INTRODUCTION

It is generally allowed that the invention of the mechanical clock was one of the most important turning-points in the history of science and technology. Not only was it the earliest complex device, heralding a whole age of machine-making, but also its regular imitation of the natural motion of the sun and the heavens fascinated men and exerted no small influence on their philosophy and theology. If such a major innovation had come as a single stroke of genius we should expect to find some record of the inventor and his work; if on the other hand there had been gradual evolution over a long period of time we should be able to trace some stages in its development. Strangely enough the origin of the mechanical clock has long been shrouded in mystery and neither of these expectations has been fulfilled—we have known of no inventor and no stages along the way.

According to the view accepted until recently,[1] the problem of slowing down the rotation of a wheel so as to make it keep a constant speed continuously in time with the apparent daily turning of the heavens was first solved in Europe in the early fourteenth century A.D. by the use of the verge-and-foliot escapement fitted to a weight-driven mechanism. Before that time, it was thought, there had been only sundials and elementary water-clocks—after that date there were fully fledged mechanical clocks all over Europe. Refinements such as the spring drive (*c.* 1475), pendulum control (*c.* 1650) and the anchor escapement (1680) constituted a more or less continuous process of subsequent development.

Recent research has shown, however, that the first mechanical time-keepers were not so much an innovation as had been supposed.[2] They descended, in fact, from a long series of automatically rotated star-maps, planetary models and other devices designed primarily for exhibition and demonstration rather than for accurate time-keeping. Although such mechanisms are of the greatest interest as the earliest complex scientific machines, it has not hitherto been possible to adduce more than a few specimens, fragmentary remains, and literary descriptions tantalisingly incomplete. They give no clue to the crucial problem of the origin of the

[1] For a statement of the customary views on the origin of the mechanical clock see Sarton (1), vol. 3, pp. 1540 ff. Similar accounts are given by Beckmann (1), vol. 1, pp. 340 ff.; Usher (1), 2nd edition, pp. 191 ff., 304 ff.; Frémont (1); Baillie (1, 2); Howgrave-Graham (1); Saunier (1).

[2] A fuller account of such 'clockwork before the clock' has been given in Price (1).

mechanical escapement—a problem which has resisted all scholarly penetration for more than a century.

The examination of certain medieval Chinese texts, the relevance of which had not previously been realised, now permits us to establish the existence of a long tradition of astronomical clock-making in China between the seventh and fourteenth centuries A.D., and perhaps even having its origins as early as the second century A.D. These texts are remarkable for the wealth of historical and technical detail they provide, portraying the events, the people and the machines so clearly and so vividly that they cannot yet be matched by any comparable corpus from the history of science or technology in the West before very recent times. It happens, moreover, that these great Chinese clocks constitute an unsuspected missing link between the early water-clocks and later mechanical clocks found in the West. They are powered by a water-wheel but governed by an escapement device which checks the motion of the wheel and intermittently releases it to work astronomical devices and jacks, bells and gongs, and other indicators of the time of day and night.

From the available modern printed editions of these Chinese texts—treatises on clocks and on astronomy, dynastic histories, encyclopaedias and other sources, we have been able to trace the Chinese tradition. In the West, early history must rely largely on manuscript sources, but thanks to the early invention of printing in China (eighth or ninth century A.D.) and the attention given there to the proper keeping of records, the modern editions faithfully reproduce earlier texts, and these earlier texts, in their turn, may be facsimile editions of still more ancient books which had become scarce and were thought worthy of preservation. Often we have not only the printed word, but the original diagrams as well, faithfully copied from edition to edition and thus handed down to us in unbroken lineage.

The key text for our study is the *Hsin I Hsiang Fa Yao* (New Design for a (Mechanised) Armillary (Sphere) and (Celestial) Globe), written by Su Sung in A.D. 1090 (Fig. 3), the appropriate sections of which we have fully translated. Like so much evidence for the history of science in all parts of the world, its importance has probably been concealed because of its very technical appearance, and perhaps also in this case because Chinese specialists have not in general been familiar with the history of horology as a whole. So complete is the description in this text that it has been possible to prepare detailed working drawings of the mechanism, and to identify more than 150 technical terms of eleventh-century Chinese mechanics. It must be observed that such elucidation of technical terms is

especially vital because of the peculiarities of Chinese philology. The help given by this one text has now made it possible to understand several other texts and fundamental problems which had previously been concealed or misinterpreted.

Su Sung's 'clock' was, in fact, a great astronomical clock-tower more than thirty feet high, surmounted by a huge bronze power-driven armillary sphere for observation, and containing, in a chamber within, an automatically rotated celestial globe with which the observed places of the heavenly bodies could be compared. On the front of the tower was a pagoda structure with five storeys, each having a door through which mannikins and jacks appeared ringing bells and gongs and holding tablets to indicate the hours and other special times of the day and night. Inside the tower was the motive source, a great scoop-wheel using water and turning all the shafts working the various devices. The wheel was checked by an escapement consisting of a sort of weigh-bridge which prevented the fall of a scoop until full, and a trip-lever and parallel linkage system which arrested the forward motion of the wheel at a further point and allowed it to settle back and bring the next scoop into position on the weigh-bridge. One must imagine this giant structure going off at full-cock every quarter of an hour with a great sound of creaking and splashing, clanging and ringing; it must have been impressive, and we know that it was actually built and made to work for many years before being carried away into exile.

Fig. 3. Title-page of the *Hsin I Hsiang Fa Yao* (New Design for a (Mechanised) Armillary (Sphere) and (Celestial) Globe), written by Su Sung in A.D. 1090.

In what follows we shall examine all that is known of Su Sung and of his clock, and then trace the history of the Chinese tradition backwards and forwards from this date. Later we shall examine the relations between these clocks and those of Islam and Europe in an effort to see whether this early use of an escapement device in China might have had some effect on progress elsewhere in the world. The pursuit of these clocks and their makers through the pages of medieval Chinese history gave us a period of great excitement, picking up trails, losing them and

then unexpectedly finding them again, while one discovery followed rapidly upon another. We feel privileged and happy to throw a spotlight on Su Sung and his associates and to restore them to a place of great honour in history.

Our work was begun in 1954 and had reached a stage sufficiently advanced to be communicated in a lecture to the (British) Antiquarian Horological Society on 11 January 1956 (cf. Ward (2)). It was then published in the form of a preliminary note in *Nature* on 31 March. Not until later in the summer of that year did we find, to our great pleasure, that parallel work on the history of horological engineering in China had been proceeding at Peking. There the well-known historian of technology Dr Liu Hsien-Chou, Vice-President of Ch'ing-Hua University, had published in October 1953 an interesting paper on Chinese inventions in power-source engineering (1), followed by a second in July 1954 on Chinese inventions in power transmission (2).[1] Reference was made to Su Sung's astronomical clock in both these works, the former dealing particularly with its water-wheel, the latter with the various forms of gearing which it contained. In the second paper the mechanism of the escapement was explained, but the historical significance of any such device occurring at that date (the late eleventh century) was not discussed. Then, at the International Congress of the History of Science at Florence in September 1956, we met Dr Liu himself,[2] and had the satisfaction of learning from his communication and from many personal talks that he and his assistants had reached conclusions substantially identical with our own.[3] At the same time we received copies of a third paper published by him, on Chinese inventions in horological engineering (3), in August. Investigations proceeding in parallel without mutual knowledge in this way led to mutually confirmatory results.

We wish to thank Dr Liu Hsien-Chou for the enjoyable discussions which took place in the inspiring atmosphere of the city and countryside of Leonardo and Galileo. And we may also take this opportunity of offering our best thanks to Dr Chang Shu-I, Librarian of the National Library at Peking, for his kindness in responding to our questions about a possible Sung edition of Su Sung's book, and for sending us spontaneously photostats of variant diagrams in an eighteenth-century manuscript copy of it which is preserved there.

[1] So far as we know, this journal was not at that time available in Western countries.

[2] The delegation included also other old friends, Dr Chu K'o-Chen, the eminent historian of astronomy and meteorology, a Vice-President of Academia Sinica, and Dr Li Nien, the eminent historian of mathematics.

[3] For particulars of the only significant variation see below, p. 57.

I

BIOGRAPHY OF SU SUNG

BEFORE proceeding further, something must be said of the life of that remarkable man whose monograph has preserved for us in such unexpected detail the construction of a mechanical clock more than three centuries before the first appearance of such clocks in Europe. Though primarily an eminent civil servant, in uprightness and ability worthy of the highest traditions of the millennial Chinese mandarinate, he was evidently one of those (by no means few in medieval China) who mastered the scientific knowledge of his time, and found opportunities for applying it in the service of the State.

Su Sung [450], whose 'style', or public name[1] (*tzu* [900]), was Tzu-Jung [451], was born in A.D. 1020 at Nan-an [850] in the prefecture of Ch'üan-chow [851] in Fukien province. In the course of his career he held many offices, advancing gradually in the bureaucratic hierarchy.[2] His first position was that of Drafting Secretary in the College of All Sages [901], one of the learned organisations of the government which, like the Han-Lin Academy, was responsible for preparing the imperial edicts and for advising the emperor and his highest ministers on all kinds of matters which might arise.[3] It embodied a great library. Under the emperor Ying Tsung (A.D. 1064–7) Su Sung became Staff Supervisor of the Ministry of Finance [902]. At about this period he received the Lien-T'ui [903] decoration, an order bestowed on incorruptible officials, in company with Han Ch'i [452], who, a prominent member of the conservative party, was driven out of public life by the reformer Wang An-Shih [453] in 1069 and died in 1075. Another member of the conservative party, Fu Pi [454], at one time prime minister, and a great enemy of Wang An-Shih, praised Su Sung (some time before his death in A.D. 1083) as a 'gentleman of the good old sort' [904]. From these indications it would seem that Su Sung was associated distinctly with the old-fashioned Confucian conservative party, but though many, perhaps most, of his friends were among its adherents, and though (as we shall see in the sequel, p. 116)

[1] See note 3 on p. 10.
[2] A good account of this in Sung times has recently been given by Kracke (1).
[3] Cf. Bazin (1); des Rotours (1), vol. 1, p. 192; Kracke (1), p. 45.

he himself was regarded as connected with it, we are told that with lofty ideals he stood rather alone, winning general respect thereby.[1]

In common with other officials of similar rank, Su Sung received foreign as well as home assignments. In 1077 he was despatched as a diplomatic envoy to the Liao kingdom of the Ch'i-tan people in the north,[2] and unexpectedly there came the opportunity for him to utilise the astronomical and calendrical knowledge which, though not professionally a member of the Bureau especially concerned with these sciences, he had long been acquiring. How this arose is recounted, not in the official history of the Sung dynasty, but (in two versions) in a book of miscellaneous reminiscences and accounts written early in the following century. We give the story in the words of its author, Yeh Mêng-Tê.

Shih-Lin Yen Yü [700], ch. 9, pp. 7*a* ff., by YEH MÊNG-TÊ [455], *c.* A.D. 1130

When Su Tzu-Jung [451] (Su Sung) was taking the provincial examinations (in his youth), it happened that an essay was set on the general principles of the heavens and the earth as manifested in the (structure of the) calendar. He came out top of the list, and ever afterwards he was particularly interested in (astronomy and) calendrical science. (Later on) in the Yuan-Fêng reign-period (A.D. 1078–85) he was sent as an ambassador (from the Sung empire) to the (Liao) barbarians. He happened to be in their country (North China) at the winter solstice, which occurred at the time predicted in their calendar (but one day later than the indication of the current Sung calendar); so he hastened to the court to present congratulations one day too early. As the (Liao) barbarians had no restrictions on astronomical and calendrical study,[3] their experts in these subjects were generally better (than those of the Sung), and in fact their

[1] We do not give a translation of the biography of Su Sung in *Sung Shih* [705], ch. 340, pp. 22*a* ff., for most of it is of political interest only.

[2] Fig. 4, showing the reception of a Liao embassy at the Chinese court in A.D. 1004, gives a good idea of the ceremonial customary on such occasions.

[3] In ancient and medieval China the promulgation of the calendar by the emperor was a right corresponding to the issuing of minted coins, with image and superscription, in Western countries. It had always been one of the most important duties of the ruler of the vast agrarian culture-area of the 'black-haired people'. Acceptance of the calendar was equivalent to recognition of imperial authority. Owing to this close association between the calendar and State power, any imperial bureaucracy was likely to view with alarm the activities of independent investigators of the stars, or writers about them, since they might secretly be engaged upon calendrical calculations which could be of use to rebels planning to set up a new dynasty. New dynasties always overhauled the calendar, and issued one with a new name, and this might happen even in successive reign-periods under the same emperor. These facts explain why Matteo Ricci's mathematical books were confiscated when he was on the way to the capital in A.D. 1600 (d'Elia (1), vol. 2, p. 122; Trigault (1), p. 370). Fortunately, they were returned to him, by mistake, before he went on to Peking in the following year. From early times, Chinese astronomy had benefited by State support, but the disadvantage of this was the semi-secrecy which it involved. Some realisation of this was expressed from time to time by Chinese historians—for example, in the *Chin Shu* [775] (ch. 11, p. 5*a*) we read: 'Thus astronomical instruments have been in use from very ancient days; handed down from one dynasty to another, and closely guarded by official astronomers. Scholars have therefore had little opportunity to examine them, and this is the reason why unorthodox cosmological theories were able to spread and flourish.'

PLATE I

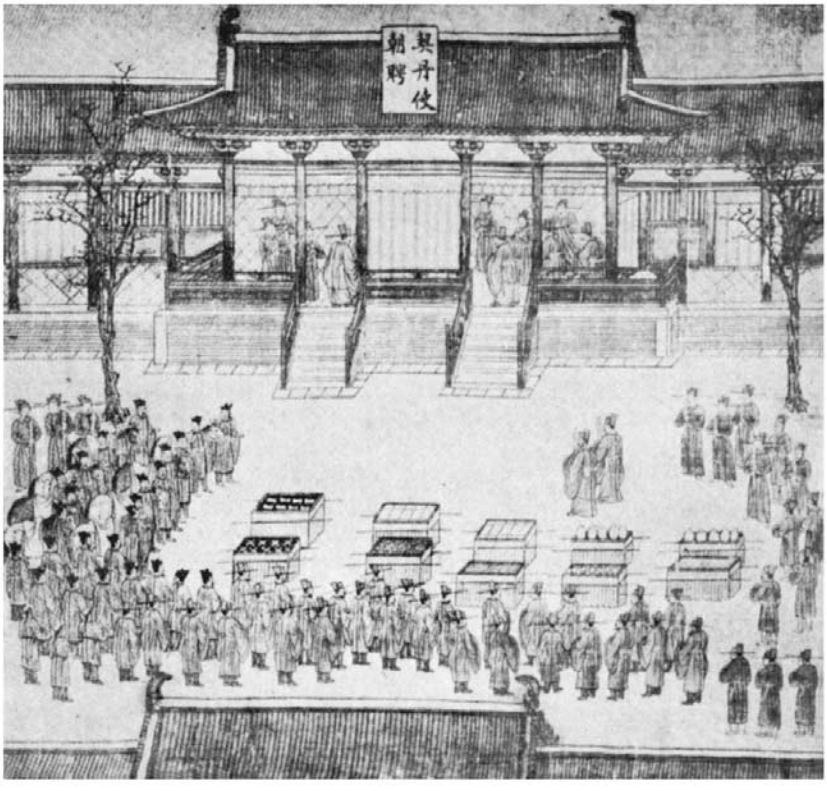

Fig. 4. Audience of a Liao (Ch'i-tan) ambassador at the Sung court in A.D. 1004. Su Sung's astronomical and calendrical knowledge served him in good stead while he was Sung ambassador to the Liao kingdom (A.D. 1077–8).

calendar was correct. Of course, Su Sung was unable to accept it,[1] but he calmly engaged in wide-ranging discussions on calendrical science, quoting many authorities, which puzzled the (Liao) barbarian (astronomers)[2] who all listened with surprise and appreciation. Finally he said that after all, the discrepancy was a small matter, for a difference of only a quarter of an hour would make a difference of one day if the solstice occurred around midnight, and that is considered much only because of convention.[3] The (Liao) barbarian (astronomers) had no answer to this, so he was allowed to carry out his mission (on the earlier of the two days). But when he returned home, he reported to the emperor Shen Tsung [951], who was very pleased at his success and at once asked which of the two calendars was right. Su Sung told him the truth, with the result that the officials of the Astronomical Bureau were all punished and fined.[4]

At the beginning of the Yuan-Yu reign-period (A.D. 1086) the emperor ordered Su Sung to reconstruct the armillary (clock) [150], and it exceeded by far all previous instruments in elaboration. A summary of data concerning it was handed down to Yuan Wei-Chi [456], Director of Astronomical Observations (Northern Region) [924]. The original model was due to Han Kung-Lien [457],[5] a first-class clerk in the Ministry of Personnel, who was a very ingenious man. By that time Su Sung had become Vice-President[6] (of the Chancellery Secretariat) and simply gave the ideas to him. He could always carry them out, so that the instrument was wonderfully elaborate and precise. When the (Chin) barbarians took the capital[7] they destroyed the Observatory (or Astronomical Clock Tower) [117] and took away with them the armillary (clock) [150]. Now it is said that the design is no longer known, even to the descendants of Su Sung himself.

Shih-Lin Yen Yü, ch. 3, p. 14*b*, by YEH MÊNG-TÊ, *c.* A.D. 1130

The calendar of the Ch'i-tan (Liao) people was different by one day from that of our own dynasty (the Sung). In the Hsi-Ning reign-period (A.D. 1068–77)[8] Su Tzu-Jung [451], (Su

[1] As a high official of the Sung dynasty, he naturally had to adhere to the Sung calendar.

[2] These men were of course also Chinese, but they had taken service with the northern 'barbarian' dynasty, the ruling house of which was that of the Ch'i-tan tribal people.

[3] Cf. Maspero (1), p. 258. Owing to an interpolation method then used for plotting the variation of gnomon shadow lengths, Ho Ch'êng-T'ien [505] missed a solstice in A.D. 436 because it occurred half-an-hour before midnight; but in 440 he got the correct day because it occurred three hours after midnight. To appreciate Su Sung's point one must remember that the quarter was the smallest time division in common non-astronomical use.

[4] In view of what is here suggested about the superiority of the astronomers serving the Liao dynasty in the north it is interesting that the *Liao Shih* [809] (ch. 44, pp. 39*a*, *b*) has extremely little to say about armillary spheres (and nothing about astronomical clocks); indeed it indicates that the Ch'i-tan people never had any at all. It does however say: 'For firmness there is nothing better than metal, and for use there is nothing more profitable than water. With the fashioning of metal and the flowing of water one can know the Tao (i.e. the way and order) of the Heavens without stirring outside one's house.' There is also a reference to the astronomical clock of I-Hsing (see p. 74), so no doubt they knew something of that. Cf. Wittfogel & Fêng (1), p. 467.

[5] The text mistakenly says Chang Shih-Lien [458].

[6] Or Principal Executive Officer.

[7] In A.D. 1126. This statement is found also in the *Sung Shih*, ch. 48, p. 18*a*. The Chin people (Jurchen Tartars) took away not only the clock of Su Sung, as we shall see fully later (p. 132), but also all the five astronomical clocks proposed in the Hsüan-Ho reign-period (A.D. 1119–25) which were then under construction. Cf. the passage translated from the *Chin Shih* [810], p. 131 below.

[8] A slight discrepancy will be noticed here. But presumably Su Sung left on his diplomatic mission in A.D. 1077 and returned in 1078.

Sung) was sent as ambassador to offer congratulations (to the Liao emperor) for his birthday, which happened to fall on the winter solstice. Our (Sung) calendar was ahead of that of the Ch'i-tan (Liao) kingdom by one day, and thus the assistant envoy considered that the congratulations should be offered on the earlier of the two days. But the secretary of protocol in the Ch'i-tan (Liao) Foreign Office declined to receive them on that day. Su Sung then spoke quietly and tactfully saying that after all the calendrical schools were not in agreement, some being ahead of others, and slight differences could not be avoided. As one could not hope to unify all opinions, the best way was that each should follow their own choice of date in celebrating festivals. The Ch'i-tan (Liao) people could not reject this argument, and Su Sung was permitted to offer congratulations on the day desired (by the mission). Upon his return he reported to the emperor Shen Tsung, who was pleased and said that nothing could have been more embarrassing. Since later on (foreign) ambassadors might be repeatedly refused reception because someone (at the Sung capital) did not know about the differences in the beginnings of months, and how the Sung envoys had been allowed to have their way, the emperor decided that (mutual tolerance of calendars) should be observed for the honour of the empire.

Astronomy and calendrical science, however, were not the only sciences in which Su Sung was expert. About A.D. 1070 he had produced, no doubt with a number of assistants, the best work of his time on pharmaceutical botany, zoology and mineralogy, the *Pên Ts'ao T'u Ching* [701] (Illustrated Pharmacopoeia). Still today this treatise contains precious information on subjects such as the metallurgy of iron and steel in the eleventh century, or the therapeutic use of drugs such as ephedrine. It was incorporated in the Taoist Patrology (*Tao Tsang*, no. 761), so greatly was it appreciated by the adepts, and extensively quoted in most of the subsequent compilations of the same class in successive dynasties.

Some twelve years after his diplomatic mission to the north, Su Sung was promoted to the position of Right Vice-Minister of the Ministry of Personnel [905] and concurrently a Senior Executive of the Imperial Chancellery and Secretariat [906]. It is recorded that in these responsible posts he paid special attention to the recruitment and quality of the civil service, striving to ensure that promotions were given only on merit, not at random or by means of private influence, and warning military commanders against making trouble on the frontiers in order to gain renown. But this was also the period of his scientific activity which most concerns us here. In 1086 the emperor issued an order for the examination of the existing astronomical equipment, and for the construction of some kind of astronomical clock which should equal, or if possible excel, those which had been built at the beginning of the dynasty and still earlier during the T'ang. In the memorial of Su Sung to the emperor, a document of extraordinary

interest (which we give in translation below, pp. 16 ff.), he describes how he chose his associates for the work, the most important mathematician and engineer, Han Kung-Lien, being not an official of the Bureau of Astronomy but a minor functionary in his own Ministry of Personnel. By 1088 the complete working wooden pilot model was set up for imperial approval in the Palace at K'ai-fêng, and two years later the metal parts, principally the armillary sphere and celestial globe, cast in bronze. By 1092 the writing of the explanatory monograph, the *Hsin I Hsiang Fa Yao* [702], must have been well advanced, and in 1094 (the first year of the new Shao-Shêng reign-period) this 'New Design for an Astronomical Clock' was finished and presented.

By this time Su Sung had reached the age of 75. He bore several titles, such as that of the Second Titular Rank [907], Grand Protector of the Army [908], and K'ai-Kuo Marquis of Wu-kung [909]. He was one of the Deputy Preceptors of the Heir Apparent [910]. When in A.D. 1101 he died, he left behind him a collection of literary works, as well as the two books already mentioned, both of which have circulated widely and long. He did not live to witness the fall of the capital two decades later and the retirement of the Sung empire to the southern provinces. We may think of him as one of the most outstanding of the scientifically-minded officials of the Northern Sung.