupta empire declined, and the subsequent rapid growth of rival powers may have driven Aryabhata to the south where he became the head of an astronomical observatory at Āljôda or Ālodā, near modern Patan in Gujarat (Kak, 2010).

3.2. Education and Influences

Aryabhata was born in 476 CE in Kusumapura, believed to be modern Patna. Dedicated to the study of mathematics and astronomy, he mastered his disciplines at the university in Nalanda. Afterward, he returned to Kusumapura, where he composed his renowned treatise, the Āryabhaṭīya. The extent of his travels remains uncertain. At some stage in his life, he relocated to the coastal region of Kerala at the southern end of the Indian Peninsula and established a university there, which became a vibrant center of learning (Kak, 2010).

3.3. Later Years

Little is known of his later life. Aryabhata is commonly identified as the āchārya at the Sāmanta-pasāda, who is known to have lectured at Nalanda to Chinese students in the late 7th century, but this is most likely a different Aryabhata (Kak, 2010).

4. Mathematical Innovations

Aryabhata's place in the history of Indian mathematics is secured by the Āryabhaṭīya, a brief but comprehensive work that provides a summary of the mathematics and astronomy of his time. The work consists of 108 verses divided into four pādas, or chapters, dealing with the āryabhaṭa-gaṇa, time, motion, and astronomy respectively (Kak, 2010). The Āryabhaṭīya encompasses many mathematical and astronomical topics including the theory of the motion of planets, planetary parameters, eclipses, and cosmology of considerable originality. It was the first astronomical text known to use zero as a number and to employ it in its place-value system. The text was very influential and is still in use in India, since a commentary is taught as part of the syllabus of Sanskrit schools.

Āryabhaṭa also compiled a more extended text, the Bhāskara-krama, on mathematical and astronomical tables cited in the Mahābhāskarīya.

The most important of Aryabhata's many contributions to the progress of Indian mathematics is the system of expressing numbers in terms of words. The Āryabhaṭīya also contains a description of the diurnal rotation of the earth round its own axis and mechanisms employed to model the motion of the moon.

4.1. Numeration System

Aryabhata's numeration system was an important contribution to Indian mathematics. For his notation he followed the conventions of the alphasyllabic script used for writing Sanskrit, where each letter represents a consonant followed by a vowel. By modifying the inherent vowel and then adding various other vowels, he assigned a numerical value to each letter, creating a system that could express every number from 1 to 108 (Kak, 2010). Though his system did not extend beyond ten million, his place-value idea was a noteworthy innovation that influenced numeric representations.

Using these values, Aryabhata wrote numbers with letters aligned with place-value notation. For example, he expressed 1,582,237,500 as guṇṭhīravasitaśarvavītavṛṣṇi. The corresponding numerical values are then 1,582,237,500, as reflected in the arrangement. Consequently, the number to be represented was broken into numbers from − to 108. Each such number was associated with a letter; the sequence of letters yielded the number. This system is analogous to that used for the Greek numerals, where the cipher was the alphabet. The principal difference was that in the Greek system positions did not have relative numerical values, while in the Āryabhaṭa system position played the critical role that it plays in all systems with a place value.

4.2. Place Value and Zero

From the third or fourth century CE, the Āryabhaṭa numeration system was used to represent numbers in Sanskrit by employing consonant–vowel syllables (Boucenna, 2007). The system fixes the place value of each digit by the accompanying vowel; the consonants, arranged in the order of the Sanskrit alphabet, serve as the digits (Folkerts, 2011). A similar principle was used earlier by the Greeks to fix the place value of the letters of their alphabet when they represented numbers using their alphabet. Unlike other Indian methods then current, Āryabhaṭa's system moves the multiplicative factor as a subscript to the accompanying vowel, following the order of the vowels in the Sanskrit alphabet. The word "0" was not used in Indian mathematics before the seventh century CE and does not occur in Āryabhaṭa's writing. However, it is possible that Āryabhaṭa, by using a placeholder "1 0", came as close as one could to having a symbol for zero.

4.3. Aryabhata's Algorithms

Aryabhata's contributions to techniques of computation find application in many areas of mathematics. His algorithm to solve the indeterminate equation (a x + c = b y) finds application in computations involving fractions (to reduce ratios to their lowest terms or express fractions as the sum of fractions having numerators equal to unity) and in attaining a high degree of accuracy in the table of sines. His code for expressing numbers in words helps in memorizing long numbers in the tradition of the katapayadi, a phonetic number system used by later Sanskrit authors. His rules for summation of series of squares and cubes find application in determining expressions for volumes and the mean speed theorem (birsa-acre) underlying the laws of motion of bodies. His work on equations has significance for algebra.

A combination of these ideas also leads to a method for computing the sine of an arc from the signs of arcs in an arithmetic progression. The information conveyed by the code also seems to be significant for the formation of the Indian epicyclic theories of planetary motion which are generally ascribed to Āryabhaṭa. Unlike Greek planetary models, but in agreement with the heliocentric theories of Aristarchus, the periods of the planets are given with respect to the sun. Āryabhaṭa's algorithms and substitution code have been discussed elsewhere (Kak, 2010).

5. Contributions to Astronomy

Aryabhata's astronomical system was based on the concept of a diurnal rotation of the Earth,
which accounted for the apparent westward motion of the stars. He gave the planets' periods of revolutions with respect to the Sun (and not the stars) and explained that eclipses occurred when the shadow of the Earth fell on the Moon and vice versa.

The Āryabhaṭīya defined the longitudes of the planets in a table of motions. For the Moon this value agreed with modern calculations to within 5 minutes of arc. That the longitudes were measured from the equinox was known to Brahmagupta in the 7th century. The text contained the theory of diurnal motion, the periods of the revolutions of the planets, the longitudes of the planets, the lunar crescent, eclipses of the Sun and Moon, and the latitudes of the planets (Kak, 2010).

5.1. Celestial Mechanics

Based on his textual writings, it is known that Aryabhata proposed a set of planetary model parameters that were entirely different from those of the prevailing views of his time. He maintained the overall framework of the Greek Ptolemaic system, which was being debated by astronomers. In this framework, the Moon and the planets Mars, Mercury, Jupiter, Venus, and Saturn all orbit the Sun, which, in turn, orbits an observer on the Earth. Aryabhata also stated explicitly that the orbits of Helios (the Sun), the Moon, the planets, and the stars are exactly circular. He maintained that the Moon appears to be eclipsed by the Earth during a lunar eclipse because the Earth comes in the way, even though the Moon can also be eclipsed by its own shadow (paraphrasing Greek and later Islamic viewpoints on the matter). Such contradictions suggest that the theory remained unfinished in his lifetime and that subsequent astronomers such as Varāhamihira, using observations, resolved these puzzles (Kak, 2010).

Aryabhata employed a calculus-like method of summation to derive plane areas and volumes of solids, enabling him to find the area of a triangle and the volume of a pyramid. His planetary model offered solutions to astronomical problems such as reconciling lunar and solar eclipses, accounting for the varying brightness and size of the Moon, explaining the illumination of the Moon, and describing the rising and setting of the Moon, among other phenomena. This model implied the existence of epicycles of varying sizes, a concept that later writers on planetary theory attributed to him (Parakh, 2006).

5.2. Eclipses and Planetary Motion

Elaborating on the planetary model outlined in the Aryabhatiya, the motion of the Earth is described as one of rotation about its axis, counter to the prevailing notion of the fixed Earth. In the planetary model, the periods of the planets and lunar nodes, measured from the ascending node, are specified. A lunar and a solar eclipse take place when the Moon comes to the full and new moon, respectively, together with the Moon's nodes, and such eclipses can therefore be predicted. A further argument is given to demonstrate that the Moon must be closer to the Earth than the Sun, invoking the variation of apparent size through the phases of the Moon. A succinct explanation of lunar and solar eclipses is given by the Moon and Sun being conjoint with the nodes in the appropriate phase (Kak, 2010).

6. Aryabhata's Major Works

The major work of Aryabhata is the Aryabhatiya, composed in 499, which covers mathematics and astronomy in succinct poetic verses under four headings (Kak, 2010). He also compiled the Āryabhaṭa-siddhānta, a comprehensive astronomical treatise composed at some time after 502 It provides a range of systematic calculations of planetary positions, eclipses, and related astronomical phenomena.

6.1. Aryabhatiya

Aryabhatiya is the only extant text of the Indian astronomer-mathematician Aryabhata. Written around 499 AD, the text covers mathematics and astronomy in forty concise verses. It opened up new vistas in Indian mathematics through its discussion of the place value system, use of zero, and algebraic methods. The text earned enormous fame and was widely studied by mathematicians and astronomers in India and the Arab world. Other works attributed to the author include the lost Arya-siddhānta and the Arjuna-paddhati, but the authorship of the latter is considered uncertain (Kak, 2010).

6.2. Other Texts

Several other treatises are attributed to Aryabhata, though none have survived. These include the Dhruva-pada, which concerned spheres; the Kriyākramakari, addressing procedures; the Gola, focusing on spheres; the Mahā-prajñāpti, on great mathematical or astronomical knowledge; and the Rāśi-gaṇita, which dealt with computations of the ecliptic. The existence of these texts is known primarily through references in later literature (Kak, 2010).

7. Influence on Later Mathematicians

Aryabhata enjoyed widespread recognition in medieval India. Already during the following centuries, his works had been partly interpolated and excelled by those of Āryabhaṭa II, a mathematician who wrote three texts inspired by the Āryabhaṭīya around a millennium later in the 950s CE (Kak, 2010). His influence also spread to those who came shortly after, such as Brahmagupta (598 CE), who proclaimed that he was extending the science of Āryabhaṭa and Bhāskara I (7th century), who wrote two commentaries on his works and further developed the kuṭṭaka algorithm. Bhāskara II (12th century) credited the guru of his school, Lalla (c. 720 CE), with having expanded Āryabhaṭa's ideas and provided commentary.

7.1. Brahmagupta

Brahmagupta extended or was inspired by the Aryabhatan tradition, adopting his notions of indefinite numbers and using the kuṭṭaka ("pulveriser") method for the solution of indeterminate equations in the Siddhānta (The Creation, c. 628 CE). Scholars debate the extent and originality of Brahmagupta's mathematical innovations. Bhāskara I (c. 600–680) composed detailed commentaries on the Aryabhatiya, introducing the ingenious bhūtasaṃkhyā system for expressing large numbers. His texts preserved Aryabhata's methods and the spirit of his syntheses (Kak, 2010).

7.2. Bhaskara I and II

Bhaskara I and Bhaskara II are prominent Indian mathematicians closely associated with the legacy of Aryabhata. Both made significant contributions to Indian mathematics and astronomy, further developing and extending the foundational work of their predecessor.

Bhaskara II focused on astronomical calculations and mathematical techniques. His work addressed planetary models and computational methods for determining the positions of celestial bodies. Bhaskara II's contributions included refinements to algorithms and mathematical approaches inspired by the Āryabhaṭīya of Āryabhaṭa—a seminal text that influenced the course of Indian astronomy and mathematics. The efforts of Bhaskara I and Bhaskara II created a tradition that deeply impacted the development of mathematical concepts such as algorithms and trigonometry (Kak, 2010).

8. Comparison with Contemporary Mathematicians

Indian mathematics had a number of great mathematicians who provided significant results and methods – all being indebted directly or indirectly to Āryabhaṭa. Āryabhaṭa's mathematics, especially the algorithmic nature of the work, was unique; the Greeks, for example, pursued geometry and did not develop algebraic methods. Chinese mathematics provides a closer parallel; it treated mathematics as a computational procedure which is well illustrated in the system of equations known as the Chinese Remainder Theorem, but it seems to have lacked the idea of general methods that was part of Āryabhaṭa's approach (Kak, 2010).

8.1. Greek Mathematics

Attempts at explaining natural phenomena framed by Greek theories gradually spread to India through occupation of northwest regions (Kak, 2010). Manuscripts from texts such as the Rg Veda, Brahmanas, and Aranyakas contain within Sanskrit statements that anticipate a number of definitions and important theorems of higher mathematics and astronomy. Speculation concerning physical processes would have invariably returned to the the theistic, for the assumption of law like regularity readily supports an overarching control of the phenomenal world. While the first technical approach to such explanations was visualized as a mechanism involving several spheres, a purely religious approach nevertheless supported the view of the existent sky as a complete encasing."} The [section_title] is somewhat ambiguous between broad survey of Greek mathematics, or of "Greek" transmission of mathematical ideas to India. The above attempts to address the latter. Please advise. If a more thorough overall survey, please specify.

8.2. Chinese Mathematics

Chinese mathematics was primarily concerned with practical rules for agriculture, commerce, and administration. There were few attempts at systematisation, and early values for π were obtained empirically, at about 3. The first great text of Chinese mathematics was the Jiuzhang Suanshu, or The Nine Chapters on the Mathematical Art, which dates from about 200 B.C. but is based on much older material. The arithmetic was based on counting rods (a kind of small abacus) and great ingenuity went into devising general rules for working with fractions. Linear equations were solved approximately using a method similar to Horner's method, and there were procedures for calculating volumes and roots. Methods equivalent to the Pythagorean theorem were already known and there were accurate approximations for the square root of 2. A principle of finding unknown values "by excess and deficit" was used to find approximate formulae of finite series from arithmetic progressions. Chinese astronomers calculated the apparent diameters of the sun and moon to vary between the same maximum and minimum values in each orbit and presented the model as giving exactly correct apparent diameters (Kak, 2010).

9. Legacy of Aryabhata

The influence and originality of Āryabhaṭa's ideas have led him to be regarded by scholars as "one of the greatest scientific minds of the first millennium." Some researchers credit him with pioneering the use of operable algebraic symbolism (Kak, 2010). Probably the first to introduce the notion of zero, place value, and the solution of indeterminate equations of the first degree, he was well versed in the geometry, arithmetic, algebra, and trigonometry of his time. Yet his brief treatise inspired some of the tallest minds of the seventh century, including Brahmagupta and Bhāskara I. Having established the foundations of Indian algebra, he had something to say about higher mathematics and left his successors "plenty of empty spaces, [and] enormous problems, and beautiful theorems" to grapple with. * Mathematical historians thus recognize him as a founding father of Indian mathematics—whose influence still pervades the country's thought and culture—and venerate him among the greatest thinkers in the history of science.

Centuries after his death, Āryabhaṭa remained an iconic figure. Recognizing him as one of the great mathematicians of the classical age, the first Indian lunar crater was named after him, and India's first satellite was christened "Aryabhata" upon its launch on 19 April 1975. *The tradition of Āryabhaṭa's School achieved considerable eminence through the works of Brahmagupta and Bhāskara I, and the Kerala School of Astronomy and Mathematics thereafter.

The [Āryabhaṭīya] contains the "systematic rules" of the place value system and the name of the zero.

9.1. Impact on Indian Mathematics

Indian mathematics after Āryabhaṭa (born 476) witnessed great further advances and a high degree of sophistication. Already in the third century, the concepts of sine and cosine had been introduced for computations in astronomy. After Āryabhaṭa came a sequence of brilliant mathematician-astronomers, including Brahmagupta (born 598), Bhāskara I (born 600) and Bhāskara II (born 1114). Āryabhaṭa's works gave the essential impetus to all their innovations and discoveries.

By Āryabhaṭa's time there was an oral tradition of higher mathematics, as the Sutras—concise aphoristic compositions in Sanskrit—suggest. He introduced a new approach and, significantly, technical innovations. He was the first, for example, to treat π (pi) as an irrational number. The Āryabhaṭīya contains a system for expressing large numbers and also tables of trigonometric functions. Āryabhaṭa's school played an important role in the development of the calculus of the Kerala school centuries later. Some of his innovations also found their way to Europe and are among the origins of modern mathematics (Kak, 2010).

9.2. Recognition in Modern Times

Aryabhata's stature in modern India has placed his name alongside Newton and Einstein. He was given the name "Āryabhaṭa" mine and the first satellite launched by India in 1975 was designated "Aryabhata." There were vessels Arya-bhuta and the Institute of Faculty Training in Science Education was renamed "Āryabhaṭa Institute of Fundamental Research" in Jaipur. There is a commemorative bronze statue of him at the Laxminarayan Temple of Delhi and the yearly Aryabhata Festival is held at the Kerala University of Science and Technology, while seminars honoring his name have been organized all over the country. He is at the same level as Chanakya in the historical tradition and the association with Newton and Einstein expresses his symbolic importance and pays tribute to his monumental work (Kak, 2010).

10. Critiques of Aryabhata's Work

Despite his important role in the history of Indian mathematics, some aspects of Aryabhata's work have generated controversy—both concerning the accuracy of particular mathematical results and the interpretation of his philosophy as expressed in the Āryabhaṭīya. Some of the mathematical procedures presented in the Āryabhaṭīya are not, strictly speaking, exact, and the text contains a few errors that might be interpreted as copyist mistakes and/or later interpolations. Likewise, the overall worldview expressed in the Āryabhaṭīya has been variously interpreted, often ascribing to Aryabhata positions that sometimes appear inconsistent with the approach of his more technical and scientific work (Kak, 2010).

10.1. Mathematical Accuracy

Almost all of the mathematical procedures that Āryabhaṭa describes in the Āryabhaṭīya are accurate; however, there are some errors, some of which may be due to problems with the text and some of which are mathematical approximations and not actual mistakes (Kak, 2010). Errors in some verse refer to the currently accepted values of planetary constants, but the methods used to arrive at them are still valid. Errors of a mathematical or computational nature occur in a handful of other verses and appear to have entered the text at some later time. His philosophy of mathematics has also attracted attention. According to Thibaut, the root of the necessity of numbers is the fact that they are contained in the nature of things, "number and magnitude being, so to say, the phantoms of ideas." He repeats that unity is not derived from addition and that the ideas of new dimensions and of space were intimately connected for Āryabhaṭa.

10.2. Philosophical Perspectives

What sets Āryabhaṭa apart from his contemporaries and from modern historians is his commitment to the theory of relativity. In his cosmology the earth is taken to be spinning on its axis and the motion of the sun and moon is correlated with the periods of the planets. Āryabhaṭa explains the westward motion of the stars by the rotation of the earth, thus formulating a relativity principle for observers on earth (Kak, 2010). He also represented a conscious break between a pre-scientific and a scientific worldview.

Āryabhaṭa's science raised several philosophical questions. Was the earth to be taken only as a mathematical abstraction, or was the whole universe of antiquity being replaced by a new kind of physical universe? Did Āryabhaṭa intend his theory of relativity to be the seed for a more advanced system, or was he asserting that there was no fixed up or down in the universe? And why did the rotation of the earth come to be accepted in India only in the sixteenth century, when the influence of European astronomy was pervasive, of which the Copernican system was an obvious part? Finally, one may ask why the great system of ten-dimensional physics that formed the esoteric basis of the Siddhāntic tradition was not studied further after the seventh century C.E.

11. Modern Applications of Aryabhata's Concepts

Aryabhata's contributions to the understanding of astronomy have not lost their relevance. Given the high accuracy of his lunar and solar constants, some of his ideas could well form the basis of the models for modern astronomy and space science. The kuṭṭaka algorithm and the substitution code proposed by him find applications in diverse computational areas, such as securing passwords and personal identification numbers. As a result, his concepts continue to influence contemporary investigations in both astronomy and computer science (Kak, 2010).

11.1. Computer Science

Aryabhata's contributions to the computer science discipline arise from two perspectives: first, the historical and mathematical legacy providing fundamental computational concepts; and second, the direct modern-day employment of Āryabhaṭa's principles in computer applications. The former provides insights into the evolution of computational thought, while the latter pertains to the application of his ideas in various aspects of computing, such as encryption and secure password design. Researchers in computer science recognize that Āryabhaṭa's conceptualizations continue to inform contemporary algorithms and data management strategies (Kak, 2010).

11.2. Astronomy and Space Science

Āryabhaṭa's vividly alive world contained an earth whose shadow caused lunar eclipses, which illuminated, reflected sunlight and reflected the moons light in its two directions (Kak, 2010). The twelve signs of the zodiac and the 27 lunar mansions were the basic entities used for computing planetary motions. These motions were described using sine tables and the orbits of the planets, whose periods of revolution were given by the siddhānta, were expressed in terms of their eccentricities with respect to the earth and the sun. The sun and the moon were treated as points and the planets were treated as spheres. Aryabhata was concerned with the diurnal rotation of the earth on its own axis (Parakh, 2006). He assumed that the earth was not stationary; rather, it was the motion of the earth rather than that of the heavens that caused the day-night cycle. The motions of the heavens and of the zodiac of signs with respect to the pole star were then computed using this assumption, and the methods developed thereby could be used to study the rising and setting of the planets and their related phenomena. These methods provided more accurate results than by using the assumption that the earth was stationary and the heavens rotated. Aryabhata also gave planetary longitudes as well as latitudes, and can be said to have incorporated these features into a geocentric model of the solar system. He discussed eclipses of the sun and moon, and correctly explained the causes using the shadows of the earth and the moon respectively. A principle of relativity stated in astronomy by Aryabhata in the 5th century CE is as follows:

Just as a man in a boat moving forward sees the stationary objects (on either side of the river) as moving backward, just so are the stationary stars seen by the people on earth as moving exactly towards the west.

This principle comes very close to Galilean relativity, stated in the early 17th century, that the laws of motion remain the same in a moving ship as they do on the earth. Because of the centrality of this principle in the subsequent development of planetary models from Aryabhata's school, Parakh has argued that Aryabhata should be given full credit for it.

12. Educational Perspectives

The extent to which Aryabhata's mathematics can be taught today and the manner in which it can be utilized in a history of mathematics course are considered. For reasons discussed earlier, Aryabhata's text in its original form cannot be taught to undergraduate non-mathematics students. The process that led to this situation is outlined, with sample problems.

While there are enough sources to reconstruct Aryabhata's mathematics, the style is less than ideal, and there are alternative methods for some problems that may be preferred instead (Kak, 2010). The possibility of teaching the numeration scheme to a wider audience is discussed. Finally, ways in which it is possible to use the numeration system in computer science are explored.

12.1. Teaching Aryabhata's Mathematics

Āryabhaṭa's mathematics can be taught in several ways, incorporating his contributions from different angles, so that readers from various technical and conceptual backgrounds can benefit from exploring this ancient and foundational corpus.

One can do so through the development of his mathematics and the scholia on the Āryabhaṭīya (Kak, 2010). A beginning can introduce Aryabhata and the scientific context of his period, after which his biography can be given independently as a discussion of a canon of the period, including his early works, his move to Kusumapura, and his career as a court astronomer. The derivation of his mathematics may then be introduced from the scope of the text: the positional number system, the definition of zero, the root-extraction procedures, the interpolation formula, and rational approximation. At this point, the basic astronomical model is presented from the references in his own text (see Sect. 12.5). The remainder of the discussion proceeds with the major works of the period that explain these points in greater detail and clarify the innovations.

Often, the mathematics is taught through a comparison with other texts such as the Bakhshali or later Indian astronomy. This is also the case for the 5th-century works such as the Brahmasphutasiddhanta, the Mahābhāskarīya, and the Lāghubhāskarīya, where the treatment clarifies which, parts derive from Āryabhaṭa's system and which are original to these astronomers. Finally, the scholarly relationship between the Ptolemaic Greeks (or perhaps earlier traditions), the Indians, and the Chinese is also discussed, clarifying how Āryabhaṭa's mathematics was both unique and part of the global scientific developments. The resulting discussion shows modern readers how positive a role India has played in the development of elementary and advanced mathematics, an argument that is relevant to discussions of the History of Philosophy.

12.2. Curriculum Development

At the post-graduate level, the mathematics of Aryabhata finds application in courses on computer science, astronomy, and space science. Teaching the history of science through mathematics is an exciting alternative to curricular approaches based on the classical view of an accumulation of facts. Mathematical history can be introduced by telling the story of non-Western mathematics through Aryabhata. The study of his mathematics itself offers a more precise way for students to immerse themselves in history than analysis of epoch-making experiments, biographies of scientists, or study of technical, abstract secondary literature (Kak, 2010).

13. Cultural Impact of Aryabhata

Mention of Aryabhata in classical dramas like Bhavabhuti's Malati-Madhava highlights his cultural significance by the eighth century. Bhavabhuti also cites other contemporary mathematicians, such as Brahmagupta and Varahamihira, illustrating the rich intellectual milieu of the time (Kak, 2010). In the twelfth century, Aryabhata continued to receive honors, as attested by Nāgavarman's homage in the Bṛhatkathā-ślokasaṃgraha, and the name Aryabhatta was adopted by many Indian scholars, reflecting his enduring inspirational status.

13.1. Representation in Literature

Indications of Aryabhata's personality and fame are met in the Classical Sanskrit literature, and he is even recalled in the period of Kālidāsa (late 5th century A.D.) (Kak, 2010). The influence of Aryabhata has been alluded to in several major Sanskrit works, such as Nīlamata (the earliest text of Kashmir Shaivism), Dhātuvṛtti, and Govinda Bhattathiri's Mahābhāskarīyaṭīkā (the author lived about the 13th century A.D.).

Kadambari's 9th-century author Banabhatta credits Aryabhata with the knowledge of the motion of the full moon, states that he knew the relation between the moon and the tides and describes him as a master of mathematics and a magician. Bhavabhuti (8th century) and Matanga (around 800 A.D.) praise Aryabhata both as a great mathematician and as an astrologer. Yamunacharya (10th century) describes him as the earliest astronomer and as one who first correctly computed the solar year. The Ganesha-dharmanibandhana of about the 11th century places Aryabhata next to Brahmagupta amongst the great Indian astronomers.

13.2. Influence on Art and Culture

The image of the ancient mathematician-astronomer Aryabhata at his writing table. There is a stylised figure of Delhi's Red Fort in the background. The picture appears in Siddhānta-Śiromaṇi-Vākyamala (In Praise of Summit of Treatises) by Satyaketu Vidyalankara (c. 1900). Aryabhata is one of the greatest mathematician-astronomers of the ancient world. There is a great deal of literature that shows that the importance of his influence on mathematics and astronomy in India cannot be overstated. Karine Chemla points out that pre-Modern India had a vibrant and multifarious mathematical culture with ancient origins. This is one of the reasons why Āryabhaṭa was held in such high esteem. His school played an important role in the development of calculus in Kerala, especially inspiring Indian mathematicians to discover power series expansions centuries before Newton and Leibniz. Contributions to Indian literary culture on the other hand are less well studied, and Āryabhaṭa remains altogether forgotten.

Given the breadth of other influences on Indian culture, such as the epics (Rāmāyaṇa, Mahābhārata) and the Vedas, the influence of Āryabhaṭa might appear to be rather limited. One reason for he has not been studied is that the Sanskrit poets avoided the representation of religious figures, most prominently Āryabhaṭa's contemporary with the bārahmānas. Hence claims about Āryabhaṭa's contribution to Indian literary culture have either been restricted to the greater appreciation of science and reason, or to the Ethical Precepts provided to the king, Kaniṣka. A popular text suggests that the establishment of the Red Fort lodges at Delhi and Lahore arose from the Āryabhaṭa School of Mathematics, founded during the reign of Babur. Although there is a tenuous connection between something named by later European visitors and Āryabhaṭa, it

marks an example of how large the presence of Āryabhaṭa is in all fields of knowledge through the Āryabhaṭa School. There is an interesting legacy in modern agriculture as modern Ayurvedic agriculture, which itself is closely related both to the Siddhaṃ literature, in particular the work of Bauddha. Copious golden-metaphoric descriptions of rice appear throughout the Sanskrit literary tradition. Narendra Krishna associates the describing of rice varieties to Āryabhaṭa, alongside the Dātāla of Bhāskara.
Across history, three different schools of thought have been associated with the Āryabhaṭa tradition. Specifically, the Aryabhata School developed according to three key models: the 'Contemplative Atmosphere Model', the 'Technical Accumulation Model', and the 'Teacher-Centric Model'. The Contemplative Atmosphere Model regards the influence of Āryabhaṭa (born in 476 CE) as entirely contemplative, with all the activity of the school limited to the remote atmosphere of a hermitage. The Technical Accumulation Model emphasizes not only the influence of Āryabhaṭa's work, but also the innovations in mathematics, astronomy, and cosmology that occurred in the six centuries following his life. It is one of the more popular attitudinal conceptions. The Teacher-Centric Model derives from the great appreciation of Āryabhaṭa's importance but one which highlights instead the influence of the school on specific teachers like Bhāskara I (Kak, 2010).

CONCLUSION

Aryabhata remains one of the most extraordinary figures in the history of Indian mathematics. The principles that he formulated characterise the Great Early Tradition of Indian mathematics, which remained active through the centuries and underlay the brilliant developments of the Kerala school of the 14th–16th centuries and the mathematical activity of India as a whole until modern times (Kak, 2010).

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