ASTRONOMICAL INSTRUMENTS IN BRAHMAGUPTA'S *BRĀHMASPHUṬASIDDHĀNTA*

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Brahmagupta (b. A.D. 598) is well known as an excellent astronomer and mathematician. His two works, the *Brāhmasphuṭasiddhānta* (*BSS*)[1] and the *Khaṇḍakhādyaka*, written respectively in A.D. 628 and 665, exercised a great deal of influence both within India and outside. It is through the Arabic translations or adaptations of these two texts that the Islamic world became acquainted with Indian astronomy.[2] He also occupies a prominent place in the history of observational astronomy, for the *BSS* is the first extant text to contain a systematic discussion on the construction and use of a large number of astronomical instruments. It is, of course, true that before him Āryabhaṭa I (b. A.D. 476) had described some instruments in his *Āryabhaṭasiddhānta*. This text is no more extant, but the portion on instruments survives in quotations, notably in Rāmakṛṣṇa Ārādhya's commentary (A.D. 1327) on the *Sūryasiddhānta*.[3] Varāhamihira (*c.* A.D. 550) also briefly mentioned a few instruments in his *Pañcasiddhāntikā* (14. 19-32). But the instruments of these two astronomers did not find acceptance in later times as those discussed by Brahmagupta did.

In the twenty-second chapter of the *BSS*, called appropriately *Yantrādhyāya*, Brahmagupta not only describes many instruments, but also teaches methods of computing various astronomical elements from the readings taken with these instruments. These instruments and computational techniques were adopted in almost all later *siddhāntas* like the *Śiṣyadhīvṛddhida* of Lalla (eighth century), the *Siddhāntaśekhara* (A.D. 1039) of

*I wish to gratefully acknowledge the financial assistance generously provided to me by the Indian Council of Historical Research, New Delhi, for attending the Seventh World Sanskrit Conference held at the Kern Institute, Leiden, in August 1987, where this paper was presented. It is worthwhile recalling here that Professor H. Kern, after whom the Institute is named, brought out the first edition of the *Āryabhaṭīya* (Leiden, 1874) and also the first edition (Calcutta, 1865) and English translation (*JRAS*, 1870-75) of Varāhamihira's *Bṛhatsaṃhitā*.

1 I use the *editio princeps* by Sudhakara Dvivedi (Benares, 1902). Dr A.K. Bag, Indian National Science Academy, New Delhi, has kindly sent me a photocopy of the twenty-second chapter. The second edition by Ram Swarup Sharma (New Delhi, 1966) in four heavy volumes is quite innocent of textual criticism and even of proof-reading.

2 On the dissemination of Indian astronomy in the Islamic world, notably through Brahmagupta's works, see Faut Sezgin, *Geschichte des Arabischen Schrifttums*, Band VI. Astronomie bis ca. 430 H. (Leiden, 1978), pp. 116-20.

3 Collected by K.S. Shukla in "Āryabhaṭa I's Astronomy with Midnight Day-reckoning", *Gaṇita*, Vol. XVIII (1967), pp. 83-105; and "Glimpses from the *Āryabhaṭasiddhānta*", *Indian Journal of History of Science*, Vol. XII (1977), pp. 181-86. The Sanskrit stanzas on the instruments together with Shukla's translation are reprinted in B.V. Subbarayappa and K.V. Sarma, *Indian Astronomy: A Source-Book* (henceforth *Source-Book*) (Bombay, 1985), pp. 86-99, 182,

Śrīpati and the *Siddhāntaśiromaṇi* (A.D. 1150) of Bhāskara II. Therefore, in order to understand the nature and function of astronomical instruments in pre-Islamic India, it is essential to study the *BSS*.[1]

The instruments discussed by Brahmagupta can be divided into four groups: (i) accessories, (*ii*) astronomical instruments proper for measuring time and observing celestial bodies, (*iii*) instruments that turn automatically for one day, and (*iv*) those that rotate perpetually.

I

Under accessories (*saṃsādhana*), Brahmagupta enumerates eight items: water, a pair of compasses (*bhrama*), plumb-line (*avalamba*), hypotenuse (*karṇa*), shadow (*chāyā*), midday (*dinārdha*), the sun and the local latitude (*akṣa*).[2] Āryabhaṭa mentions only the first four,[3] to which Brahmagupta adds, apparently for the sake of comprehensiveness, the four natural phenomena, the presence or the knowledge of which is required while using the astronomical instruments. However, the first four deserve our attention as they refer to primitive geometrical tools or methods for drawing circles or for aligning an instrument or a figure in all the three dimensions, namely, horizontal, vertical and lateral. That is to say, whether a plane is horizontal or not is tested by means of water, and whether a plane or line is truly vertical or not is ascertained with the plumb-line. By "lateral" (*tiryak*) is meant the following: when a straight line is extended sideways to enclose an area in the form of a triangle or rectangle, a pair of hypotenuses are needed to complete the figure. Their measurements constitute the fourth accessory called *karṇa*. Brahmagupta does not describe any of these methods or tools. However, the commentaries on the *Āryabhaṭīya* offer some interesting information.

These commentaries do not seem to be familiar with any simple level instrument. Instead, they recommend two methods of using water for determining the horizontality. Bhāskara I, who completed his commentary on the *Āryabhaṭīya* in A.D. 629, states:

> When there is no wind, place a jar full of water upon a tripod on the ground which had been made plane by means of eye or thread, and bore a [fine] hole [at the bottom of the jar] so that water may have a continuous flow. Where the water falling on the ground spreads in a circle, there the ground is in perfect level; where the water accumulates after departing from the circle of water, there it is low; and where the water does not reach, there it is high.[4]

1 Little attention has been paid to Indian astronomical instruments before Jai Singh. Cf. S.R. Das, "Astronomical Instruments of the Hindus", *IHQ*, Vol. IV (1928), pp. 259-69; R.N. Rai, "Astronomical Instruments", *Indian Journal of History of Science*, Vol. XX (1986), pp. 308-36; Sankara Balakrishna Dikshita, *Bhāratīya Jyotiṣa*, tr. into Hindi by Sivanatha Jharakhandi (Lucknow, 1963), pp. 452-68; D.M. Bose *et al*, *A Concise History of Science in India* (New Delhi, 1971), pp. 124-26; David Pingree, *Jyotiḥśāstra: Astral and Mathematical Literature* (Wiesbaden, 1981), pp. 52-54; *Source-Book*, pp. 74-99.

2 *BSS*, 22.6-7.

3 *Āryabhaṭīya Gaṇita*, ~~Vol. XIII.~~ Verse 13.

4 K.S. Shukla, ed, *Āryabhaṭīya* with the Commentary of Bhāskara I and Someśvara (New Delhi, 1976), p. 87. The translation is from Ibid., p. 55.

Since this was written a year after Brahmagupta completed the *BSS* and since both are from the same geographical area—Brahmagupta belonged to Bhillamāla and Bhāskara to Valabhī—it is likely that Brahmagupta was familiar with this method. The second method is described by Parameśvara who lived in Kerala in the fifteenth century:

> First make the ground level by sight or by using a rope. Then draw a circle on the ground....[With the same centre] draw another circle around the first one at a distance of one or two inches from the first. Dig the ground between the two circumferences and thus make a channel. Fill the channel with water. If the water is up to the level of the ground all around, then the ground is plane; where the ground is low, the level of water will be higher, and so on.[1]

Again, we owe to Parameśvara the only description of preparing a pair of compasses that is available in Sanskrit. He recommends as follows:

> Get hold of some straight stick. Tie its top firmly with a rope, then splice the stick from bottom to top so that there are now two sticks. Sharpen their [lower] ends. Thus is made a pair of compasses with their points downwards. Then insert [another] stick between the two sticks and thus make the mouth of the compass wide. By moving the inserted stick up and down, the mouth of the compass can be widened so as to equal the radius of the desired circle. Then press the tip of one stick at the centre of the circle to be drawn and the other tip at its rim. Rotate the compass and you will get the desired circle.[2]

It is surprising that as late as the fifteenth century, Parameśvara describes such a crude tool. Did the metal compass not reach south India or is the one described here a large version meant exclusively for drawing circles on the grounds? Whatever the case may be, this account illustrates the Indian astronomer's predilection for simple makeshift tools and instruments. This point will be substantiated when one looks at Brahmagupta's choice of astronomical instruments.

II

The actual astronomical instruments described by Brahmagupta are nine in number, namely, *dhanuṣ, turyagola, cakra, yaṣṭi, śaṅku, ghaṭikā, kapāla, kartarī,* and *pīṭha*.[3] Of these, *śaṅku* (gnomon) and *ghaṭikā* (clepsydra) were in use in India at least from the fourth century B.C. Brahmagupta's reference to these two instruments is extremely

1 H. Kern, ed, *The Āryabhaṭīya* with the commentary *Bhaṭadīpikā* of Paramādīśvara [Parameśvara] (Leiden, 1874), pp. 32-33. This, in fact, is the method adopted by Sawai Jai Singh (1688-1743) in his astronomical observatories. The water channels for testing the level of the ground are still intact in Jaipur. Cf. Prahlad Singh, *Stone Observatories in India* (Varanasi, 1978), p. 75. Based on the same principle is also the levelling device called *afādain*, described by al 'Urdī in his account of the observatory at Marāgha, established in 1259. Cf. Hugo J. Seemann, *Instrumente der Sternwarte zu Marāgha nach den Mitteilungen von al 'Urdī* (Erlangen, 1928), pp. 49-50.

2 Ibid., p. 32.

3 Bhaṭṭotpala, in his commentary on the *Bṛhatsaṃhitā*, enumerates the same nine instruments, cf. Avadha Vihari Tripathi, ed, *Bṛhatsaṃhitā*, Vol. I, (Varanasi, 1966), p. 42: *yantraiś ca cakra-dhanuṣ-turyagola-yaṣṭi-śaṅku-ghaṭikā-kapāla-kartarī-pīṭhaiḥ kālaparicchedakaiḥ*. Other writers adopted the

brief, either because these two are well known instruments, or more possibly because he prefers to use other instruments in lieu of these two.

The clepsydra mentioned by Brahmagupta is the sinking-bowl type. It is a hemispherical bowl with a minute hole at the bottom and, when placed in a larger receptacle of water, it takes one *ghaṭikā* (24 minutes or 1/60th part of a civil day) to fill and sink.[1] There is another, and perhaps older, variety. This is the outflow type, that is, the vessel emptied itself through a hole at the base. From Varāhamihira's reference to it in the *Pañcasiddhāntikā*,[2] it appears that the vessel was a large one which emptied itself once in a nychthemeron. Jacobi thinks that such vessels must have been of cylindrical shape because it is easy to calibrate them into 60 equal units (each unit representing a *ghaṭikā*) and that the cylinder itself was called *nāḍikā* whence the time-unit received the same name.[3] Thus the basic unit of time of 24 minutes has two names in Sanskrit: *ghaṭikā* (literally, small pot), since it is measured by a small pot, that is, hemispherical bowl, and *nāḍikā* (literally small tube) since it is ascertained by means of the cylinder-shaped outflow clepsydra. Jacobi goes on to say that the outflow clepsydra was not accurate and therefore was replaced by the sinking-bowl type. In fact, with the exception of Varāhamihira, no other astronomer mentions it among the instruments to measure time directly. Yet it survived as an essential component of complex machines.

Of the other instruments, the *cakra* (circle), *dhanuṣ* (semi-circle) and *turyagola* (quadrant) are closely related in shape and function. *Cakra* is a circular wooden plate with its circumference graduated into 360 degrees, *dhanuṣ* is its half, and *turyagola* the quarter. In all the three, a perforation is made at the centre into which a peg is inserted like an axis, and also a plumb-line is suspended from the centre. These instruments are so held towards the sun that the axis throws a shadow on the circumference. Then the arc intercepted between the nadir (indicated by the plumb-line) and the shadow is the zenith-distance. One can also measure with these instruments the angular distance between the sun and the moon, or the longitude of a planet, or the time since sunrise, and so on.

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same set with minor changes. Thus Lalla's *Śiṣyadhīvṛddhida* (ch. 21) deals with twelve instruments, namely, *gola, bhagaṇa, cakra, dhanuṣ, ghaṭī, śaṅku, śakaṭa, kartarī, pīṭha, kapāla, śalākā* and *yaṣṭi*. Śrīpati's *Siddhāntaśekhara* (ch. 19) has ten: *gola, cakra, cāpa* (*dhanuṣ*), *kartārī, kapāla, pītha, śaṅku, ghaṭī, yaṣṭi* and *gantrī* (*śakaṭa*). Bhāskara's *Siddhāntaśiromaṇi* (*Golādhyāya, Yantrādhyāya*) discards some of Brahmagupta's instruments and introduces some of its own such as, *gola, nāḍīvalya, ghaṭikā, śaṅku, cakra, phalaka, yaṣṭi* and *dhīyantra*.

1 *BSS*, 22.41. I-Tsing, who visited India during the lifetime of Brahmagupta, gives a detailed account of the time-keeping establishment at the Buddhist monastery of Nalanda; cf. J. Takakusu, tr., *A Record of the Buddhist Religion as Practised in India and in Malay Archipelago* (London, 1896), pp. 144-46. While the clepsydra described by Brahmagupta (and other astronomers) measures constant *ghaṭikās* of 24 minutes each, the one at Nalanda shows variable *ghaṭikās*, that is, the length of the *ghaṭikā* varies according to the duration of the daylight. This distinction has not always been kept in mind in the little that was written on the history of horology in India.

2 *Pañcasiddhāntikā*, 14.31: *dyuniśi viniḥsṛtatoyād iṣṭacchidreṇa ṣaṣṭibhāgo yaḥ, sā nāḍī. . . .*

3 Hermann Jacobi, "Einteilung des Tages und Zeitmessung im alten Indien", *ZDMG*, Vol. 74 (1920), pp. 247-63, esp. p. 251. See also J.F. Fleet, "The Ancient Indian Water-Clock", *JRAS* (1915), pp. 213-30 and F.E. Pargiter, "The Telling of Time in Ancient India", ibid., pp. 699-715.

Brahmagupta prefers the semi-circular variety, for he explains all functions in connection with *dhanuṣ* and adds that the same can be done with *turyagola* and *cakra*.[1] But his successors show a marked preference for the *cakra*, presumably because it has an ideal shape; the *dhanuṣ* is ignored by Bhāskara while the quadrant does not appeal to Lalla or Śrīpati or Bhāskara.[2]

The other instruments are generally variations of the *cakra* or *dhanuṣ*. Thus *pīṭha* is a horizontally placed *cakra*.[3] It is a circular platform set up at the observer's eye-level, with a vertical axis equal in length to the radius of the circle. The circumference is marked with 360 degrees, and north-south and east-west lines are drawn through the centre. At sunrise and sunset, *agrās* are laid off respectively in the west and east. From the line joining the ends of these *agrās*, one can read directly the *ghaṭikās* elapsed since sunrise.[4]

The *kapāla* and *kartarī* as envisaged by Brahmagupta are variations of *dhanuṣ*. The former is a horizontally placed semi-circular plate, the axis pointing upwards, the diameter in the north-south direction, and the arc to the east or to the west where the shadow happens to fall. Like the previous instrument, this too is used for measuring the time since sunrise or the time up to sunset.[5]

In *kartarī*, two semi-circular plates are so joined that one forms the lower half of the plane of equator and the other the meridian plane, its diameter forming the polar axis. A peg is fixed at the junction of the two diameters. From its shadow on the equatorial plane, the time since sunrise can be read. Apparently, the equatorial plate can be rotated in its own plane, and this movement presumably gave rise to the name *kartarī* (literally, a pair of scissors).[6]

Brahmagupta's account of *yaṣṭi* (staff) is the longest of all, where he discusses several types of measurements that can be carried out with a staff, in conjunction with a plumb-line and /or a dial drawn on the ground.[7] In fact, later writers treat some of the individual functions of the staff as separate instruments. These functions are determining the time since sunrise, measuring the equinoctial shadow, finding the angular distance between the sun and the moon, estimating the heights and distances of objects on the land, and so on. For each of these functions, Brahmagupta teaches several methods of computation.

1 Thus Brahmagupta devotes nine stanzas for *dhanuṣ* (*BSS*, 22.8-16) and just one each for *turyagola* (17) and *cakra* (18). Āryabhaṭa also has a *dhanuṣ*, but its function is more cumbersome; cf. R.N. Rai, op. cit., p. 326. Instead of the word *dhanuṣ*, Śrīpati uses its synonyms *cāpa* (*Siddhāntaśekhara*, 19.13) and *kārmuka* (ibid., 19.27). This led some modern writers to conclude wrongly that *dhanuṣ* and *cāpa* are two different instruments; cf. S.R. Das, op. cit., pp. 262-63; D.M. Bose *et al*, op. cit., p. 125.

2 Cakradhara (fifteenth/sixteenth century) developed an improved model of the quadrant called *yantracintāmaṇi*; cf. R.N. Rai, op. cit., pp. 326-28.

3 *BSS*, 22.45.

4 Āryabhaṭa's *chatrayantra* works on the same principle. A similar instrument is described by Bhāskara I in his *Mahābhāskarīya*, 3.56-59, without any specific name.

5 *BSS*, 22.42-43.

6 *BSS*, 22.43-44. In their version of this instrument, Lalla (*Śiṣyadhīvṛddhida*, 21.24) and Śrīpati (*Siddhāntaśekhara*, 19.14) use only a single semi-circular plate to represent the equatorial plane.

7 *BSS*, 22. 19-38.

For measuring the angular distance between the sun and the moon, two staves are used. These are joined together at the lower end, the upper ends pointing to the sun and the moon respectively. In this position, the two staves look like the Roman letter "V" or like two shafts of a cart joined at the yoke. Hence Lalla and Śrīpati treat this as a separate instrument called *śakaṭa* (cart).[1] When the staff is used in land survey for measuring, for instance, the height and distance of buildings, this particular function is designated as *dhīyantra* by Bhāskara because it is the *dhī* (intellect) of the observer that is important.[2]

These, in brief, are the instruments and their functions according to Brahmagupta. Several of these are mentioned by him for the first time, but it is immaterial whether he invented any of them. More important is that he offers the first systematic study of the instruments and their use, with several alternative methods of computation, to go into which is beyond the scope of this paper. But when we compare the instruments selected by Brahmagupta with those mentioned by Āryabhaṭa or Varāhamihira, we are struck by the utter simplicity of design in Brahmagupta's instruments. Leaving aside the clepsydra—since there were many alternative methods of measuring the time since sunrise, it was not really essential—the rest of the instruments can be reduced to two basic types: a wooden circle with a graduated rim, and a wooden staff. With these two, the astronomer measured the zenith distance as an arc and the gnomonic shadow as a line, and calculated the rest from such simple measurements.

These instruments, and also the accessories mentioned before, are such that they can be manufactured everywhere with little or no skill. The basic idea seems to be that a tool or an instrument is just a means to an end. The end may be elaborate but the means must be the simplest possible. Even Bhāskara II who invented the *phalaka-yantra,* the only pre-Islamic instrument of some complexity, shares this attitude when he declares:

> What does a man of genius want with complex instruments on which scores of books have been written? Let him just take a staff in his hand and cast his eye from its one end to the top. There is no object in sight of which he cannot find out the measurements, be it on the earth, in water, or in the sky.[3]

This does not mean that the Indian astronomer totally ignored the observational aspect. He was well aware that the success of the *siddhānta* depended upon *dṛksāmya*, that is, the exact correspondence between the computed and observed results. When there was none, the *siddhānta* had to be revised accordingly. Thus Nīlakaṇṭha says: *yaḥ siddhānto darśanāvisaṃvādī bhavati so'nveṣaṇīyaḥ*: "when there are many textbooks, choose one that accords well with actual observations".[4] But it was thought that a few occasional sightings were enough for this purpose, and we have no record of systematic observations stretching over a long span of time (except in the case of

1 *Śiṣyadhīvṛddhida*, 21. 42-47; *Siddhāntaśekhara*, 19. 26-27.

2 *Siddhāntaśiromaṇi*, *Golādhyāya*, *Yantrādhyāya*, 40-49.

3 Ibid., 40.

4 In the *Jyotirmīmāṃsā*, quoted in *Source-Book*, p. 7.

Parameśvara of Kerala, who computed and observed a large number of eclipses between A.D. 1393 and 1432).

The result was that astronomical instruments did not develop any further from their simple design, nor did they lead to any significant advances in instrumentation technology. The instruments were of the simplest design and were made of wood or bamboo. These, then, could not have provided much precision in measurement, nor did their construction involve a meaningful interaction between the *siddhāntin* and *śilpin*. Hence these instruments could not vie with the astrolabe when it was introduced into India in the thirteenth century. On this versatile instrument, several elements can be read off directly without resorting to lengthy computations. Since its manufacture required a high degree of cooperation between the astronomer and the artisan, it also offered greater precision. Consequently, when Sawai Jai Singh II (1686-1743) looked for prototype instruments for carrying out systematic and precise observations, Sanskrit tradition had nothing to offer him, and he had to turn to Central Asian models.

III

The picture of the Indian astronomer that emerges from the discussion so far is that of one who took an occasional observation with the simplest of instruments but depended otherwise on his superior computational skill. No special tool or material was needed for computation either; it was carried out with the tip of his finger writing in the dust and was even called *dhūlikarman*. Therefore, it comes as a surprise that Brahmagupta and others devoted considerable space to complex automatic devices called *svayaṃvaha yantras* (self-propelling machines). It is difficult to reconcile these two attitudes: on the one hand, stark austerity as regards what we would consider today as an astronomer's essential equipment; on the other, free rein to imagination in devising more and more complex or amusing automata. Possibly, to a people forced to empty the sinking-bowl type of clepsydra sixty times in the course of a nychthemeron, the notion of a *yantra* that turned by itself was greatly tempting. Be that as it may, these devices form an interesting chapter in the history of human effort to master the sources of energy, and Brahmagupta's contribution to this chapter is not insignificant. It is, however, convenient to begin with Āryabhaṭa because he was the first to describe such machines. In a cryptic stanza in his *Āryabhaṭīya*, he says:

> The Sphere which is made of wood, perfectly spherical, uniformly dense all round but light (in weight) should be made to rotate keeping pace with time with the help of mercury, oil and water by the application of one's own intellect.[1]

Here he is obviously referring to a globe that rotates around its axis automatically at the rate of one rotation per 24 hours, but he does not tell us how to construct such a device. Fortunately, his commentators, Someśvara (eleventh/twelfth century), Sūryadeva

1 *Āryabhaṭīya, Gola*, 22: *kāṣṭhamayaṃ samavṛttaṃ samantataḥ samaguruṃ laghuṃ golam, pāradatailajalaistaṃ bhramayet svadhiyā ca kālasamam*. The translation is by K.S. Shukla; cf. his edited and translated version of the *Āryabhaṭīya*, op. cit., p. 129.

Yajvan (b. A.D. 1191), Parameśvara (*c.* A.D. 1450) and Nīlakaṇṭha Somasutvan (*c.* A.D. 1501), explain the process with a rare degree of unanimity. This is how Sūryadeva Yajvan describes the apparatus:

> Having set up two pillars on the ground, one towards the south and the other towards the north, mount on them the ends of the iron needle (rod) (which forms the axis of rotation of the Sphere). In the holes of the Sphere, at the south and north poles, pour some oil so that the Sphere may rotate smoothly. Then, underneath the west point of the Sphere, dig a pit and put into it a cylindrical jar with a hole in the bottom and as deep as the circumference of the Sphere. Fill it with water. Then, having fixed a nail at the west point of the Sphere, and having fastened one end of a string to it, carry the string downwards along the equator towards the east point, then stretch it upwards and carry it to the west point (again), and then fasten it to a dry hollow gourd (appropriately) filled with mercury and place it on the surface of water inside the cylindrical jar underneath, which is already filled with water. Then open the hole at the bottom of the jar so that with the outflow of water, the water inside the jar goes down. Consequently, the gourd which, due to the weight of mercury within it, does not leave the water, pulls the Sphere westwards. The outflow of water should be manipulated in such a way that in 30 *ghaṭīs* (=12 hours) half the water of the jar flows out and the Sphere makes one half of a rotation, and similarly, in the next 30 *ghaṭīs* the entire water of the jar flows out, the gourd reaches the bottom of the jar and the Sphere performs one complete rotation.[1]

In other words, this apparatus is powered by an outflow type clepsydra which empties itself in 60 *ghaṭikās*. Varāhamihira prescribed such a clepsydra for measuring time directly, but other astronomers rejected it. In his *Āryabhaṭasiddhānta* also, Āryabhaṭa describes some devices powered by the same type of cylindrical clepsydra which he calls a hollow pillar.[2]

Brahmagupta first makes an innovation in this clepsydra. He suggests that the length of the cylindrical jar (*nalaka*) should be calibrated into 60 equal divisions, each one denoting a *ghaṭikā*. Then, instead of simple string, a long narrow strip of cloth (*cīrī*) should be attached to the mercury-filled gourd. In this strip of cloth, 60 knots are tied at distances equal to the divisions marked on the cylinder, and the knots are numbered serially. Then, as the float goes down it pulls the strip of cloth with the knots downwards, and the passage of each knot beyond a certain point indicates the passage of a *ghaṭikā*.[3]

With this basic design, Brahmagupta devises a number of models. In the first, a male doll is set up in such a manner that, as the float goes down, the strip of cloth issues out of the doll's mouth. Thus after each *ghaṭikā*, the doll "spits out" a knot with the appropriate serial number written on it.[4] Or one can set up two dolls, a bride and bridegroom,

1 See K.V. Sarma, ed, *Āryabhaṭīya* with the commentary by Sūryadeva Yajvan (New Delhi, 1976), pp. 143-44 for the Sanskrit text; and K.S. Shukla, ed and tr., *Āryabhaṭīya*, op. cit., pp. 129-30 for the English translation.

2 See *Source-Book*, p. 84.

3 *BSS*, 22. 46-47.

4 Ibid., 22. 47-48.

and the numbered knots pass from the bridegroom's mouth to the bride's, like sweetmeat in some marriage ritual.[1] Another variation is to fix a small figurine or jack on each knot. As it passes a certain point, it releases a lever which hits a drum or rings a bell. Thus, after each *ghaṭikā*, a drum can be beaten or a bell rung.[2] Likewise, a peacock can be so constructed that it swallows or vomits a certain length of a snake in each *ghaṭikā*.[3]

All these ingenious devices are based on the erroneous assumption that the water level in the clepsydra falls by equal distances in equal time intervals. But the clepsydra used here is a regular cylinder called *stambha* by Āryabhaṭa and *nalaka* by Brahmagupta, and here the outflow of water cannot be uniform because of the changing water pressure. Consequently, the *ghaṭikās* indicated by these devices will not be of the same duration.

Nīlakaṇṭha Somasutvan raises this problem for the first time in his commentary on the *Āryabhaṭīya* written at the beginning of the sixteenth century. He says that if the cylinder has the same circumference at the top and the bottom, the outflow will be faster at the beginning, with the result that the armillary sphere will make a quarter rotation long before it is midday. Nīlakaṇṭha's solution to this problem is to vary the circumference at the top and the bottom, but he does not say how this should be done.[4]

Nīlakaṇṭha's solution is not entirely correct nor is it novel. The ancient Egyptians tried to regulate the water pressure by adopting a vessel with sloping sides. Their clepsydras shaped like truncated cones or buckets are attested from the thirteenth century B.C., but these did not show uniform time intervals either.[5] Therefore, in the Classical world, the Romans introduced cylindrical inflow clepsydra. Here water dripped into the cylindrical vessels from a reservoir in which the water level was kept constant. Hence, water dripped into the cylinder with a uniform speed and the water level in the cylinder rose accordingly. A float was set up in the cylinder, which rose along with the water level and marked the time against a scale. The same principle was followed in China.

Coming back to the automatic devices of Āryabhaṭa and Brahmagupta, these are survivals from the period when outflow clepsydra was used for measuring time directly. These automatic devices are technically feasible, but would indicate irregular time intervals. Lalla and Śrīpati accept Brahmagupta's automata without any hesitation,[6] but Bhāskara II rejects them as rustic contrivances (*grāmya*). His reason for rejection is not the absence of a uniform outflow—he is silent on this point—but that the cylinder has to be filled afresh every day. He would like instruments that turn absolutely on their own

1 Ibid., 22. 50.
2 Ibid., 22. 51-52.
3 Ibid., 22. 51.
4 *The Āryabhaṭīyam* with the Bhāṣya of Nīlakaṇṭha Somasutvan, Pt III (Trivandrum, 1957), pp. 38-39.
5 Curiously enough, in the thirteenth century A.D., al-Jazarī employs a bucket-shaped clepsydra with a float as the driving force for one of his water clocks. In this connection, Donald Hill remarks: "It would be exceedingly difficult to make a vessel by empirical methods, so that the water level fell by equal distances in equal time intervals". See Ibn al-Razzāz al-Jazarī, *The Book of Knowledge of Ingenious Mechanical Devices*, tr. and annotated by Donald R. Hill (Dordrecht/Boston, 1974), pp. 71-74, 250-51, esp. p. 250.
6 *Śiṣyadhīvṛddhida*, 21. 10-17; *Siddhāntaśekhara*, 19. 7-11.

without the aid of any human agency (*nirapekṣa*) and for ever.[1] The credit for conceiving such a machine goes to Brahmagupta.

IV

Brahmagupta's *perpetuum mobile* or machine with perpetual motion is a wheel made of light wood. Into its rim are inserted, at equal intervals, hollow spokes of equal size. Each spoke is half filled with mercury and then sealed. When the axle of this wheel is set up on two supports, the mercury runs up and down the spokes, and the wheel turns perpetually (*ajasraṃ bhramati*).[2] But what is the connection between this wheel and astronomy? Brahmagupta seems to think that by regulating the quantity of mercury, the speed of rotation can be so adjusted that the wheel functions as a time-keeping device.[3]

The idea of a mercury-powered wheel with perpetual motion seems to be Brahmagupta's own. Just as the alchemist thought that mercury can transmute base metals into gold, so does Brahmagupta hold that it can overcome inertia and cause the wheel to turn eternally. The belief in the miraculous power of mercury persisted in the eleventh century also when King Bhoja of Dhara assumed that it could overcome gravity and so raise an aerial car from the ground.[4]

Brahmagupta's *perpetuum mobile* was taken up enthusiastically by Lalla and Bhāskara. The former states that if the wheel with mercury-filled spokes is joined to the axle of an armillary sphere, it will rotate the armillary sphere continuously.[5] Bhāskara II suggests that the spokes should be slightly curved, all in the same direction as in a *nandyāvarta*. The wheel will then turn for ever because at some places the mercury runs towards the nave of the wheel and at other places towards the rim. He also proposes a new variation, in which a channel is cut in the rim of the wheel and filled half with water and half with mercury.[6]

One is apt to ridicule these devices as mere flights of fantasy and Brahmagupta's treatment of instruments as a tiresome mixture of science and superstition. Even Bhāskara did not see any connection between the serious pursuit of astronomy and these self-propelling devices. For him these were part of the juggler's (*kuhaka*) equipment, and he discussed them only because the previous astronomers (like Brahmagupta) had done so.[7] But he does not seem to entertain any doubts about the functioning of these devices.

Lynn White argues that such fantasies are also important in the history of ideas, and that the notion of perpetual motion, originating in India, led to important inventions in

1 *Siddhāntaśiromaṇi, Golādhyāya, Yantrādhyāya*, 57.
2 *BSS*, 22. 53-54.
3 *BSS*, 22. 55.
4 *Samarāṅgaṇa-Sūtradhāra*, ed, T. Ganapati Sastri and revised by V.S. Agrawala (Baroda, 1966), 31. 95-100. Some time-keeping devices are also described at 31. 66-71, but their mechanism is obscure. See also V. Raghavan, *Yantras or Mechanical Contrivances in Ancient India* (Indian Institute of Culture, Transaction No. 10), 2nd edn (Bangalore, 1956), pp. 24, 29.
5 *Śiṣyadhīvṛddhida*, 21. 18-19.
6 *Siddhāntaśiromaṇi, Golādhyāya, Yantrādhyāya*, 50-53.
7 Ibid., 58.

Europe. He observes:

> The symptom of the emergence of a conscious and generalized lust for natural energy and its application to human purposes is the enthusiastic adoption by thirteenth-century Europe of an idea which had originated in twelfth-century India—perpetual motion.[1]

Lynn White goes on to describe Bhāskara's two versions of *perpetuum mobile* and shows how this idea was instantly picked up and elaborated upon by the Islamic world and then transmitted to Europe. There the idea was received with intense and widespread interest and soon attempts were made to apply it for the benefit of mankind. Thus was laid the foundation of power technology in the modern world.

Now this study of Brahmagupta's instruments should enable us to see that the idea of perpetual motion, or more precisely the design for a perpetually moving machine, originated not in twelfth century India but much earlier—with Brahmagupta in the seventh century.

Needham, however, detects Chinese inspiration in Indian devices. He states:

> One gets a strong impression from some of the Sanskrit texts that the writer was trying to describe water-wheel clocks of Chinese type in veiled language, or else that he knew only vaguely how they worked. Indeed one begins to entertain the belief that the stimulus for the flood of ideas on perpetual motion devices may have been derived from Indian monks or Arabic merchants standing before a clock-tower such as that of Su Sung and marvelling at its regular action.[2]

In the light of the evidence which we have, it is difficult to agree with Needham's line of thinking. The Sanskrit texts he has in mind are the *Sūryasiddhānta* and the *Siddhānta-śiromaṇi* of Bhāskara; he is not aware that it is Brahmagupta who realized the feasibility of a perpetual motion machine. Moreover, Su Sung's clock-tower was built in A.D. 1090 and received the power from a water-wheel that was made to turn in the following manner:

> Water stored in the upper reservoir is delivered into the constant-level tank by a siphon and so passes to the scoops of the driving-wheel. ... As each scoop in turn descends the water is delivered into a sump. Apparently the clock was never so located as to be able to take advantage of a continuous water supply; instead of this, the water was raised by hand-operated norias in two stages to the upper reservoir.[3]

On the other hand, our attempt in this paper to chronologically study the automatic devices from Āryabhaṭa up to Bhāskara establishes, it is hoped, that these devices had a long history in India and operated on a totally different principle, namely, outflow clepsydra and sinking float, which was never popular in China as Needham admits.[4]

1 L. White, *Medieval Technology and Social Change* (Oxford, 1962), pp. 129-30.
2 J. Needham, *Science and Civilisation in China*, Vol. IV, Pt II (Cambridge, 1965), p. 540.
3 Ibid., pp. 457-58.
4 Ibid., p. 469.

However, Su Sung's clock-tower found an echo in India in one instance. Besides the two varieties of mercury-powered *perpetuum mobile* which we have discussed above, Bhāskara describes a third one. This consists of a large wheel to the rim of which pots are attached as in a noria. Through a copper siphon water is released into the topmost pot from a reservoir. As the pot is filled, it becomes heavy and goes down, and thus the wheel is rotated. The water falling down from the wheel is collected in a channel and "is made to go up into the reservoir, so that it need not be filled again".[1] This is the first and only mention of such water-wheels in Sanskrit texts. Bhāskara describes the siphon and its working principle in great detail as if it were a novelty. It would be interesting to investigate what Bhāskara's sources are.

After Bhāskara, the idea of perpetual motion does not seem to have enthused any astronomer in India. In the early seventeenth century, Raṅganātha thought that such machines were possible only in Europe. Commenting on the *Sūryasiddhānta's* reference to these devices, he declares:

> This science of self-propelling machines (*svayaṃvaha-vidyā*) is well practised by the people known as Firangis who live beyond the Seven Seas. Since it is part of jugglery (*kuhaka-vidyā*), there is no need to discuss it here at length.[2]

Raṅganātha belonged to an influential family of astrologers with contacts at the Moghul court. His brother was a protégé of Khān-i-Khānān Abdul Rahim Khan and a favourite of Jahangir.[3] Raṅganātha, therefore, may have seen or heard about the mechanical clocks and other contrivances brought by Europeans as gifts to the Moghul court. His, then, is one of the first Indian responses to European technology.

1 *Siddhāntaśiromaṇi*, *Golādhyāya*, *Yantrādhyāya*, 53-56.

2 In his commentary called *Gūḍhārthaprakāśa* on *Sūryasiddhānta*, 13. 22. The commentary is available in several editions.

3 For his genealogy, see Pingree, op. cit., p. 126.