# Astronomical computation for the history of Indian Astronomy

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*Introduction*

In any branch of the history of astronomy one has to be sure that the texts describe heavenly phenomena in way that is in some sense 'realistic', and not pure fantasy. We are in a better position now than ever before to compute the positions of the Sun, Moon and planets for medieval and ancient periods, and accordingly better able to understand the true status of early texts. In Sanskrit texts there has always been an acute problem, in that the numerical apparatus makes use of immense intervals of time, and an origin in an impossibly remote past. Moreover the texts lack any reference to observations or other circumstantial details, so that many scholars have concluded that the numerical details were the product of armchair speculation, or were at best borrowed from non-Indian sources, such as Greek or Babylonian astronomy. This of course ignores the fact that there is a multitude of Sanskrit texts and inscriptions, apart from the astronomical literature, which record not only the dates in terms of the luni-solar calendar, implying a precise time of lunation, but also the times and circumstances of various lunar and solar eclipses.

In recent years the main opponent of the view that the parameters were either speculative or borrowed from non-Indian sources has been Roger Billard (1922-2000), who made use of the best available methods of calculation in order to test thoroughly the mean parameters of a large number of texts. In this way he established for each canon the years for the best agreement with the real sky, and from this derived a hierarchy of texts in the historical order of their composition. He found, in particular, that the work of Āryabhaṭa was based on observations carried out very near to A.D. 499. In extending this to establish the optimum meridian of reference simultaneously with the optimum year, of these texts, I found for the same parameters of Āryabhaṭa that the observations were carried out on a meridian passing through central India. It would be misleading to isolate his approach as a special 'method'. Any competent historian, Indian or Western, would approach the matter in this way, and one only needs to recollect the efforts of Bentley early in the 19th century, or Dikshit at the end of that century. Billard excelled, however, in his use of exceptionally precise calculations from modern parameters, supported by modern computer programming, and also in his use of statistical estimates. On this last point however, his approach depended on the assumption of Gaussian statistics, an assumption which fails because of the small number of variables involved in the least squares analysis; he should have used the Student and Chi-square distributions. [1]

In this article I will look in some detail at three examples where precise modern computation throws a clear light on problems in Indian astronomy.

### *Citrā pakṣa*

One of the defining features of Indian astronomy is the use of sidereal longitudes, by which all longitudes are measured from a point of the ecliptic fixed in relation to the stars. To be sure, any appreciation of the 'reality' of Indian astronomy, of its true scientific context, depends on a satisfactory identification of that origin point.

The origin can only be established by a comparison between the calculations from the Indian canon and modern calculations. In his pioneering history of Indian astronomy, *Bhāratīya Jyotiṣa* (written in Marathi in 1896)[2], Dikshit explored a number of aspects of this problem, but he always understood the need to approach it by a comparison with modern parameters. In order to fix the 'zero ayanāṃśa year' he assumed it was a matter of finding the year in which the true Sun enters Aries (true Meṣa saṅkrānti) at the same time by both modern calculation and calculation from the canon. Dikshit saw this as merely a realisation of the rule often stated in the Sanskrit canons, that the ayanāṃśa was to be found by comparing the Sun as found by observation with that found by calculation from the canon. For example, to fix the 'zero ayanāṃśa year' for the canon of Āryabhaṭa Dikshit calculated first the time of mean Meṣa saṅkrānti in Śaka 450, as Caitra su 14, $45^{gh}$ $6.2^{p}$ (A.D. 528 March 20, Noon + $12^{h}$;2,28.8), then he estimated that the true saṅkrānti occurred $2^{d}$ $10^{gh}$ $24^{p}$ earlier, making that Caitra su 12, $34^{gh}$ $42^{p}$ (A.D. 528 March 18, Noon + $7^{h}$;52,48). Dikshit compared this with the 'modern' computation, which he obtained from the *Planetary Tables* of 'Keropant'.[3] At the time of true saṅkrānti the (modern) true Sun was 359;58,48, according to Keropant.[4] This was sufficient to show that the 'zero ayanāṃśa year' was indeed within one year of Śaka 450.[5] Dikshit used this approach many times, obtaining in his own way results generally consistent with those found by the modern systematic approach through deviation curves. Since the ayanāṃśa is defined in relation to the equinoctial point it is natural to try to fix it in relation to the Sun, the primary marker of the equinoxes. However, once a system of sidereal longitudes is fixed for the

Moon and planets as well, it is quite legitimate to study those by comparison with the tropical longitudes, as was done by Billard.

Billard's deviations were always between mean longitudes, but this simplification leads only to small differences in the estimated year of zero ayanāṃśa, resulting from the small difference between the ancient and modern values of the equation of the Sun. The deviation curves, when all nine are taken together, define by their 'node' the year when they best agree jointly with the real sky. When found for the Āryabhaṭīya, this indicates observations close to A.D. 500, and a meridian through central India. Of course, this date of the node must be distinguished from the date of zero ayanāṃśa.

In Dikshit's survey of the reference stars that might have been used in India astronomy he mentions ζ Psc (Revatī) and α Vir (Citrā, Spica). [6] The identification of the junction star of Revatī with ζ Psc appears to be due to Colebrooke, and from his time this star was commonly noted as the origin of the Indian sidereal ecliptic.[7] Dikshit dismisses the use of this star in the direct observational measurements of longitudes since it is so faint (5$^{th}$ Mag) that no one would ever have used it in practice, and one would scarcely disagree with that. As to α Vir (Citrā), although most texts give it a longitude of 183, in the later Sūrya Siddhānta it is placed at 180, and so that the sidereal origin is diametrically opposed, and in effect this star serves to mark the origin.

The zero ayanāṃśa years can be seen by inspection of the deviation curves published by Billard from numerous canons, and it is clear that they lie in the fifth century. Thus the origin of the sidereal coordinates employed by Āryabhaṭa and all later Indian astronomers is, if not exactly ζ Psc, at least it is no more than one degree from it. If the reference star were truly α Vir the zero ayanāṃśa year would be around A.D. 290, and there are no canons which prescribe such an ayanāṃśa.

However, with the reforms initiated by Venkatesh Bapuji Ketkar (b. 1854), there was a shift to just that view.[8] In his *Jyotirgaṇitam* of 1898, and also in his *Grahagaṇitam*, Ketkar proposed a calendar reform, which he named 'Ketaki Calendar', in which the sidereal longitudes were measured from the point opposite to ζ Vir (Citrā, Spica), as a consequence of which the zero date of the ayanāṃśa was 291 A.D. In 1923 he summarised his arguments in English in his *Indian and foreign chronology*.[9] He set out his view that it was the consensus of Indian astronomers, past and contemporary, that the correct origin of sidereal longitudes in Indian astronomy was the point diametrically opposed to α Vir (Spica). He calculated that the Equinoctial point thus coincided with this point in 291 A.D. [10] The earliest support was found, he claimed, in

Varāhamihira's *Pañcasiddhāntikā*, xiv.37, where the coordinates of Citrā are given. However, he gave his own individual reading of this passage,

*citrārdhāśramabhāge dakṣiṇayaḥ...*

in place of the usual reading,

*citrārdhāṣṭamabhāge dakṣiṇayaḥ...*

The compound *ardhāṣṭamabhāge* simply means 7½ degrees, *ardhāṣṭama* being a regular formation for 7½. Ketkar however read *ardhāśramabhāge* 'in the middlepoint of the Chitra-nakshatra-division'[11]; *āśrama* means 'abode', usually in a religious context, such as an abode of monks, while *bhage* is taken to mean not degree but the division of the *nakṣatra*. Since the division runs from $13 \times 13;20 = 173;20$ to $14 \times 13;20 = 186;40$, the mid-point is 180. It is noteworthy that as a result of this reading the position of the *nakṣatra* Citrā then agrees with that given in the later Sūrya Siddhānta, viii.3, where the star is stated to be 6;40 from the start of its portion (*bhoga*, not *bhāga*) : 6;40 is half of 13;20. However interesting and satisfactory, in view of the resulting consistency with the position in the Sūrya Siddhānta, Ketkar's reading of *Pañcasiddhāntikā*, xiv.37 is at variance with the text as read by three independent editors.[12] Ketkar looked for support for his view from a good number of Western and Indian scholars, including Sir William Jones, Samuel Davies, and Sudhākara Dvivedi.

In any case, his proposals eventually found wide acceptance, and of the 50 Pañcāṅgas described in the *Report of the Calendar Reform Committee*, the great majority of Pañcāṅga makers surveyed for the Committee in 1954 had come to follow Ketkar's reform. Even when they do not explicitly acknowledge Ketkar's *Grahagaṇitam* or *Jyotirgaṇitam* as the source, the majority still adopt an ayanāṃśa calculation with a zero year in the range A.D. $290 \pm 2$. In addition to his new interpretation of the ayanāṃśa Ketkar revised the astronomical parameters, abandoning the mean longitudes taken from Indian sources, and adopting in their place some modern parameters.[13] Other compilers, who did not follow Ketkar, made use of some older authority, such as the *Grahalāghava*. As a result, and after consulting among various scholars, the Committee decided to adopt as part of the definition of ayanāṃśa that it should equal 23;15 on 1956 Mar 21, so as to 'reconcile most of the Pañcāṅgas in India based on modern constants.'[14] It is indeed strange and disappointing to observe the way in which Ketkar's erroneous view as to the origin point of the sidereal coordinate has gained general acceptance.

*Zero-point of the Hindu Zodiac*

In the Committee's Report there is also an Appendix[15] devoted to a further clarification of the zero-point of the Hindu zodiac. It is stressed that ζ Psc is not at the point diametrically opposite to α Vir, but is 3;58 distant from it, according to modern coordinates of those stars. Correspondingly, the zero-ayanāṃśa years of ζ Psc and anti-α Vir differ by about 284 years. The conclusion in the Appendix is that there were probably three attempts to fix the equinoctial point in relation to the stars, around the years A.D. 285, 500 and 570.

Among those who were involved in the Committee's work there was N.C. Lahiri[16], the author of the well known *Indian Ephemeris of Planets' Positions*, published annually. Lahiri followed Ketkar's reform, in fixing the origin of sidereal longitudes at the point opposite α Vir. In a popular article written in 1976 Lahiri argued for the use of this 'Citrā Pakṣa', as he called it, recognizing that it was now in line with general practice[17]. Even then he argued for some slight adjustment of Ketkar's ayanāṃśa, partly in view of the secular variation of the position of Spica. Lahiri also looked for support from the English astrological writer Cyril Fagan[18], who had taken the sidereal origin as the Equinoctial point of A.D. 213, when the point was diametrically opposite Spica, which he understood, however, to be at Virgo 29;0. For example, he takes the longitude of α Vir on 1976 Jan 1 as 203;30,22, so the point diametrically opposite is 203;30,22 - 180 = 23;30,22. For some reason, however, he took the zero point one degree further, so that on 1976 Jan 1 the ayanāṃśa is 24;30,22.

In recent decades pañcāṅgas have been computed not from any of the traditional siddhāntas but from strictly modern methods, so as to be in line with the *Astronomical Almanac* as published in Washington or London. However, these longitudes are tabulated as nirayana, calculated from modern tropical values by subtracting the ayanāṃśa. The result is that now the ayanāṃśa is the sole survivor of ancient astronomical methods. This is done to serve not only the interests of astrologers, but also indirectly the requirements of *dharmaśāstra*. It is characteristic of astrology to continue with a blindly conservative use of what were at one time genuine technical procedures. Surely it would now be for the best if the whole apparatus of the Indian sidereal zodiac were simply abandoned, especially since the ayanāṃśa as used now in pañcāṅgas is based on Ketkar's incorrect view. Dikshit, at the end of a long discussion of the *sāyana* and *nirayana* systems, concluded that it would be more in line with modern scientific astronomy, and would do no serious harm to the traditional applications of Indian astronomy, if the *sāyana* system were adopted.[19]

*The α Vir and ζ Psc alignment*

All these attempts by recent Indian scholars to reconcile references to ζ Psc and α Vir can hardly be viewed as successful or convincing. However I demonstrated in 1976 that there is a sense in which the two stars together are part of a consistent reference system.[20] This was an alignment that takes one back to Greek astronomy, and to Hipparchus, the principal author of the star catalogue known from Ptolemy's Almagest. Hipparchus is known to have observed on the island of Rhodes, whose latitude is 36º. Now I found that the two stars, ζ Psc and α Vir, together with α Ari and β Ari, at a certain moment, lie on the horizon when the latitude is 36º. Indeed, for an observer at that latitude, when ζ Psc (Revatī) rises in the East, so too do α Ari and β Ari (which together constitute Aśvinī), while α Vir (Citrā) sets in the West. This very remarkable simultaneity of risings and settings is quite exactly true when the Ptolemaic coordinates are used, and very closely true even when the star coordinates are given their modern values. The further remarkable feature is that the ecliptic intersects this circle of alignment at a point very close to ζ Psc. If we take the four stars according to their Hipparchian coordinates (that is, with longitude reduced by 2;40 relative to those given by Ptolemy), then on such a scale the intesection with the ecliptic lies at the longitude -9;23 on the Hipparchian scale. In the following table the coordinates are given for these four stars according to both the Hipparchian scale, and on a longitude scale such that longitudes are measured from the point where the ecliptic intersects this circle of alignment, which I would choose to call the 'Indian coordinate system'.

| | Hipparchian | | 'Indian' | |
|---|---|---|---|---|
| | longitude | latitude | longitude | latitude |
| α Vir | 174;0 | -2;0 | 183;23 | -2;0 |
| β Ari | 8;0 | 10;30 | 17;23 | 10;30 |
| α Ari | 5;0 | 8;20 | 14;23 | 8;20 |
| ζ Psc | -9;40 | -0;10 | -0;17 | -0;10 |

These 'Indian' longitudes are of course hypothetical, although comparable to the various documented positions of the junction stars. Thus we have here an alignment of exceptional importance, one which links the Greek star coordinates and the latitude of Hipparchus' observatory, together with the sidereal origin of Indian longitudes. Here, shown for the first time, is the link between the two stars commonly assumed to be the reference stars of Indian sidereal measurement, ζ Psc and α Vir. If, as Dikshit correctly argued, ζ Psc is too faint ever to have served as an origin of sidereal coordinates, it is nevertheless part of this reference circle anchored to brighter and more significant stars. The essential matter is not the faint star ζ Psc in itself, but the point of the ecliptic near it where the ecliptic intersects this circle of alignment. It is not to be forgotten that the position of the yogatāra of Revatī is placed at -0;10 according to the later Sūrya Siddhānta, a confused fragment of the earliest tradition.

It remains as a great difficulty for me now, as it did in1976, to discover precisly how the features of this alignment functioned within the broad context of Indian astronomy, especially with respect to the elements that were drawn from the Greek background. For certainly there was some degree of transmission from the Greek/Hellenistic world.

Ideally one would like to discover the Greek-Indian point of contact in the earliest canons, those created by Āryabhaṭa, but the trouble is that in these works (the Āryabhaṭīya and the early Sūrya Siddhānta) there is no reference to either the junction stars of the nakṣatra, nor to precession. In the later Sūrya Siddhānta, however, both those elements are present, although unfortunately, so are many small corrections (bīja) that were introduced perhaps in the tenth century, and which might serve to undermine the argument.

Before considering the later Sūrya Siddhānta, let us note that in the comparison between tropical and sidereal coordinates the Moon plays a more central role than the Sun. For, considerations of the ayanāṃśa lead in most discussions to consideration of the tropical longitude, then to the position of the equinoctial point, and finally to the time of the Spring Equinox, This therefore focuses attention on the Sun, as we have seen in Dikshit's calculation of the zero ayanāṃśa year. However, at night, when the stars are visible, it is the Moon, not the Sun, that serves as the 'hand' of the celestial clock. The sidereal coordinates of the Sun are only derived from those of the Moon through the synodic parameters of the Sun and Moon, such as the mean synodic month.

Let us examine the deviation curves of the later Sūrya Siddhānta. If the ayanāṃśa is included, we see that of all the deviation curves, that of the Moon is nearest to zero. Thus the ayanāṃśa has been adjusted jointly with the mean sidereal Moon to produce a tropical Moon that is very close to 'reality' at all times, from the time of Hipparchus until about the year A.D. 1000, after which time it departs further from zero. On the other hand, when the ayanāṃśa is omitted, the lunar deviation vanishes simultaneously with the ayanāṃśa itself, (in AD. 499, Ś 421), but at the time of the Hipparchian star catalogue, A.D. -127, the deviation approximately equals 9;20, just the difference between the Hipparchian and 'Indian' positions of ζ Psc.

*The date of the Mahāsiddhānta*

A Sanskrit astronomical canon entitled Mahāsiddhānta, edited in 1910 by Sudhākara, had been discussed before that time by S.B. Dikshit.[21] The author of this canon calls himself Āryabhaṭa, and Dikshit (and others since then) refer to him as Āryabhaṭa II, having no solid information about the author's true identity. Partly as a result of the anonymity of the canon there has been some dispute about the date of composition. Dikshit argued from the value of the ayanāṃśa given in the work that it had to have been composed 'around Śaka 900' (A.D. 978). Billard, on the other hand, after applying more rigorous considerations to all the parameters given in the work, concluded that it was composed in the early 16th century. I have already reviewed these arguments to show the way in which Dikshit was misled into arguing for such an early date, and also reviewed the problematic and confusing nature of references to earlier authors, to Āryabhaṭa in particular, in Sanskrit works.

The formula for the ayanāṃśa in the Mahāsiddhānta is an oscillatory motion attributed to the equinoctial point,

$$A = \sin^{-1}\left[\sin(0.504^{r} + 578159^{r}\, t')\sin 24^{\circ}\right]$$

where $t' = (t-t_o)/Y$, where

$t_o$ = beginning of the Kaliyuga at sunrise

= J.D. 588465.75 referred to the local Indian meridian;

Y = 1577917542000;

the affix $^{r}$ means 'revolutions'.

If the year is the sidereal year defined in this canon (Y/4320000000 days), then the function $A$ has a period of very nearly 7472 years, an amplitude of 24°, and vanishes when J.D. = 1942155.4, which is A.D. 605 Apr 30 (Julian). The other dates at which $A$ vanishes lie far outside the historical period.

This quantity A is added to the mean Sun as defined in the canon, which is of course the mean Sun measured from some sidereally fixed point, in order to obtain the tropical mean Sun. Dikshit, as Billard was to do 60 years later, proceeded to compare this tropical mean sun with that which he could calculate from modern parameters.[22] He gave no details of this comparison, but only stated his conclusion in the briefest terms:

> The time when the ayanāṃśas, obtained from the second Ārya Siddhānta, would be equal to the Sun's tropical longitude at the true vernal equinox, comes to be about Śaka 900. If he had lived before this year, the date must have been only a few years earlier.

Dikshit's conclusion as it stands reveals little of his exact procedure, but it must have been similar to the calculation he gave earlier in fixing the zero ayanāṃśa year of the Āryabhaṭīya, which I summarised above in the section of the Citra Pakṣa.

The study of set of differences between mean longitudes in the canon and a modern calculation forms the heart of Billard's approach. As he well knew he was not the first to attempt such a comparison, but in reflecting on this problem of dating the Ārya Siddhānta, it should be understood, especially by those who insist that Dikshit's calculation marks an end of the matter as far as this canon is concerned, that his was a mere adumbration of the correct method, and that his conclusion was far from adequate.

The set of deviation curves for the Ārya Siddhānta are given by Billard, and again in my own earlier examination of the question.[23] In great contrast with the set of deviations for the earliest of the Sanskrit canons, which converge dramatically to one point to reveal the optimum date and meridian, here the deviations do not converge in striking way. Nevertheless there is a clear indication that the time of composition is towards the early 16th century, if not to a precisely defined date. In any case there is no convergence at all towards the 10th century. Why was Dikshit wrongly led to a date in the 10th century ?  The answer is clear from the deviation curves. One sees in these curves that because of the non-linear behaviour of the ayanāṃśa the deviation curve for the Sun vanishes twice, once around 1000, and again around 1600. Plainly, Dikshit isolated only the earlier date.

A survey of references to this canon reveals many quotations from it in the commentaries written in the early 17th century by Munīśvara and Nṛsiṃha on Bhāskara's Golādhyāya. No quotations from it have been found in early works. I refer to my detailed study of these passages.

*Earth rotation*

In the application of modern astronomical computation to old sources it is not enough to calculate the longitudes of Sun, Moon and planets as if they were viewed from the centre of the earth. However, in order to establish how they are seen from a point on the earth's surface it necessary to allow for the fact that the rate of rotation of the earth on its axis has never been constant; that is to say the length of the day (l.o.d.) is changing, and is on whole increasing. To be more precise, the rate of rotation is slowing down relative to the time scale established by dynamical astronomy. The solar system is to be seen as a 'clock' if the Newtonian dynamical equations are taken to be in exact accord with the observations of the Sun, Moon and planets, for then these equations may be solved for the time. This is called Ephemeris Time (ET), defined indeed as the time scale for which the observed orbit of the earth (as judged by the position of the Sun) is in exact agreement with dynamical astronomy. The difference between ET and the time measured by the rotation of the earth, Universal Time (UT), is always denoted $\Delta T$, defined as ET-UT. The slowing down of the earth's spin is partly due to tidal friction, but there is also a random component due to movements within the earth which change the earth's moment of inertia. There is no theoretical model for either of these contributions, so that values of $\Delta T$ can only be established by a careful interpretation of past observations. Since the original work of Spencer Jones (1939), which yielded an expression for $\Delta T$ as a quadratic function of UT, much work has been done by Stephenson, who exploited ancient observations. For the pre-telescopic period he relied on Islamic, Chinese and Babylonian sources in order to fix values of $\Delta T$.[24] In fact, as I shall now explain, Sanskrit sources as well can be exploited to give values of this quantity.

Billard's original studies of the Āryabhaṭīya and other canons were extended by me to allow for a search of the optimum meridian jointly with the optimum date.[25] In that study (in which the formula of Spencer Jones for $\Delta T$ was used) it was found that the optimum meridians of the canons lay in central India, evidently supporting the common reference in the Sanskrit sources to Ujjain as the 'Greenwich' of Indian astronomy. If the logic of this argument is turned around, that is if we establish the optimum meridian by making the calculations solely in terms of ET without regard to $\Delta T$, and then observe the interval between that meridian and Ujjain, we have a value of $\Delta T$ (by conversion of the difference in longitude to time).

The calculation proceeds by computing the deviations as functions of time and meridian, and then the variance, that is the sum of squares, of some or all of these. The results of such a calculation can be displayed as a series of level curves of the variance plotted against year and meridian the minimum variance is found at the centre of the curves. For the canon of Āryabhaṭa, allowing only for the four eclipse elements (mean Sun, mean Moon, lunar node, lunar apogee), the optimum year and meridian are

| | |
|---|---|
| Year | $498.14 \pm 17.4$ (499 Feb 19) |
| Meridian | $56.98 \pm 3.60$ |

These represent the best estimates of the time when the underlying observations had been made, and of the meridian (East of Greenwich) on which they were made. The statistical bounds derive from the scatter among the four deviations

The meridian 56.98 is distant from that of Ujjain, (75.767 East of Greenwich), by 18.79 degrees, or 4510 secs. Thus from this examination of Āryabhaṭa's mean longitudes we would get $\Delta T = 4510$ secs. As one can see from the graphical display of the values of $\Delta T$ given by Stephenson[26] the value 4510 lies well within the range of uncertainties attached to other data at that time (from Chinese sources). According to the curve fitted to Stephenson's data by Morrison at this date, $\Delta T = 5709$ secs. If that value of $\Delta T$ had been used, the optimum meridian would be $80.76 \pm 3.24$.

Many similar results, distributed over the centuries, can be obtained from the other Sanskrit canons, so adding to the values of $\Delta T$ from other Oriental sources.

*Conclusion*

The real depths of Indian astronomy are revealed only when the full power of modern computation is brought to bear on the numerical data of he canons. This is available now more than ever before, not only because of the common availability of desktop computers, but because calculation according to the best astronomical modern parameters is now codified in the semi-analytical solutions produced at the Paris Observatory in the 1980's.

1. In this way it is clear that the Ayanāṃśa incorporated in the modern Pañcāṅgas is quite wrong, since there is nothing in the earlier canons to support a zero Ayanāṃśa year around A.D. 290; it was always at some point in the 6th century.
2. The confusion that has reigned over the use of α Vir versus ζ Psc is clarified by the discovery that these two stars are both part of a alignment that lay at the heart of the Greek star catalogue.
3. The date of the Mahāsiddhānta was wrongly placed in the 10th century by Dikshit, who, although he started on the correct lines, did not allow for the non-linear

character of ayanāṃśa in that work, which allowed a good agreement between sidereal and tropical Meṣa saṅkrānti not only in the 10th century, but also in the 16th.

4. The mean parameters of some of the canons, such as the Āryabhaṭīya, are so accurate that they may be used to contribute a value to ΔT, so adding to the collection of values already gathered from ancient and medieval sources, mainly Babylonian and Chinese.

## REFERENCES

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[1] Billard (1971); Mercier (1987).

[2] Available in an English translation Dîkshit (1985), and in an earlier Hindi version (1957, and reprints).

[3] Nānā (1850); Dikshit (1885), p. 179. Nānā also composed an almanac, *Paṭavardhanī pañcāṅga*, published serially Ś 1799-Ś 1808, Chhatre (1886).

[4] Modern calculations, for the meridan 76° East of Greenwich, give 0;1,1.7.

[5] Dikshit (1885), p. 216.

[6] Dikshit (1885), p. 218-221.

[7] Colebrooke (1837), 302.

[8] Dikshit (1885), p. 183.

[9] Ketkar (1923).

[10] Ketkar (1923), Art. 200, pp. 148-154.

[11] Ketkar (1923), p. 149.

[12] Thibault (1889), Neugebauer and Pingree (1970), and Sastry (1993).

[13] Since I have not been able to see either of the works *Grahagaṇitam* or *Jyotirgaṇitam* I cannot say what precisely these parameters were.

[14] RCRC, p. 16.

[15] RCRC, Appendix 5-B, p. 263.

[16] In 1976, when visiting Calcutta, I had the pleasure of meeting with Lahiri and his son.

[17] Lahiri (1976).

[18] Fagan (1950), Fagan (1951).

[19] Dîkshit (1985), pp. 315, 323.

[20] Mercier (1976), pp. 33-6; Mercier (1977).

[21] Sudhakara (1910); Dikshit (1985), p. 97, and noted on p. 217.

[22] While Billard had used the modern formulae of Newcomb, Leverrier and Brown, I now use the semi-analytical solution of Bretagnon and colleagues of the Paris Observatory, a solution known as VSOP87, and ELP-2000/82. See Meeus (1991).

[23] Mercier (1993).

[24] An exact account of the matter as it stood before Stephenson's studies is given by Woolard and Clemence (1966), chapter 16; Clemence had originally introduced the term 'Newtonian Time' for what is now denoted Ephemeris Time.

[25] Mercier (1987).

[26] Stephenson (1997), Fig. 14.4 (p. 508).

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