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ON ASTRONOMY IN ANCIENT INDIA

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The development of astronomy in ancient India is reviewed in the light of new discoveries and insights regarding the rise of early science and mathematics.

A history of science or of ideas, in contrast to that of nations or governments, presents special problems. Assuming contemporary records have survived, it is easy to sketch the fortunes of kings, generals, and demagogues. In a history of ideas, on the other hand, the objective includes finding sources and transformations of ideas. The system of professional journals makes this task possible for our times. In contrast, the historian of ancient science is like a mariner in wide ocean who feels that a sighting of a bird points to the nearing of land, when the birds may themselves be crossing the ocean.

The temptation to the historian of ancient science to take a few scattered clues, dispersed in time, and create a story of birth and borrowing of ideas is immense. It is easy to be reckless and speak with an imperative especially if the story is likely to be popular with the readers. No wonder then that many students of ancient science have succumbed to this temptation. Who will not be a prophet, especially if there is some chance that one may be right ?

Yet, the scientific method requires that no history be accepted unless preponderant evidence exists that rules out any other reconstruction. Scientific theories must not merely explain, but they must exclude other possibilities.[1] This is the reason why the views regarding the Greek birth of early geometry, popular for several decades, to give just one example, are now being dismissed as being ahistorical.

Richard W. Hamming, a distinguished computing scientist of our times, has expressed the limitations of certain histories particularly effectively :

> "For many years the Egyptians were thought to have done their impressive stonework by brute strength and awkwardness. But consider the fact that the moving of an obelisk a few hundred feet taxed the abilities of the engineers

at the end of the Renaissance. The problem was that the obelisk was so large that if it were supported only at both ends, it would break in the middle due to its own weight. Yet the Egyptians quarried it, moved it down the Nile, and set it up; the Romans took it down, moved it across the Mediterranean, and set it up. Let us recognize that the ancients must have known a great deal to have done what they did, and not merely done it with masses of men.

"I have long been interested in the cathedrals of the Middle Ages. Just looking at them I cannot believe they were built by dumb luck and by trial and error. As a result of remarks along these lines I went down to Princeton one afternoon to meet with some historians of the Middle Ages, and to discuss how much the builders must have known. The historians claimed that because they had the curriculum of the schools they therefore knew what the builders did and did not know. I remarked that if they thought that the Princeton University curriculum in mathematics has much relation to what we know and use in mathematics, then they were very wrong.

"The historians claimed that since Beauvais fell down that proved that the builders had no adequate theory. I replied that the Tacoma bridge blew down but that does not prove we had no theory—only that the engineer had been careless.

"Finally, they claimed that there were large cost overruns for many of the cathedrals. I remarked that the Sidney Opera House had a great cost overrun, and that the military was famous for cost overruns, but that this does not prove the lack of adequate theory.

"Studies of the cathedrals by others indicate that they were remarkably well designed. The fact that they have lasted this long is obvious proof without making any technical studies.

"I have long had a hobby of looking at old engineering feats, like old tunnels, and speculating on what the builders probably knew and had technical control over. My conclusions are often at great variance from what I read in history books. When you further consider the social and economic climate that could produce the works you find further differences between what common sense suggests and books report. To repeat my point, the differences arise from the historian's refusal to believe that the past knew more than the documents that have come down to us indicate. They refuse to apply informed common sense plus a feeling for practical engineering and to try to guess at probable states of information, technology, economics, and social organization".[2]

How should one then address the problem of discovering the origin and transmission of ideas ? Perhaps we see such patterns that our minds can relate to. The potential to understand any phenomenon exists in the human consciousness, by definition. It is not inconceivable then, that ideas and patterns can arise independently in many different minds, and they must have arisen thus in the past. One cannot always identify sources. Of greater probability of success than a history of ideas, is the enterprise of the history of technology, and of written documents. Obviously, such histories are circumscribed by the accident of certain records having survived. Perhaps it is this reason why the ancient Indians downplayed history. Having done so they remained, paradoxically, more aware of the antiquity of their past than any other people.

Hamming's observations are especially valid when one examines accounts of ancient Indian astronomy. This is not only because very few ancient texts have come down to us, but also because recent archaeological discoveries are forcing a revision of the chronology of ancient India.[3] This revision has generally been overlooked by the historian of science. Furthermore, the important work of Seidenberg[4] has shown how the ritual geometry of the *Śulbasūtras* should be dated to at least 1700 B.C. The *Śulbas* deal with linear indeterminate equations to solve problems of altar design. Similar equations are at the basis of later Indian astronomy. The question that arises is whether the later astronomy only reflects attitudes that go back to the second millennium B.C. or even earlier. The revision of the chronology of ancient India also requires that the astronomical references in the Vedic and later Sanskrit literature,[5] that have been ignored in the past, be evaluated afresh.

The traditions of Indian astronomy may be divided into three periods :

1. First period (upto *c.* 1000 B.C.—this includes the Harappan and Vedic phases)
2. Middle period (1000 B.C.—400 A.D.)
3. Classical period (400 A.D. onwards)

While our increasing understanding of the Harappan and the Vedic times is bound to effect most the history of the first two periods, a detailed chronology of the scientific developments in these periods is still lacking. Therefore, I shall only briefly comment on these two periods, and do so merely to call attention to their relation to the third period, and not speculate on the astronomical developments that may have occurred in, say, the Harappan age.[6] The main objective of this essay is to review our understanding of the broad developments leading to the Classical period, in light of the new archaeological and literary evidence. I shall also comment on the controversy[7] between Billard[8] and Pingree[9] whose opposite viewpoints may be seen as successors to similar polarized debates that took place in the 19th century.

I begin with a summary of the main physical assumptions behind the models used in the Classical period. In order to keep my presentation brief, I describe the system of *Āryabhaṭīya* alone. This choice is made because it is the first major canon of the Classical period that is known relatively completely to us, and also because similar models lay at the bases of the other canons. Indeed, the connections to computing techniques implied by *Āryabhaṭīya* are generally true for the entire Classical period.

II

Consider first Āryabhaṭa's method of science. This can only be guessed since, like Pāṇini's grammar, *Āryabhaṭīya* is a summary of results so that the reader must find the theoretical framowork himself.[10]

1.1 In a *yuga* the revolutions of the Sun are 4,320,000, of the Moon 57,753,336, of the Earth eastward 1,582,237,500, of Saturn 146,564, of Jupiter 364,224, of Mars 2,296,824, of Mercury and Venus the same as those of the Sun,

1.2 of the apsis of the Moon 488,219, of (the conjunction of) Mercury 17,937,020, of (the conjunction of) Venus 7,022,388, of (the conjunctions of) the others the same as those of the Sun, of the node of the Moon westward 232,226 starting at the beginning of Meṣa at sunrise on Wednesday at Laṅkā.

Not only do these stanzas include declaration of the rotation of the Earth on its axis, they also imply that the universe is dynamic with repeating behaviour that can be determined. Taking the Earth to rotate, in contrast to most astronomers of the day who took the asterisms to move, is an example of choosing a simpler model that is also a well-known tradition of the Indian grammarians.

1.3 There are 14 Manus in a day of Brahman [a *kalpa*], and 72 *yugas* constitute the period of a Manu. Since the beginning of this *kalpa* up to the Thursday of the Bhārata battle 6 Manus, 27 *yugas*, and 3 *yugapādas* have elapsed.

According to later tradition, Āryabhaṭa believed in each *yuga* having four equal parts, whereas the conventional usage had been division in the proportion of 4,3,2, and 1. Āryabhaṭa divided a *kalpa* into $14 \times 72 = 1008$ *yugas*. The peculiar division of a *kalpa* into 14 parts has been taken by some to indicate a knowledge of the precession of the equinoxes.[11] The current quarteryuga, *Kaliyuga*, is taken by Āryabhaṭa to have begun on Friday, February 18, 3102 B.C. at the time of the famous Bhārata War. Sengupta has argued that this reference to the epoch of the War could not be based on fact.[12]

The periodicities inherent in the *yugas* seem a reflection of the cosmology of *Sāṃkhya*. One can argue that the figure of 4320 million years for the *kalpa* is the least common multiple of all the periodicities observed in the motions of the planets.

> 1.4 The revolutions of the Moon (in a *yuga*) multiplied by 12 are signs [*rāśi*]. The signs multiplied by 30 are degrees. The degrees multiplied by 60 are minutes. The minutes multipled by 10 are *yojanas* (of the circumference of the sky). The Earth moves one minute in a *prāṇa*. The circumference of the sky (in *yojanas*) divided by the revolutions of a planet in a *yuga* gives the *yojanas* of the planet's orbits. The orbit of the Sun is a sixtieth part of the circle of asterisms.

Apparently the model used by Āryabhaṭa to describe the planets is one where all the mean planets move with the same speed. The Earth is taken to move 600 *yojanas* per *prāṇa*. The circumference of the sky (Universe) amounts to 12,474,720,576,000 *yojanas*.

The next stanzas describe a double epicycle theory in detail which is developed further in part 3 of *Āryabhaṭīya*. In the Indian epicycle theories the planets move on a weighted sum of two concentric epicycles, called *manda* and *śīghra*, the centre of which in turn orbits the centre of the earth ; the sun and the moon likewise orbit the earth, now riding a single *manda* epicycle each. The integration of the two epicycles is done by defining points (*ucca*) on the *manda* and *śīghra* from where forces pull the planets on to their epicycles. The exact method of integration varies from one school of astronomers to another. The earliest evidence of this double epicycle theory is the *Paitāmaha Siddhānta*, which is anterior to Āryabhaṭa, but is available to us in a later compilation called *Viṣṇudharmottara Purāṇa*. In *Āryabhaṭīya* the *manda* and the *śīghra* epicycles of the planets are taken to be pulsating (A 1.8 and A 1.9).

> 4.8 During a day of Brahman the sphere of the Earth increases a *yojana* in size all around. During a night of Brahman, which is equal in length to a day of Brahman, there is a decrease by the same amount of the Earth which has been increased by Earth.

This implies a system where the universe goes through cycles of expansion and contraction. It should be noted that this expansion does not start from a singularity, as in modern theories of cosmology. It is hard to imagine what physical insight may have been used by Āryabhaṭa to make his assertion about expansion and contraction. We do not know how this was reconciled to the conservation principle at the basis of evolution in *Sāṃkhya*, nor if it requires an explanation only available from other contemporary comentators.

The planets were assumed to move pushed by a wind. Yet this wind was really a visualization of a process, since it was taken to be the cause of the motion of all astronomical objects. There does not appear to have been an attempt to create a science of dynamics. The systems of Āryabhaṭa and others were merely computational systems. It was thus considered reasonable if a set of parameters worked for several decades or a few centuries, so long as the system allowed change of constants to reflect later observations. In other words astronomy was taken as a science like grammar, where new rules or modifications to old rules may be needed as language itself changed.

Āryabhaṭa himself does not refer to the shifting of equinoxes, yet other canons contemporaneous and ones that follow do. For instance Varāha (*c.* 550 A.D.) mentions a theory of trepidation over an arc of 46 ; 40° to −23 ; 20″. According to Govindasvāmin (*c.* 850 A.D.), Āryabhaṭa claimed that the equinox moved at the rate of 0 ; 1° in one year down for 24° and then back up through the same range. Govindasvāmin further adds that (vernal) equinox was measured by Āryabhaṭa to be at the beginning of Aries in Śaka 444 (522 A.D.). This seems to be reasonable because if Āryabhaṭa made his own careful measurements starting 510 A.D., his system would have been fully developed much later. The establishment of his school can thus be taken to be *c.* 520 A.D. or thereabouts.

Bhāskara I (*c.* 550 A.D.) mentions a precession rate of about 0 ; 0,57° per year. On the other hand Bhāskara II (*c.* 1150 A.D.) speaks of a rate of precession that is close to 0 ; 1° per year.

To what extent was this physical model of Āryabhaṭa's time indebted to models and observations elsewhere, say in Persia, Babylon and Alexandria, is hard to establish conclusively now. No doubt there was considerable interaction, and many words in Sanskrit dealing with astronomy seem to be derived from Greek words. On the other hand the history of India during the Middle period is full of such gaps that it may not be possible to sketch the story of the birth and transfer of ideas. Also note that according to Herodotus the empire of Darius [Darayavahuś] (reigned 521-486 B.C.) that stretched from Ionia and Egypt to the Indus, included fringes of West India as just one province out of a total of twenty, yet one third of the total tribute paid by all these provinces came from the Indian province.[13] Since the wealth of a nation and its scientific development seem to be correlated, one cannot dismiss the possibility that India's was a civilization with the most highly advanced science during those times.

III

The first important analysis of Indian astronomy was done by Jean Sylvain Bailly (1736-1793) who, in 1787, published his *Traite de l'Astronomie Indienne et*

Orientale and argued that the Indian tables were based on accurate observations, some of which were made as early as 4300 B.C. Bailly's main thesis found a champion in the great mathematician and astronomer Laplace who, having discovered the inequality in the motions of Jupiter and Saturn, wrote in 1787 : "I find by my theory, that at the Indian epoch of 3101 years before Christ, the apparent and annual mean motion of Saturn was 12° 13′ 14″, and the Indian tables make it 12° 13′ 13″. In like manner, I find that the annual and apparent mean motion of Jupiter at that epoch was 30° 20′ 42″, precisely as in the Indian astronomy".[14]

The views of Bailly and Laplace were attacked by several scholars mainly on the ground that as later Indian astronomy does not indicate evidence of careful and accurate observations, ascribing precise measurements to a much earlier epoch could not be accepted. This criticism is only partly true, and the explanation of the data that led Bailly and Laplace to their conclusions is yet to come. In particular the following question is of great interest : if these values were the incorrect observations of a later epoch, can one make an estimate of that epoch ? On the other hand if these values were extrapolated in comparatively recent times then what model was used for that extrapolation ?

William Jones argued that as Parāśara mentions the equinoctial points to have been at one time in Meṣa and Tulā, this must have occurred about 1181 B.C. This was followed by papers by John Bentley who criticized Bailly's assumptions and argued that the Indian system could not have great antiquity. H.T. Colebrooke, in an essay in 1816, pointed out that several technical terms used by the later Indian astrologers and astronomers were of non-Sanskrit origin, two examples being *horā* (ωρα) for hour, and *kendra* (κεντρον) for the distance of a planet from the apsis of its orbit. Earlier he had noted the correspondence of the Indian signs of the Zodiac with those of the Greeks.

Colebrooke's review noted that the Indian systems had some similarity with the Greek, though there were differences. He wrote "At the first glance it will remind the reader of the hypothesis of an eccentric orbit devised by Hipparchus ; and of that of an epicycle on a deferent, said to have been invented by Apollonius, but applied by Hipparchus, At the same time the omission of an equant (having double the eccentricity of the deferent), imagined by Ptolemy for the five minor planets, as well as the epicycle with a defetent of the centre of the eccentric, contrived by him to account for the evection of the Moon—and the circle of anomaly of eccentricity, adapted to the inequality of Mercury's motions—cannot fail to attract notice".[15]

This suggested that the latter Indian astronomy borrowed several ideas from Greek sources before the time of Ptolemy. Colebrooke did note, however, that the equation of the centre of the sun, as deduced from the epicycles used by

Brahmagupta and others was closer to the truth than Ptolemy, At the same time their values for the mean motions of the planets were worse. Colebrooke concluded that apart ftom using Greek tables, Indians must have made their own observations.

After Colebrooke, the discovery of new manuscripts revealing the existence of several schools showed that Indian astronomy could not be viewed as a monolithic entity. The diversity of the literature gave enough arguments to the protagonists of both the opposing viewpoints: 1) Indian astronomy is essentially an independens development, 2) It is derived ftom Greek sources.

To summarize, the notion that the Classical Indian astronomy uses key Greek ideas is based on the followina premises: 1) Several technical terms in sanskrit are apparently of Greek origin, 2) There was definite interaction between the Greek and the Indians after Alexander, 3) Ideas used at a much later period in Indian astronomy are known to have been in use in Greece, 4) Many observations in the *Siddhāntas* are inaccurate suggesting that the Indians did not have good instruments. This last premise was reinforced by al-Bīrūnī[16] who claimed that the Indians were ill-informed regarding the fixed stars, astronomical objects that can be measured most accurately. But it is well known that Bīrūnī's statements cannot be generally accepted at the face value since he did not have access to the main centres of learning in Banaras and Kashmir. Furthermore the country was at war and it is likely that his informants were mere dabblers in astronomy. Colebrooke's own admission of some accurate observations by the Indians and Roger Billard's demonstration that Āryabhaṭa, Brahmagupta and others must have made very accurate observations in their own epochs go counter to a Greek origin. Also the Indian epicycle theories are different to the Greek epicycle theories, and if the double epicycle was borrowed from Greece there is no explanation why the Ptolemaic system made no inroads in India. Furthermore, the Indian astronomical treatises of the post-Āryabhaṭa age always claim to be based on earlier native traditions.

IV

Let me briefly review the knowledge of astronomy during the Vedic and the Middle periods.

Vedic Astronomy

There is mention of *yugas* of different periods, but the most frequent duration is that of 3 years. The year is divided into two parts (*ayanas*); in the *uttarāyana* the sun travels north, in the *dakṣināyana* it travels south, This division suggests that the solstices were well defined, The year is divided into twelve synodic months of 29 or 30 days. An intercalary month, *adhimāsa,* was used to make the beginning of the sun's *ayanas* fall in the correct months. While the exact rule of intercalation is not known, it is easy to establish that the *Vedāṅga Jyotiṣa* period relation of

3 solar years = 62 synodic months ;

= 1830 sidereal days;

must have been known.

To establish this I begin with the fact that the *nakṣatras* were known to the *Ṛgvedic ṛṣis* and an argument has been made for the Harappans also possessing this knowledge. The *nakṣatras* are the 27 (or 28) star groups with one of each the moon is conjoined each night, The fact that the Abhijit, the 28th *nakṣatra,* is mentioned infrequently means that the Vedic Indians knew that the sidereal month was between 27 and 28 days. At the same time the synodic month was taken to be 29 or 30 days, Given these facts and the knowledge that a five year *yuga* contained 1830 sidereal or civil days (which a people greatly concerned about a sidereal month can be safely taken to have possessed), if the number of intercalary months were i, then

$$(60+i)\ (29+0.y) = 1{,}830$$

Now i is an integer, and $0.y$ a fraction, A simple calculation will show that the only value i can take is 2, This conclusion is true regardless of whether sidereal or civil days are taken.

This above argument is corroborated by the date of the *Vedāṅga Jyotiṣa* of Lagadha as fixed by its verses 5-6 in the Ṛk recension :

> The beginning of the *uttarāyana,* the *Śuklapakṣa* of Māgha, and the *yuga* is fixed by the moon and the sun conjoined with Vāsava (the *nakṣatra* Śraviṣṭhā). At the beginning of Śraviṣṭhā in (the month of) Māgha the sun and the moon proceed northwards ; at the middle of Sarpa [Āśleṣā], in (the month of) Śrāvaṇa, they proceed southwards,

This implies a date of 1180 B.C. because that is when the beginning of Śraviṣṭhā coincided with the winter solstice. It has been argued by Pingree[17] that this date is not to be trusted because an error of 10° in the definition of the *nakṣatra* and that of 10 days in computing the date of the winter solstice would bring the date down to 500 B.C. or so, Pingree's argument is not valid because even without very precise measurements, repeated observations tend to bring the average of a measurement close to the true value, and it is unreasonable to imply that the *Vedāṅga Jyotiṣa* statement is based on a single value. In fact, given that the cumulative effect of the displacement of the beginning of Śraviṣṭhā as well as the computation of the winter solstice is given approximately be the Gaussian distribution the date of the *Vedāṅga Jyotiṣa* would be fixed at plus-minus a few decades of 1180 B.C. Furthermore, the fact that the period relation of the *Vedāṅga Jyotiṣa* is implied in the astronomical references in the Vedas and the Brāhmaṇas (all anterior to 1000 B.C.) corroborates out the dating.

The *Vedāṅga Jyotiṣa* also mentions a division of a synodic month into 30 *tithis*, as well as the use of a waterclock to measure the length of daylight. The waterclock is attested in cuneiform texts of Babylon from about 700 B.C. on, Furthermore, it takes the ratio of the longest to the shortest day of the year as 1.5 which was also used by the Babylonians.

Considering that Kassites, a proto-Indoaryan people, ruled Babylon for 600 years until the 12th century B.C., and that the Vedic period itself stretches back to 2000 B.C. if not much earlier, the only conclusion that follows is that the Babylonians must have received Vedic astronomy in the second millennium B.C. itself, to which they later made important contributions.

The reverse conclusion that the *Vedāṅga Jyotiṣa* follows Babylonian astronomy is ruled out because (1) its internal date precedes the Babylonian astronomy by several centuries, (2) the *Vedāṅga Jyotiṣa* period information is implied in the Vedic references that again date centuries earlier, (3) the rule of the Kassites attests the interaction of the proto-Indoaryan (Vedic ?) people and Babylon.

The *Vedāṅga Jyotiṣa* is likely to have expressed astronomical knowledge of an eveu earlier age. During the early Vedic age the Aryans were confined to northwest India. For this region the ratio of 3 : 2 for the durations of the longest and the shortest days is correct. To force, in contradiction to data, the epoch of the *Vedāṅga Jyotiṣa* to half a millennium later, and to a different geographical region and then claim that this ratio was now approximate makes no sense.

Lagadha in his *Vedāṅga Jyotiṣa* also gives the linear zigzag function used several centuries later by the Babylonians to determine the amount of water to be put in the waterclock to measure the daily sunlight. The use of such zigrzg functions by the Babylonians must, therefore, be taken as a borrowing from the Vedic period.

The Middle Period

The contributions of the Middle period can only be inferred from the *Siddhāntas* of the Classical period in so much as these were revisions of the earlier siddhāntas. Thus Lagadha's zigzag function also appears in a *Paitāmahasiddhānta* of 11 January, 80 A.D. In general one sees a continuity with the Vedic concepts. The new development, that must have occurred in the Middle period, is the idea of epicycles.

We have mentioned that the general view is that the epicycle theory was borrowed from the Greeks before the time of Ptolemy. New evidence put forward by Neugebauer,[18] and by van der Waerden[19] necessitates a change in this view. Neugebauer's analysis of Papyrus Michigan 149 shows an epicycle theory where the epicycles of the outer planets Mars, Jupiter and Saturn move to the right, which is the wrong sense in terms of Ptolemy. According to van der Waerden, a primitive epicycle theory must have been known before Apollonius (*c.* 200 B.C.), and even before Aristarchus (*c.* 280 B.C.). He has argued that even Plato (427-347) alludes to an epicycle theory in *Republic* and *Timaeus*. In fact there is an old tradition in Greece that attributes to Pythagoras a knowledge of epicycles and eccentrics. Neugebauer and van der Waerden's work has established that this tradition should be considered as reliable.

To summarize van der Waerden's reconstruction, a primitive epicycle theory was known to the Pythagoreans. This theory worked well for the Sun, Mercury, and Venus but was quite inadequate for the other planets. In order to obtain a uniform theory for all planets, Plato asked the question : "By what assumptions of uniform, ordered, circular motion can one save the appearances ?" This is what lead to the concentric spheres of Eudoxus. Eventually, the mature epicycle theory of Apollonius and Hipparchus evolved.

Now it has been shown by Neugebauer, van der Waerden and others how the so called theorem of Pythagoras was known a thousand years before Pythagoras to the Babylonians. Seidenberg[20] has presented a powerful case for a ritual origin of geometry and mathematics and shown how the early mathematics of the Greeks and the Babylonians is to be seen as resulting from an earlier mathematics preserved in the ritual mathematics of the Vedic world. It is natural, therefore, to suppose that the primitive epicycle theory of the Pythagoreans was likewise known to the Vedic Indians much before the time of Pythagoras. Indeed, as has already been observed, the presence of the proto-Indoaryans in West Asia in the second millennium B.C. establishes a possible causal link.

To push this argument further, the epicycle astronomy of the Indians evolved out of this primitive epicycle theory of the proto-Indoaryans. This epicycle theory was developed further by the Greeks and the Indians separately. This separate development explains why the Indian epicycle astronomy has features that do not include the widely known developments of Greek astronomy, in particular the Ptolemaic system. The Middle period of Indian astronomy did see interaction with the Greeks. That is how certain Greek advances became known to the Indians. The names of the *Siddhāntas* such as Romaka and Puliśa attests to this. Classical Indian astronomy from the time of Āryabhaṭa onwards must be considered syncretic, therefore. In opposition to the opinion of Pingree who claims this phase to be essentially Greek, I believe that the correct view is to take it as essentially Indian with some Greek influence. There is no other explanation possible for the fact that the Indians ignored most aspects of Ptolemaic astronomy until the seventeenth century. Furthermore, in support of my view consider the very last verse of *Āryabhaṭīya* :

> This work, *Āryabhaṭīya* by name, is the same as the ancient *Svāyambhūva* (which was revealed by Svayambhū) and as such it is true for all time. [Shukla and Sarma translation].

This means that Āryabhaṭa was using models that were known to the Indians for a very long time.

V

Consider now the implications of Roger Billard's fundamental work on our understanding of Indian astronomy. Every canon of the Classical period presents a basic set of elements from which the planetary positions can be computed for any time. These computations begin with the calculations of mean longitudes, which are taken to be linear functions of time. Three other functions of time that are considered are the vernal equinox, the lunar node, and the lunar apogee. Billard has investigated these ten linear functions : five for the planets, two for the sun (that includes the vernal equinox), and three for the moon.

Billard has plotted the difference between the values for these ten functions using the Indian *Siddhāntas* and modern theory. Since the Indian systems become progressively less exact with time, and require introduction of corrections, or *bīja*, with time if it is desired that they should continue to be exact, it is possible to find when a particular system, without the *bīja* was accurate. Billard thus finds that the Āryabhaṭa systems were based on very accurate observations in 510 A.D. where these differences (called *ecarts* in Billard's book) are nearly zero for all planets except Mercury. Similar convergence allows Billard to date the observations used in the other canons. We reproduce two graphs from Billard (Figs. 1 & 2) that demonstrates an epoch of 500 A.D. for the *Sūryasiddhānta* and 510 A.D. for Āryabhaṭa's measurements. The system of Lalla based on measurements of Āryabhaṭa and his own made around 898 A.D. gives accurate sidereal longitudes for all planets except Mercury for the whole period from 400 A.D. to 900 A.D.. This is summarized in another Figure (3) taken from Billard.

The inference to be drawn from these dates is that measurements and not mere theorizing led to the development of Indian schools of astronomy. The double epicycle evolved independently in India, perhaps as a modification of a primitive epicycle theory generally known to the Indo-Europeans already by 700 B.C. The systems of Indian astronomy were so established by 300 A.D. or so that the *Romaka* and *Puliśa Siddhāntas*, that are obviously of a non-Indian inspiration, had to be cast in the framework of Indian astronomy.

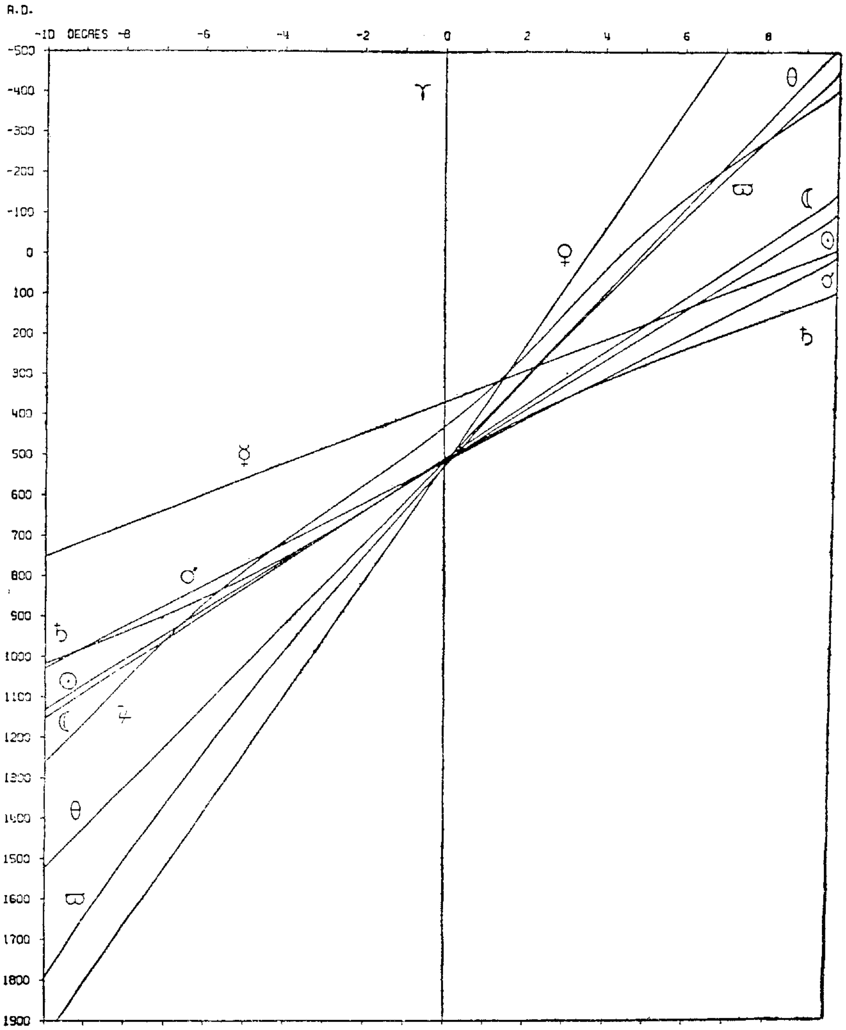

Fig. 1. Differences in Longitudes (*Sūryasiddhānta*)

In conclusion, there is strong evidence to date the *Vedāṅga Jyotiṣa* of Lagadha back to its own internal date of around 1180 B.C. Furthermore, the recent demonstration that an epicycle theory can be dated back to Pythagoras suggests that he may have received knowledge of it from his masters just as he is supposed to have learnt the famous theorem now named after him. While we cannot say where the primitive epicycle theory was first conceived, it is easy to see how the Indian double epicycle theories must have developed independently. Only an independent development explains the resistance in India to the later advances of Greek astronomy.

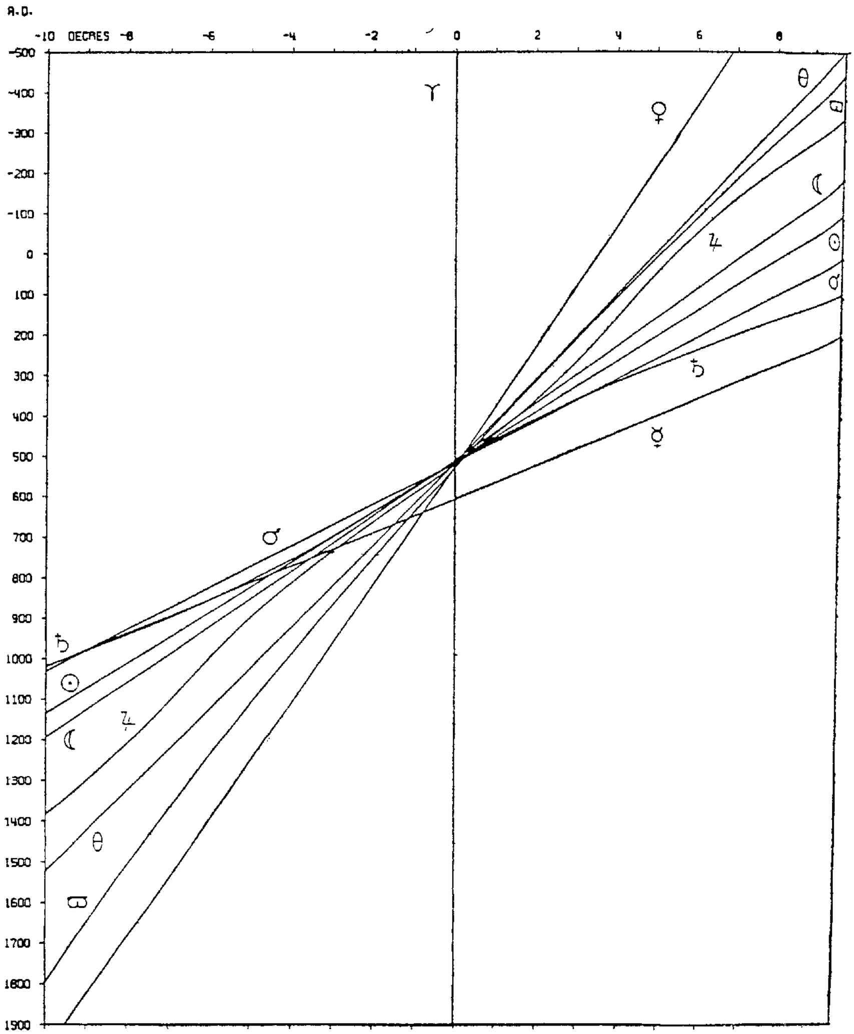

Fig. 2. Difference in Longitudes (*Āryabhaṭīya*)

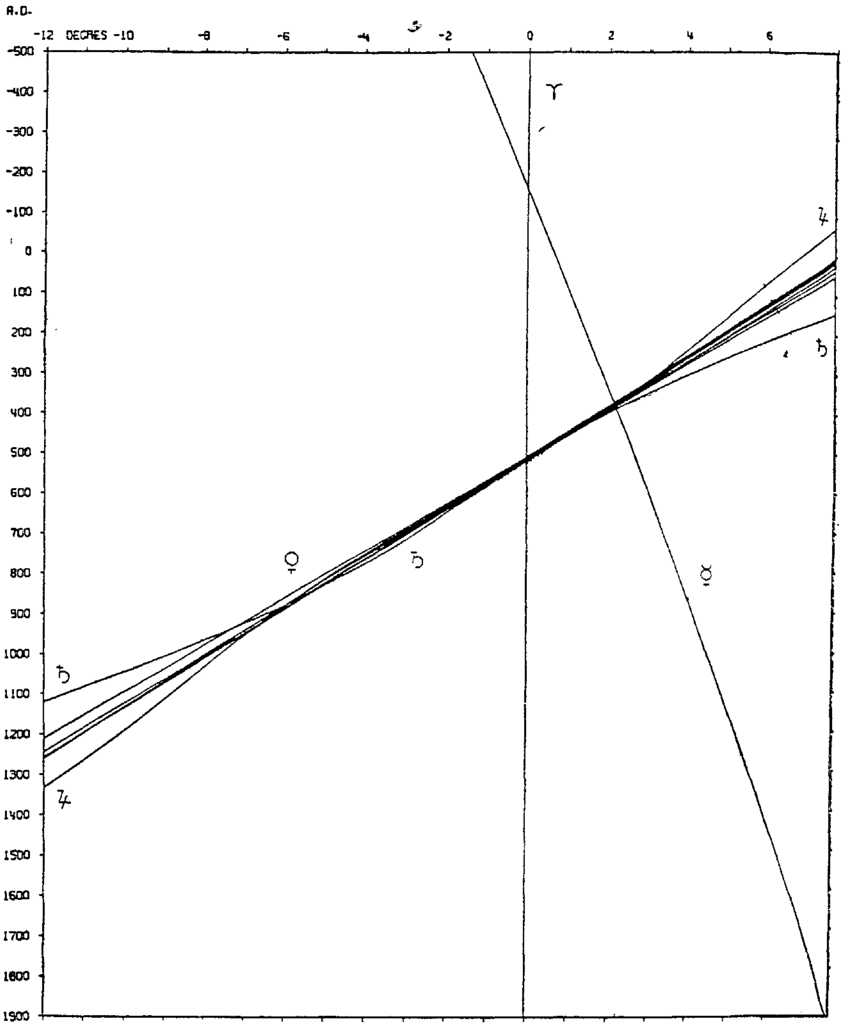

Fig. 3. Difference in Longitudes (*Lalla*)

REFERENCES AND NOTES

[1] The essential scientific method was captured, unwittingly, in a memorable phrase by John Whittaker who talking about Mussolini's Italy in Saturday Evening Post (December 23, 1939, p. 53) wrote : Coffee is forbidden, the use of motorcars banned and meat proscribed twice a week, until one says of Fascism, *Everything which is not compulsory is forbidden.* Of course what is true of Fascism is also true of several fundamentalist movements.

[2] Hamming, R. W., We would Know what They Thought when They Did it, in *A History of Computing in the Twentieth Century*, Edited by N. Metropolis, J. Howlett, and G.—C Rota, New York, 1980,

[3] Burrow, T., The Proto-Indoaryans, *J. Royal Asiatic Society*, 123-140, 1973 ; Allchin, B. and Allchin, R., *The Rise of Civilization in India and Pakistan*, Cambridge, 1982 ; Kak, S., On the Chronology of Ancient India, *Indian Journal of History of Science*, **22**, 222-234, 1987.

[4] Seidenberg, A., The Ritual Origin of Geometry, *Archive for History of Exact Sciences*, **1**, 488-527, 1962 ; The Origin of Mathematics, *Archive for History of Exact Sciences*, **18**, 301-342, 1978.

[5] Sengupta, P. C., Bhārata-battle Traditions, *J. Royal Society of Bengal Letters*, **4**, 393-413, 1938 ; Kak, S., *op.cit.*.

[6] For two conjectural accounts of the contributions of the Harappans *see* Parpola, A., Tasks, Methods and Results in the Study of the Indus Script, *J. Royal Asiatic Society*, No. 2, 178-209. 1975 ; Ashfaque, S. M., Astronomy in Indus Valley Civilization, *Centaurus*, **21**, 149-193, 1977.

[7] *See* for example van der Waerden, B. L., Two Treatises on Indian Astronomy, *J. for the History of Astronomy*, **11**, 50-62, 1980.

[8] Billard, R., *L'astronomie Indienne*, Paris, 1971.

[9] Pingree, D., History of Mathematical Astronomy in India, *Dictionary of Scientific Biography*, 1978, Vol. 15, pp. 533-633.

[10] One of earliest reference to *kalpa* dates to the time of *Dharma Śāstra.* In another system 1 *kalpa* = 4320 million years = $(14 \times 714 + 4)$ times a Great *Yuga* of 432 thousand years. Since the solstice goes back 14° (50,400 seconds) in 1000 years, this gives a precession of 50.4″ (Brennand, 1986).

There are allusions to *kalpa* in the *Ṛgveda* itself. Accoring to G. de Santillana and H. von Dechend (*Hamlet's Mill*, Boston, 1969) the total number of syllables in the 10,800 stanzas of the *Ṛgveda* is 432,000. Also in *RV* 4.58 the verses 2 and 3 go :

So let the Brahman hear the praise we utter.
This has the four-horned Buffalo revealed.
Four are his horns three are his feet that bear him ;
his heads are two, his hands are seven in number.
Bound threefold, the bull bellows. The mighty god has entered mortals.

According to McClain (McClain, E.G., *The Myth of Invariance*, Boulder, 1978) the Indians must have known a positional number system at the time of the composition of the hymn :

4	:	horns
3	:	feet
2	:	heads
000 0000	:	seven hands (10^7 fingers)
4,320,000,000	:	years in *kalpa*.

He further interprets the 'triple bonds' to be the powers of the three prime numbers: $2^{11} \times 3^{3} \times 5^{7}$ = 4,320,000,000. Elsewhere, McClain also discusses allusions to a knowledge of precession. This suggests that the 'Great Year' of the Babylonians (432,000 years) described by Berossos, the last priest of Marduk (300 B.C.), was most probably derived from the Indians.

[11] The translation of *Āryabhaṭīya* that follows are from Clark, W.E., *The Aryabhaṭiya of Aryabhaṭa*. Chicago, 1930.

[12] Sengupta, P. C., *op.cit.* ; see also Van der Wearden, B. L., The Conjunction of 3102 B.C., *Centaurus*, **24**, 117-131, 1980.

[13]Herodotus, *The Histories*, Tr. by Aubrey de Selincourt, Harmondsworth, 1983, p. 244. Note that the reign of Darius precedes the golden age of Babylonian astronomy (5th-4th century B.C.)

[14]Quoted in Burgess, J., Notes on Hindu Astronomy and the History of Our Knowledge of It, *J. Royal Asiatic Society*, 717-761, 1893.

[15]Colebrooke, H. T., On the Notion of the Hindu Astronomers Concerning the Precession of Equinoxes and Motions of the Planets, *Asiatic Researches*, **12**, 209-250, 1816.

[16]Al-Bīrūnī (1030 A.D.) in *Alberuni's India* by Sachau, E.C., (1888). Reprinted, Delhi, 1964.

[17]Pingree, D., The Mesopotamian Origin of Early Indian Mathematical Astronomy, *J. for the History of Astronomy*, **4**, 1-12, 1973.

Also see Kuppanna Sastry, T. S., *Vedāṅga Jyotiṣa of Lagadha*, New Delhi, 1985.

[18]Neugebauer, O., Planetary Motion in P. Michigan 149, *Bull. Amer. Soc. Papyrologists*, **9**, 19-22, 1972.

[19]Van der Waerden, B. L., The Earliest Form of the Epicycle Theory, *J. for the History of Astronomy*, **5**, 175-85, 1974.

[20]Seidenborg, A., *op. cit.*