Jour. Korean Earth Science Society, v. 29, no. 5, p. 408–418, September 2008

A Study of Solar Eclipse Records during the Three Kingdoms Period in Korea

Ki-Won Lee[1,2,*]

[1]History of Astronomy Research Group, Korea Astronomy and Space Science Institute, Daejeon 305-348, Korea
[2]Astrophysical Research Center for the Structure and Evolution of the Comos, Sejong University, Seoul 143-747, Korea

Abstract: In this study, solar eclipse records were investigated during the Three Kingdoms era of ancient Korea using astronomical calculations and numerical simulations. Under the condition that the solar eclipses were actually observed at the well known capitals of the Three Kingdoms, I investigated the probabilities that the optimal observation areas of the Early Silla, Goguryeo, and Baekje records would appear around Chinese continent. I found higher probabilities than those suggested by Park and La (1994), although the numerical values are still low, especially in the case of the Early Silla records. On the other hand, the probability that the optimal observation area of the Later Silla records will be present around South Korea is only 13.6%, although the area shows a good match with the known capital. I also analyzed the number distribution of the eclipse records for the Three Kingdoms (except for the latter Silla's) according to the observers' locations: at the optimal observation areas and at the known capitals. And then I compared with the number distribution of all eclipses observable from those locations. From the χ^2-test, I found that the Goguryeo and Baekje records had better representation of their population distributions at the latter regions (χ^2=27.93 and 205.5) than at the former ones (χ^2=34.19 and 211.5). Therefore, it is difficult to conclude that the observers' locations during the Three Kingdoms period were either near China, as suggested by Park and La, or in the Korean peninsula, solely based on these results. It is thus recommended that more studies are required to confirm the real observers' locations during the Three Kingdoms era.

Keywords: history of astronomy, the Three Kingdoms period, ancient astronomical records, solar eclipse, numerical simulation

Introduction

The Three Kingdoms in Korea, Silla (B.C. 57-A.D. 935), Goguryeo (B.C. 37-A.D. 668), and Baekje (B.C. 18-A.D. 660), were influenced by the civilizations of ancient China. However, each nation created a culture that is unique enough to exert influence on Japan. This is true in the field of astronomy (see Jeon, 1974, 1998, Rufus, 1936 for detailed reviews) Nonetheless, literatures and astronomical inheritances of the Three Kingdoms era are quite rare, so Samguksagi (History of the Three Kingdoms) and Samgukyusa (Reminiscences of the Three Kingdoms) are valuable sources to access astronomical works at that time. In Samguksagi, there are about 240 astronomical records such as events of solar eclipses, comets, meteors, and so forth (Park and La, 1994; Yang, 2004). However, since it was written in A.D. 1145, around five centuries after the end of the Three Kingdom's era, by the historian Kim Bu-Sik of the Goryeo dynasty (A.D. 918-1392), there have been long debates about the authenticity of Samguksagi.

According to Park and La (1994; hereafter PL94), Ijima (1926) suggested that Korean historical records before the fifth century were just copies from Chinese records. This idea is also widely accepted in western countries (Stephenson and Houlden, 1986; Xu et al., 2000). Through the analysis of various astronomical and meteorological records in Samguksagi, on the other hand, PL94 showed that not only were astronomical events real but that each kingdom performed its own observations. Considering the characteristics of solar eclipse and rainfall records, however, they concluded

*Corresponding author: kwlee@kasi.re.kr
Tel: 82-42-865-2102
Fax: 82-42-861-5610

that the observers' locations in each Kingdom were in the area of the Yangtze River of China, the north of Manchuria, and the Bohai gulf near Beijing for the Early Silla, Goguryeo, and Baekje, respectively (refer to plus marks in lefthand panels of Fig. 1). This caused great puzzles because the known capitals of the Three Kingdoms do not coincide with any of those regions. The main purpose of this paper is to reexamine PL94's method used in the study of solar eclipse records, rather than to prove whether or not the Three Kingdoms' records were copied from other sources. Because PL94's paper was written in Korean, I summarize their work as follows.

Based on the mechanical calculation of celestial phenomena and the analysis of rainfall distributions, PL94 proved that astronomical records in Samguksagi are the results of real and independent observations of the Three Kingdoms. Furthermore, they have suggested that *the optimal observation areas* (refer to below) of the solar eclipse records were observers' locations at that time.

Firstly, they found that eight records of the daytime appearance of Venus and seventeen records of close encounter of the Moon with planets are independent ones (i.e., those are not given in the history books of neighbouring countries) and confirmed that those were real phenomena from celestial mechanical calculations.

Secondly, they calculated the greatest magnitude for each eclipse with respect to latitude and longitude from the solar eclipse records in Samguksagi. They then plotted a contour diagram using the mean magnitude at each location. As a result, they found that the Early Silla, the Later Silla, Goguryeo, and Baekje data showed the maximum values around the Yangtze River of China, South Korea, the north of Manchuria, and Bohai gulf near Beijing (named '*optimal observation areas*'), respectively. As well, they used a Monte Carlo technique to prove that the eclipse records were not merely random copies from Chinese history books. From 79 solar eclipse data of China covering the periods of the Three Kingdoms' data, they randomly selected eclipses as the same number as each kingdom's data. They then investigated both the position showing the maximum value and the magnitude at that position using the same method as the mentioned above. Through ten thousand times simulations, they found that the cases which the maximum value is located around the Yangtze River with over 0.71 magnitude are twenty four times, i.e., the probability that the Early Silla data (16 records) are the duplication of Chinese records is 0.24%. Considering Goguryeo data (8 records), they found 11% probability, which the maximum value will be presented above 52°N with over 0.6 magnitude. Each probability is an independent event, and the joint probability will become smaller, if Baekje data (20 records) were considered. Hence, they concluded that the probability that the eclipse records in Samguksagi were copied from Chinese ones is much less than 0.026%. Besides, they investigated the possibility that *the optimal observation area* estimated from the solar eclipse records is wrong. First of all, PL94 said that if the eclipses of the Early Silla were observed around the basin of the Yellow River (i.e., the capital of China at that time) then the probability of the maximum value to be presented around Yangtze River is 0.24%, as mentioned above. Using the eclipse records of the Gogyeo dynasty (i.e., assumed that the eclipses of the Early Silla were observed around Korean peninsula) as a population, they also investigated the probability that *the optimal observation area* will be presented around Yangtze River and found 0.4% probability; say, the eclipse records of the Early Silla were not in the basin of the Yellow River or in Korean peninsula but in *the optimal observation area.* Furthermore, based on the theory that the larger value of the greatest magnitude of a solar eclipse at a location, the higher probability of observing it, PL94 suggested that *the optimal observation areas* of eclipse records for the Three Kingdoms are observer's locations, say, their individual capitals. As the check of this theory, they used 99 amongst 138 records in Goryeosa (History of the Goryeo dynasty in Korea) and 57 amongst 75 records in Whohanseo (History of the Later Han dynasty in China) and constructed contour maps for the eclipses using the same manner as mentioned above. As a result, they said that *the maximum points* of both data sets are in a good match with the known capitals, Gaeseong of the Goryseo dynasty and Luoyang of the Later Han dynasty (see Fig. 9 and 11 in PL94), respectively, although the result for the Later Han data was predicted as an area slightly further northern from the capital. Finally, they concluded that the solar eclipse records of the Three Kingdoms were observed in *the optimal observation areas*, i.e., *the maximum points* of contour maps for the eclipse records. As a proof of their claim which each kingdom performed independent observations for the eclipses, they pointed out that *the optimal observation areas* of the Three Kingdoms are different from each other both regionally and from China as a whole.

Lastly, they also analyzed meteorological characteristics of the rainfall records in Samguksagi and concluded that observer's locations estimated by the analysis of rainfall records show a good agreement with *the optimal observation areas* estimated by the study of solar eclipses.

Once again, I would like to emphasize the fact that the principal purpose of this study is to re-investigate the solar eclipse records of the Three Kingdoms in order to understand contradiction between the well known history and the PL94's result. The eclipse records of the Three Kingdoms are summarized together with some comments on a few records and the results of the astronomical calculations are provided.

Data Analysis

Solar Eclipse Data

In Table 1, we summarise the solar eclipse records of the Three Kingdoms presented in Samguksagi. The first and fourth columns list the observed dates written in terms of the lunar calendar. The second and fifth are the corresponding astronomical Julian calendar dates in UT. In matching the lunar calendar to Julian calendar, we assume that if there is a solar eclipse record within about one month before a event listed (in Julian calendar date) in a modern catalogue of solar eclipses, then the solar eclipse was a real event. If there is no matched event in the catalogue with a recorded eclipse, we leave Julian calendar date field as the blank in Table 1. The third and last columns represent the kingdom which the eclipse datum was recorded, and whether or not it was visible in East Asia: 'S' is Silla, 'G' is Goguryeo, and 'B' is Baekje, whilst 'O' or 'X' symbol means that the solar eclipse phenomenon was visible or unvisible, respectively.

For the reasons that Silla unified the Three Kingdoms in A.D. 668, and so as to compare our results with PL94, we also classify the eclipse data into the four groups: SD1 for Silla data from B.C. 54 to A.D. 201, SD2 for Silla data from A.D. 787 to 911, GD for Goguryeo data from A.D. 116 to 219, and BD for Baekje data from B.C. 13 to A.D. 572. As Rufus (1936) pointed out, Silla has no solar eclipse records during the 530 years between A.D. 257 and 786, although other astronomical phenomena such as the daytime appearances of Venus were recorded. On the other hand, Baekje data show an almost continuous record until the fall of the kingdom.

There are 67 records in total: 30 in Silla (19 in SD1 and 11 in SD2), 11 in Goguryeo, and 26 in Baekje. Amongst them, three records overlap with each other, e.g., Silla and Goguryeo in A.D. 124. Based on astronomical calculations, we confirm the occurrences of 27 events in the S data, 9 in the G, and 24 in the B data; say, 3 in the S, and 2 in the G and B are non-events. As well, there are 5 non-visible events (in East Asia) in the B data and one in both S and G amongst occurred events.

An interesting feature in Table 1 is that most of the solar eclipses before A.D. 273 were recorded in the end day of lunar month, and after then all did in the first day of lunar month except the A.D. 554 (Goguryeo) and the A.D. 592 (Baekje), in which the former record (A.D. 554) did not happen and the latter one (A.D. 592) was not visible. Other some comments on a few records are given in the following;

In the Baekje Volume of Samguksagi, it is written that "there was a solar eclipse on the last moon of

Table 1. The summary of the solar eclipse events recorded in Samguksagi

Recorded date (Lunar calendar)				Identified date (Julian calendar)[a]			Notes[b]	Recorded date (Lunar calendar)				Identified date (Julian calendar)[a]			Notes[b]
B.C.	1	Apr	54	9	May	−53	S(O)	A.D	29	Jun	221	5	Aug	221	B(O)
	29	Jun	34				S		29	Nov	222	19	Jan	223	B(O)
	29	Apr	28	19	Jun	−27	S(O)		29	Oct	256				S
	29	Aug	26	23	Oct	−25	S(O)		1	Jul	273				G
	29	Feb	15	29	Mar	−14	S(O)		1	Jan	308				B
	29	Jul	13	31	Aug	−12	B(O)		1	Oct	335				B
	1	Jan	2	5	Feb	−1	S(O)		1	Mar	368	3	Apr	368	B(O)
A.D.	29	Sep	2	23	Nov	2	S(O)		1	May	392	7	Jun	392	B(O)
	1	Oct	6				S		1	Jun	400	8	Jul	400	B(O)
	29	Jul	16	21	Aug	16	S(O)		1	Jan	417	3	Feb	417	B(O)
	29	May	73	23	Jul	73	B(O)		1	Nov	419	3	Dec	419	B(O)
	29	Aug	87	15	Oct	87	B(O)		1	Apr	440	17	May	440	B(O)
	1	Jun	92	23	Jul	92	B(O)		1	Oct	468	1	Nov	468	B(O)
		Mar	114	22	May	114	G(X)		1	Mar	478	18	Apr	478	B(X)
		Mar	116	31	Mar	116	G(O)		1	May	495[c]	8	Jun	495	B(X)
	29	Sep	124	25	Oct	124	S,G(O)		1	Mar	516	18	Apr	516	B(O)
	1	Jul	127	25	Aug	127	S(O)		1	Jan	547	6	Feb	547	B(O)
	29	Sep	141	16	Nov	141	S(O)		29	Dec	554				G
	29	Apr	149	23	Jun	149	G(O)		1	May	559	21	Jun	559	B(X)
	29	May	158	13	Jul	158	G(O)		1	Sep	572	23	Sep	572	B(O)
	29	Jan	165	28	Feb	165	B,G(O)		29	Jul	592	11	Sep	592	B(X)
	1	Jan	166	17	Feb	166	S(O)		1	Aug	787	16	Sep	787	S(O)
	29	Mar	170	3	May	170	B(X)		1	Jan	789	31	Jan	789	S(O)
	29	Oct	178	27	Nov	178	G(O)		1	Nov	792	19	Nov	792	S(O)
	29	May	186	4	Jul	186	S,G(O)		1	May	801	15	Jun	801	S(O)
	1	Apr	189	3	May	189	B(O)		1	Jul	808	27	Jul	808	S(O)
	1	Jan	193	19	Feb	193	S(O)		1	Aug	815	7	Sep	815	S(O)
	29	Jun	194	3	Aug	194	S(O)		1	Jun	818	7	Jul	818	S(O)
	1	Sep	200	26	Sep	200	S(O)		1	Jan	836	22	Jan	836	S(X)
	1	Mar	201	21	Mar	201	S(O)		1	Feb	844	22	Feb	844	S(O)
	29	Jun	212	14	Aug	212	B(O)		1	Mar	888	15	Apr	888	S(O)
	29	Feb	219	2	Apr	219	G(O)		1	Jan	911	2	Feb	911	S(O)

[a]Because zero year does not use in historical records, Julian dates lag one year behind during the B.C. period, e.g. B.C. 54 corresponds to −53 in Julian calendar, which is also different with the Gregorian calendar.
[b]'S' stands for Silla, 'G' does Goguryeo, and 'B' does Baekje, whilst 'O' or 'X' symbol represents the eclipse was visible or unvisible, respectively.
[c]Refer to text for details.

January in the 28th year of the reign of the King Gaeru (i.e., A.D. 155)". According to other contents of the record, however, that is 10 years later historical materials not the 28th ones. Therefore, it may be a mistake in the compilation of the records and should be corrected to the 38th year of the reign of the King Gaeru, A.D. 165 (Lee, 1998). Hence, we adopt this year in Table 1.

From information of the sexagenary circle of an eclipse record, PL94 (also Park, 1999) identified the seventeenth year of the King Dongsung in Baekje (i.e., A.D. 495) as being of the sixteenth (i.e., A.D. 494). However, the records also talk of a historical event, which according to Silla and Goguryeo records occurred in A.D. 495. We therefore choose the 9 June 495 eclipse datum, rather than 19 June 494 used by

PL94. The solar eclipse on 19 June 494 is total and visible in East Asia, whilst that on 9 June 495 is not visible. In order to identify the exact year of the record, we feel think more studies are required.

In Samguksagi,

"*The second year of King Aejang reign (i.e., A.D. 801): a solar eclipse was expected at the first moon, May summer, however it did not happen*".

Although no solar eclipse was observed, the Almanac of the Three Kingdoms' period compiled by Ahn et al. (2002) identified that day as the 15 June 801 (also PL94) in which a solar eclipse event occurred and visible in the Korean peninsula. In this study, we exclude this record from calculations.

Finally, we use 25 solar eclipse records in Silla (16 in SD1 and 9 in SD2), 8 in Goguryeo, and 19 in Baekje. Due to the reason described above, our Baekje data is one event smaller than PL94.

Astronomical Calculations

To calculate the magnitude of a solar eclipse in a local circumstance, we use the Meeus (1989, 1991) algorithms. Although Mucke and Meeus (1983) tabulated Besselian elements, factors describing the coordinates of the Sun and Moon for a given eclipse, ranging from -2003 to 2526, they presented only first order coefficients in each element (Meeus, 1989; the third order coefficients for the eclipses between 1951 and 2200). In order to increase the accuracy, we use Besselian elements from DE406 ephemeris (Standish et al., 1997) with maximum third order coefficients. Very recently, Choi (2006) also studied on the solar eclipse calculation and the confirmation of ancient eclipse records using much the same method as us but from different ephemeris, VSOP87 and ELP2000/82.

Because of the Earth's interaction with the Sun and the Moon, it looses energy and slows down. Therefore, one of most important elements on the investigation of ancient solar eclipses is to know the time difference between dynamical and universal time, ΔT. Stephenson and Houlden (1986) published ΔT values ranging from B.C. 1500 to A.D. 1990 based on the study of historical eclipse records. More recently, Stephenson (1997, 2003) refined ΔT values. We use spline fits to interpolate ΔT value for a year and summarise his results in Table 2 (only between -100 and 1000 years) for the purpose of the comparison with old values. In Table 2, ΔT is in the unit of second and shows a maximum of -1294 seconds (i.e., ~5.4 degrees eastward in longitude) difference between the old and new values (δT) around A.D. 300. In astronomical calculations, we treat zero as the height of observational location and neglect the effect of atmospheric refraction. Lastly, the magnitude of an eclipse is defined in units of the solar diameter (refer to Meeus, 1989).

Table 2. ΔT values with respect to years between -100 and 1000 (Stephenson and Houlden, 1986; Stephenson, 1997)

Year (Julian)	ΔT_{1986} (sec.)	ΔT_{1997} (sec.)	δT (ΔT_{1986}-ΔT_{1997})
-100	11181	11600	-419
0	9848	10600	-752
100	8608	9600	-992
200	7561	8600	-1139
300	6406	7700	-1294
400	5445	6700	-1255
500	4577	5700	-1123
600	3802	4700	-898
700	3120	3800	-680
800	2531	3000	-469
900	2035	2200	-165
1000	1625	1600	25

Results

In Fig. 1, we plot contour diagrams from the average magnitude of the greatest eclipses at a given position with respect to longitude (from 90° to 150°E) and latitude (from 10° to 60°N) in 1° intervals for the eclipse records in lefthand panel, together with the diagrams for all the eclipses observable from an assumed capital of each kingdom during the same periods as recorded data in righthand panel. In this study, we refer to '*all observable eclipses*' as the whole ones having magnitude greater than 0 at a

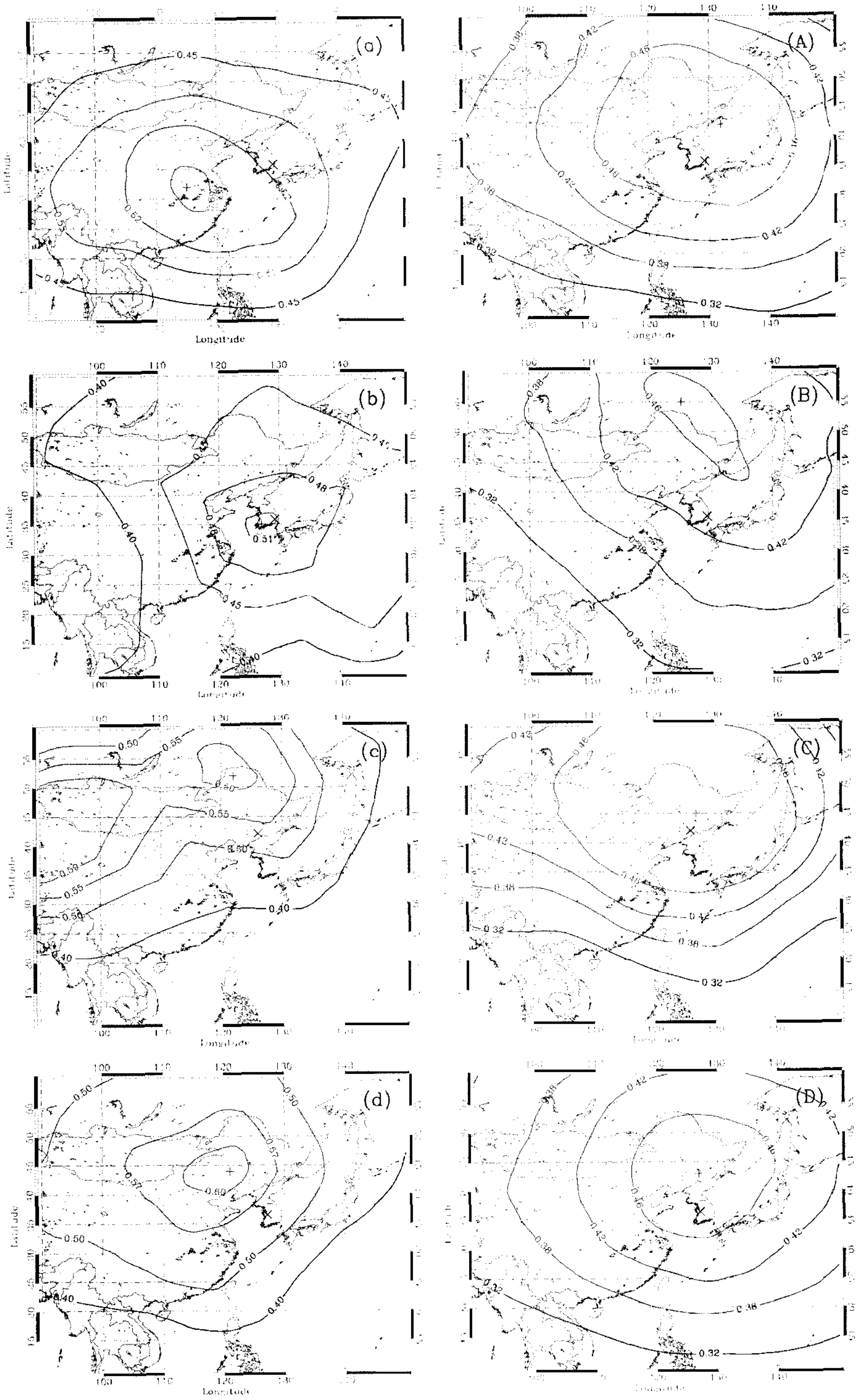

Fig. 1. The contour maps showing *the optimal observation areas* (left) and *the maximum points* of *all observable eclipses* at assumed capitals (right). The lefthand panels are for each dataset classified in this study; (a) SD1, (b) SD2, (c) GD, and (d) BD. In the righthand panels, *all observable eclipses* are for the periods corresponding to the range of each dataset used in the left-hand panels at each assumed capital, (A) and (B) at Gyeongju, (C) at Guknaeseong, and (D) at Gonju. In each figure, the '+' and 'x' signs depict the locations of *the maximum points* and the capitals, respectively (see text more details).

given location and to '*the maximum point*' as the centre point of the innermost contour, particularly to '*the optimal observation area*' as *the maximum point* of eclipse records. As the locations of assumed capital of each kingdom, we use Gyeongju (Lat.=35.843°N, Long.=129.212°E) and Gongju (Lat.=36.447°N, Long. =127.119°E) for the Silla and Baekje kingdoms. For the Goguryeo kingdom, we choose Guknaesung (around Lat.=42.0°N, Long.=126.0°E) because the data used in our calculations belong to a period before the movement of the capital to Pyeongyang by the King Jangsu in A.D. 427. Unless, we specify otherwise, the locations of adopted capital of each kingdom in this study mean those areas.

The maps in the lefthand panel of Fig. 1 are in a good agreement with PL94 (also Stephenson and Houlden, 1986; Lee et al., 2005) confirming the correctness of our calculations. However, the locations of *the optimal observation areas* are shifted ~4 degrees eastward compared to PL94 figures due to the adoption of new ΔT values. In the maps of the righthand panel and in that of Fig. 11 of PL94 (for the Later Han dynasty records from Chinese history books), *the maximum points* have a trend to be located further north than their capitals. It might be caused by the general shape of the observable region distribution of a solar eclipse leaning to northward (in the north hemisphere), such as a sector form. Even some eclipses have no visibility limit toward a pole on the latitude in a given hemisphere (Meeus, 1989). In this sense, even if we accept PL94 suggestion that *the optimal observation areas* of the Three Kingdoms era showing around Chinese continent are observers' locations at that time, the actual observers' locations might be more southern than *the maximum points*. As the same sense, it can be also naturally explained the phenomena that *the maximum points* in the righthand panels of Fig. 1 and in Fig. 11 of PL94 are placed further northern areas than each known capital. From this point of view, we suggest that the result of SD2 data which shows a perfect match with the known capital is an unusual case. Therefore, the estimation of observer's location using solar eclipse records is not an absolute method.

Next, we investigate how much the distributions of the eclipse records represent the population distributions with respect to the locations: at *the optimal observation areas* and at the capitals. In order to test the degree of relationship, we divide magnitude into 0.1 scales, calculate magnitudes for the eclipse records and for *all observable eclipses* at the given locations, count numbers belonging to each magnitude class, and then compared them using a chi-square test defined as the following (refer to Press et al., 1992)

$$\chi^2 = \sum_i \frac{(N_i - n_i)^2}{n_i}, \tag{1}$$

where N_i and n_i are the numbers of the eclipses records and of *all observable eclipses* in the ith bin, respectively. Regarding the periods of *all observable ones*, we use the same periods of the recorded data. The results are given in Fig. 2 with χ^2 values. In the figures, we assume the observers' locations as their known capitals in the lefthand panel and as *the optimal observation areas* (see cross marks in left hand side in Fig. 1) in the righthand panel, except for SD2 data. The adopted *optimal observation areas* are: Lat.=32°N and Long.=115°E for SD1 and Lat.=44°N and Long.=121°E for BD. In SD2 case, because *the optimal observation area* shows a good match with the known capital, Gyeongju, we use *the maximum point* of *all observable eclipses* at the capital, i.e., Lat.=55°N and Long.=125°E (see plus mark in Fig. 1B), in the righthand panel for the purpose of comparison. For GD data, *the optimal observation areas* occur in two places so we take the point in the righthand side (Lat.=52°N and Long.=122°E) because it is closer to the known Goyuryeo capital, although the lefthand one has slightly high value. The solid and thin-dashed lines are the number distributions for the eclipse records and for *all observable eclipses* in each location, respectively. The thick-dashed lines are the product of the number of *all observable eclipses* by the mean value of each magnitude bin. Those lines represent probability distributions to solar eclipse data (refer to below). Lastly, the recorded data numbers

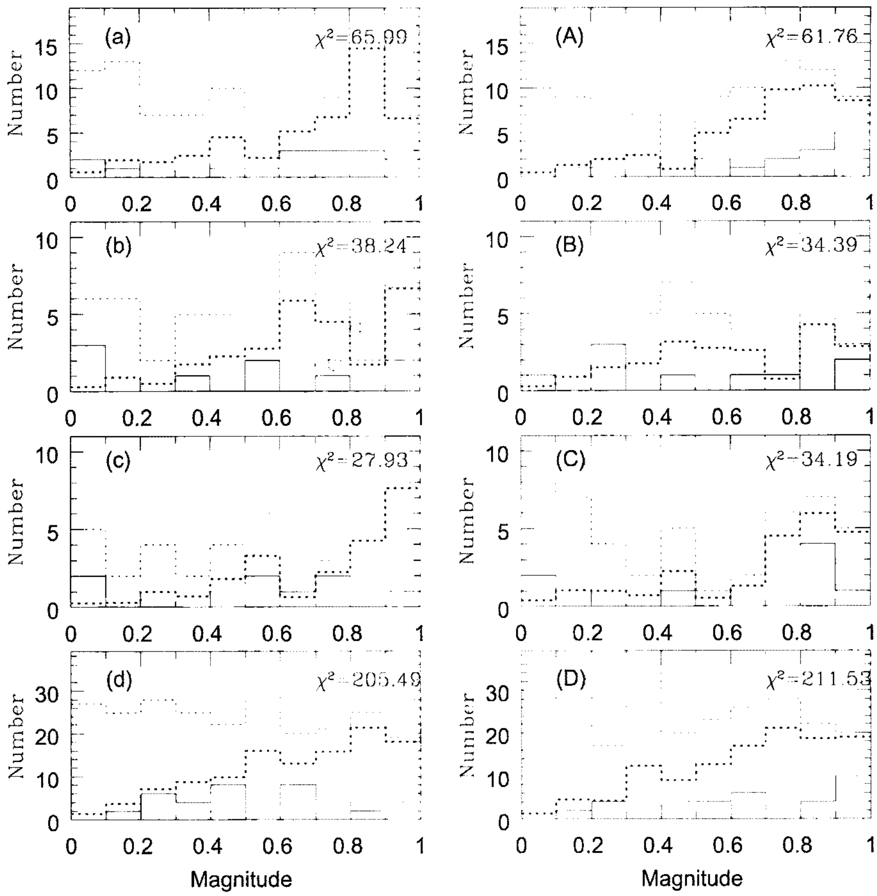

Fig. 2. The number distributions for the eclipse records (solid lines) and *all observable eclipses* (thin-dashed lines) with respect to magnitude class in each data: (a) and (A) for SD1, (b) and (B) for SD2, (c) and (C) for GD, and (d) and (D) for BD data. In BD data, the numbers of the eclipse records belonging to each bin are multiplied by two for clarity. The think-dashed lines are the products of the numbers of *all observable eclipses* by the mean value of each magnitude bin. Except for SD2 data, figures in the lefthand and in the righthand panels are for the cases when the observer's location in each kingdom is assumed as its capital and as the *optimal observation area*, respectively. In the case of SD2 data, we use *the maximum point* of *all observable eclipses* at the capital as the observer's location in the righthand figure. We also present χ^2-values in each figure so as to give a numerical comparison of the correlations.

(i.e., solid lines) are multiplied by two in Fig. 2d and 2D for clarity.

A hypothesis, the larger value of the maximum magnitude of a solar eclipse at a region, the higher probability of observing it regardless of the population distribution at that time, was the main idea of PL94 in terms of estimating the observers' locations in the Three Kingdoms. However, as can be seen in Fig. 2, the high magnitude eclipses do not always give much statistics because of their small numbers (see thick-dashed lines).

We can also see in Fig. 2 that the results of the χ^2-test for the GD and BD data show better representations of their population number distributions at the capitals than at *the optimal observation areas*. While, the results for SD2 data show a better match to the eclipse records at *the maximum point* of *all observable eclipses*, as seen from the capital (i.e., in plus mark of Fig. 1B), than at the capital itself. This implies that the population distribution is very important for the study of solar eclipse records. What we would like to emphasize is the result of the Baekje data which have the most number data points and cover the longest period amongst the four record data sets. Although *the optimal observation area* of the BD data is located further westward from its capital, the number distribution of recorded data shows a numerically better match with the population distribution in the capital than that in *the optimal observation area*, which gives an indication to the real observing location with reliable statistic. The other feature relating to the number distributions is that only Fig. 2A shows a strong positive correlation between the number and the magnitude of solar eclipses. As mentioned above, however, it is an unusual result because, in general, there are less solar eclipses with high magnitude. Therefore, the number distribution of the SD1 data, which shows an increase in the number of solar eclipses with respect to magnitude when the observer's location is assumed as *the optimal observation area*, implies that the number distribution itself is abnormal, although the χ^2-test value gives better results at *the optimal observation area*.

Lastly, we perform the Monte Carlo simulations in order to estimate the possibilities to be shown as the distributions given in the lefthand figures of Fig. 1 under the conditions of their population distributions did in the righthand ones. In simulations, we randomly select eclipse data from their population data according to the number distribution of the eclipse records. For example, if there are three records belonging to between 0.8 and 0.9 magnitudes amongst 16 records in SD1, we randomly extract three data from its population data of the same magnitude bin, and the same ways for other bins. This method is different with purely random selection regardless of the magnitudes and the number distributions of solar eclipses. It is also different with the way selecting data according to the magnitude: if the greatest magnitude of a solar eclipse in a given location is 0.9, then the probability to be selected is 90% (more details on Monte Calo technique, refer to Press et al., 1992). In this case, the distributions of selected data would statistically follow the distributions presented as the thick-dashed lines in Fig. 2. If there are many eclipse records covering the long range of period, it would be the most rational method in the simulations. It was the basic idea of PL94 in the estimation of observers' locations in the Three Kingdoms era using the solar eclipse records, despite small number of eclipse data. In numerical simulations, however, PL94 used purely random method and the eclipse records of the Goyeo dynasty not *all observable eclipses* during the Three Kingdoms era as the population.

Because the eclipse data given in Table 1 are the results affected by various factors, for example weather conditions which have nothing to do with an eclipse magnitude, and by the distributions of observable eclipses at the Three Kingdoms times (i.e., population distribution), our method is more reasonable than other two ones in the selection of data for the numerical simulations. With selected data, we calculate the magnitude of the greatest eclipses with respect to latitude and longitude, and determine the mean value in each grid. We perform this simulation for 1000 data sets to calculate the probabilities.

It is hard to describe the probability for the contour distribution, hence we count the cases from 1000 times simulations in which *the maximum point* is located within a confined latitude and/or longitude range(s) with or without an additional restriction on the value of *the maximum point*. With a percentage, we define as the probability. In SD1, we get a 23.1% and 0.9% (c.f., 0.4% in PL94) probabilities in the cases that the value of *the maximum point* is over 0.5 (i.e., the value of *the maximum point* in Fig. 1A and also in Fig. 9 of PL94) and over 0.7 (i.e., the value of *the maximum point* in Fig. 1a and the one used in PL94) lying the west area up to 120°E, regardless of latitude. Considering the value of *the maximum point*, we should keep in mind the fact that the increase in the number of eclipse data does not make the value become higher, rather it approaches to a certain value such as a median of the magnitude range. For SD2 data, the probability that *the maximum point* will be located below 40°N in the latitude is 58.9%. However, when we place constraints on the location of *the maximum point* as the region around South Korea, 30°<Lat.<40°N and 120°<Long.<130°E, it gives only 13.6%, regardless of the value in *the maximum point*. This result shows that the SD2 data is a statistically low probability case. However, PL94 did not test the probability for the case of SD2 data maybe because it showed a good match with the known capital, Gyeongju. Since it is known that Goguryeo had large territory and moved its capital several times, it is hard to give limitations on the location. For these reasons, we adopt PL94's criterion used to verify the independence of the Goguryeo records, 52°N in the latitude, as the constraint and get a 58.0% probability that *the optimal observation area* lies north of that position. Lastly in BD data, we get a 18.9% probability that *the optimal observation area* lies in the west regions up to 125°E in the longitude together with over 0.6 in the value of *the maximum points* regardless of latitude, and 15.4% when put an additional limitation on the latitude, above the north of 40°N.

Summary and Conclusion

Motivated by the study of PL94, we also investigate solar eclipse records in the Three Kingdoms period using astronomical calculations and numerical simulations with the adoption of new ΔT values. The summary of our results are given in the followings.

First, we found that *the optimal observation area* shows a trend to be presented further northern area than the capital. In this sense, the result of the Later Silla data (SD2) showing an excellent agreement with the known capital is an unusual case in PL94. According to our simulation, the probability that *the optimal observation area* will be presented around South Korea is only 13.6%.

Next, we analyze the number distributions (i.e. the number of eclipses according to magnitude bin) with respect to observer's location using the magnitudes from eclipse records and *all observable eclipses* (i.e. population). For GD and BD, we found that the number distribution of eclipse records shows numerically close correlation with that of *all observable eclipses* assumed observer's locations as the capitals not *the optimal observation areas*. In the case of SD2, *the optimal observation area* is equal to the capital so we assume observer's locations as *the maximum point* of all the eclipses observable from the capital, i.e. '+' mark in Fig. 1B, and as *the optimal observation area*, respectively. As a result, we got better relationship between eclipse records and the population at the former location than the latter one. Those facts imply that the population distribution at that time are very important to study on ancient solar eclipse records, particularly on the estimation of observer's location.

Lastly, we obtain relatively larger probability values, which will be shown as the distributions given in the lefthand panels of Fig. 1 under the assumption that the eclipse records of the Three Kingdoms were actually observed from their known capitals, than those of PL94. In the case of SD1 data, the probability value is still small in our study as well. As mentioned in the previous section, however, we would like to point out that SD1 is an unusual case showing the direct proportion of the number of eclipse data with the magnitude at *the optimal observation area*.

As a conclusion, we would like to emphasis that the estimation of the observer's location by solar eclipse data is not an absolute method. We think that it is hard to conclude that the observers' locations during the Three Kingdoms period were either near China, as suggested by PL94, or in the Korean peninsula, solely based on our results. Instead, we think that more studies including the considerations of historical and political environments during the Three Kingdoms era are needed.

Acknowledgment

This work is partly supported by Korea Science and Engineering Foundation through the Astrophysical Research Center for the Structure and Evolution of the Comos (ARCSEC). I would like to thank Dr. Hong-Jin Yang in Korea Astronomy and Space Science Institute for valuable comments, Mr. Joong-Hyun Park in Kyungpook National University for aids in the drawing of the contour maps, and Mr. Fabrizio Sidoli in University College London and Professor Myeong-Gu Park in Kyungpook National University for their careful reading of this manuscript. I also deeply thank the anonymous referees for their helpful advice that improved this work.

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Manuscript received: March 17, 2008
Revised manuscript received: July 7, 2008
Manuscript accepted: September 17, 2008