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# Identification of possible intense historical geomagnetic storms using combined sunspot and auroral observations from East Asia

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**Abstract.** Comprehensive catalogues of ancient sunspot and auroral observations from East Asia are used to identify possible intense historical geomagnetic storms in the interval 210 BC–AD 1918. There are about 270 entries in the sunspot catalogue and about 1150 entries in the auroral catalogue. Special databases have been constructed in which the scientific information in these two catalogues is placed in specified fields. For the purposes of this study, an historical geomagnetic storm is defined in terms of an auroral observation that is apparently associated with a particular sunspot observation, in the sense that the auroral observation occurred within several days of the sunspot observation. More precisely, a selection criterion is formulated for the automatic identification of such geomagnetic storms, using the oriental records stored in the sunspot and auroral databases. The selection criterion is based on specific assumptions about the duration of sunspot visibility with the unaided eye, the likely range of heliographic longitudes of an energetic solar feature, and the likely range of transit times for ejected solar plasma to travel from the Sun to the Earth. This selection criterion results in the identification of nineteen putative historical geomagnetic storms, although two of these storms are spurious in the sense that there are two examples of a single sunspot observation being associated with two different auroral observations separated by more than half a (synodic) solar rotation period. The literary and scientific reliabilities of the East Asian sunspot and auroral records that define the nineteen historical geomagnetic storms are discussed in detail in a set of appendices. A possible time sequence of events is presented for each geomagnetic storm, including possible dates for both the central meridian passage of the sunspot and the occurrence of the energetic solar feature, as well as likely transit times for the ejected solar plasma. European telescopic sunspot drawings from the seventeenth century are also used to assess the credibility of some of the later historical geomagnetic storms defined solely by the East Asian sunspot and auroral records. These drawings cast doubt on a few of the associations between sunspot and auroral observations based entirely on the oriental records, at least to the extent that the occidental drawings provide a more realistic date for central meridian passage of the sunspot actually associated with a particular auroral observation. Nevertheless, on those occasions for which European sunspot drawings are available, the dates of all the pertinent East Asian sunspot and auroral observations are corroborated, apart from just one Chinese sunspot observation. The ancient historical observations of sunspots and aurorae are discussed briefly in terms of modern observations of great geomagnetic storms.

**Keywords.** Magnetospheric physics (auroral phenomena; storms and substorms) – Solar physics, astrophysics and astronomy (photosphere and chromosphere)

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## 1 Introduction

Willis and Stephenson (2001) have drawn attention to the combined solar and auroral evidence for an intense recurrent geomagnetic storm during December in AD 1128. In particular, these authors noted that the earliest known drawing of sunspots appears in *The Chronicle of John of Worcester*, which was compiled in the first half of the twelfth century (Darlington et al., 1995; McGurk, 1998). In this medieval chronicle, the Latin text describing the sunspots is accompanied by a colourful drawing. Although idealised, this drawing shows the apparent positions and sizes of two sunspots on the solar disk. The date of this observation of sunspots from Worcester (52.2° N, 2.2° W), England, is firmly established as AD 1128 December 8 (Stephenson and Willis, 1999). About five days after this observation of two sunspots on the solar disk, on the night of AD 1128 December 13, a red auroral display was observed from Songdo (38.0° N, 126.6° E), Korea, the modern city of Kaesong (Willis and Stephenson, 2001). This auroral observation was recorded in the *Koryo-sa*, the Korean dynastic history of the period.

Apart from this direct evidence for an intense geomagnetic storm during December in AD 1128, there is additional evidence suggesting recurrent geomagnetic activity around this time (Willis and Stephenson, 2001). First, the histories from both South and North China record observations of a single sunspot on the solar disk on AD 1129 March 22 (Yau and Stephenson, 1988). This oriental sunspot observation occurred approximately four synodic-solar-rotation periods (approximately $4\times27$ days) after the sighting of the two sunspots from Worcester in England on AD 1128 December 8. Second, five Chinese and five Korean descriptions of auroral displays occurring between the middle of AD 1127 and the middle of AD 1129 were recorded in various oriental histories. These ten East Asian auroral records, which correspond to six distinct auroral events, provide evidence for recurrent, though possibly intermittent, auroral activity on a timescale almost exactly equal to the synodic-solar-rotation period. The six separate auroral events were apparently associated with two series of recurrent geomagnetic storms, both of which were sufficiently intense to produce an intermittent series of mid-latitude auroral displays in East Asia (Willis and Stephenson, 2001).

The evidence for an intense recurrent geomagnetic storm during December in AD 1128 is remarkable in the sense that it combines historical information from two entirely different cultures. The purpose of the present paper is to identify further intense historical geomagnetic storms that have occurred within about the past two millennia. This investigation is restricted to those intense historical geomagnetic storms that can be identified using solely the East Asian historical records. The merits of this restriction are twofold. First, the oriental sunspot and auroral records are readily available in a convenient form (e.g. Matsushita, 1956; Wittmann and Xu, 1987; Beijing Observatory, 1988; Yau and Stephenson, 1988; Osaki, 1994; Yau et al., 1995). Second, Chinese astronomical records have been compiled in a fairly uniform manner throughout most of the interval 210 BC–AD 1918; similar remarks apply to most of the Korean astronomical records in the interval AD 918–1910. Nonetheless, many of these oriental records are admittedly very primitive, repetitive and terse by modern scientific standards.

The inclusion of occidental sunspot and auroral records would introduce very few additional sunspot observations in the pre-telescopic period (Wittmann and Xu, 1987) but would certainly introduce many additional auroral observations in this same period (Link, 1962, 1964). Moreover, the inclusion of occidental auroral and sunspot records acquired from the post-telescopic period (e.g. Fritz, 1873; Boller, 1898; Seydl, 1954; Royal Greenwich Observatory, 1955; Réthly and Berkes, 1963; Křivský and Pejml, 1988; Loysha et al., 1989; Hoyt and Schatten, 1998) would result in the identification of a significantly non-uniform distribution of geomagnetic storms throughout the interval 210 BC–AD 1918, with a great preponderance in the eighteenth and nineteenth centuries. Indeed, the inclusion of *all* extant occidental sunspot and auroral observations would be an enormous undertaking, which is well beyond the intended scope of the present paper. An important feature of the restriction to East Asian records, however, is that many of these records have resulted from fairly regular and systematic observations of sunspots and aurorae at mid-latitudes. Conversely, most pre-1700 European sightings of sunspots and aurorae have been recorded irregularly in chronicles and other non-astronomical works. In addition, the early European observers, situated at higher latitudes, were far from consistent. Finally, historical auroral observations in East Asia (i.e. at mid-latitudes) identify just the more intense historical geomagnetic storms.

The goal of this paper is to identify possible intense geomagnetic storms that have occurred during the past two millennia, using the sunspot and auroral records from East Asia. However, the actual historical records involved in the identification of these intense geomagnetic storms are presented in appendices, in order to avoid repeated digressions. The first appendix defines the format of the historical records and presents two systems for classifying their reliability. Subsequent appendices include a critical assessment of the reliability of the relevant oriental sunspot and auroral records that define each individual geomagnetic storm.

## 2 Catalogues of East Asian sunspot and auroral observations

The oriental sunspot and auroral observations used in this study have been gleaned from various catalogues of East Asian astronomical records. The sunspot observations are those contained in an as yet unpublished sunspot catalogue compiled by F. R. Stephenson and S. S. Al-Dargazelli in 1998. This catalogue was constructed by supplementing the revised catalogue of East Asian observations of sunspots (165 BC–AD 1918) published by Yau and Stephenson (1988) with additional sunspot records included in the list published (in Chinese) by the Beijing Observatory (1988). The as yet unpublished sunspot catalogue contains 273 entries in the interval 165 BC–AD 1918: 235 entries are from the catalogue of Yau and Stephenson (1988), several of which have been amended, amplified, combined into a single entry (Catalogue Nos. 165 and 166) or separated into two entries (Catalogue No. 150); an additional 38 entries have been extracted from the list published by the Beijing Observatory (1988) and translated into English.

The 273 entries in the sunspot catalogue compiled by Stephenson and Al-Dargazelli present a wealth of sunspot records from China (both South China and North China), Korea, Japan and Vietnam. A few individual entries in the catalogue refer to observations from two different countries (e.g. South China and Korea or South China and North China) on the same date. A few more refer to observations from the same country on adjacent dates (e.g. observations on consecutive days). Several individual entries refer to different (but not necessarily independent) historical records from the same country on the same date. Therefore, there is no exact one-to-one correspondence between numbered entries

in the sunspot catalogue and distinct historical records, although each entry normally refers either to a specific date or a specific date range.

The auroral observations used in this study are based on the catalogue of auroral observations from China, Korea and Japan (193 BC–AD 1770) published by Yau et al. (1995). This compilation has as its nucleus the work of both Keimatsu (1970–1976) and Dai and Chen (1980). An independent search of East Asian history for further records was also undertaken in the process of compiling the new catalogue. Moreover, unreliable records in the work of Keimatsu (1970–1976) and Dai and Chen (1980) have been carefully expunged from the catalogue of Yau et al. (1995). For the purposes of the present study, the material from the auroral catalogue of Yau et al. (1995) has been supplemented with additional auroral data from three further sources: (1) Chinese auroral records included in the catalogue published (in Chinese) by the Beijing Observatory (1988), which extends the Chinese auroral observations back to 210 BC and up to AD 1911; (2) the list of Japanese auroral records since AD 1600 included in the catalogue published (in Japanese) by Osaki (1994); and (3) a research paper by Matsushita (1956) on ancient aurorae seen in Japan. The additional auroral records from China and Japan have been carefully translated into English, with appropriate help from experts in Classical Chinese and Japanese.

The auroral catalogue that results from the combination of all these sources contains 1155 entries in the interval 210 BC–AD 1911: 845 entries are from the catalogue of Yau et al. (1995); 212 additional Chinese entries are from the list published by the Beijing Observatory (1988); another 77 additional Japanese entries are from the book by Osaki (1994); and a further 21 additional Japanese entries are from the paper by Matsushita (1956). The Chinese auroral record for AD 22 in Yau et al. (1995) has been rejected because this date is based on rather vague wording that merely refers to "the early days of the Emperor Kuang-wu-ti". The isolated, archaic Chinese auroral records for 895 BC and 552 BC in the list compiled by the Beijing Observatory (1988) have been rejected because their reliabilities are questionable. The Chinese auroral record that is supposedly for AD 548 in this same list has also been rejected because it occurs only in a late source and the wording is almost identical to the record for AD 549 February 4, which is found in much earlier sources. As in the case of the sunspot catalogue, there is no exact one-to-one correspondence between numbered entries in the auroral catalogue and distinct historical records, although each entry normally refers either to a specific date or a specific date range.

An extremely important feature of all the sunspot and auroral catalogues is the fact that they specify the date of each observation, albeit imprecisely in some cases. The Chinese calendar, which was luni-solar, was eventually adopted with little change in Korea, Japan and Vietnam. However, in each country, years were numbered relative to the reign of the appropriate ruler. In all four countries, most years contained twelve lunar months, each of length 29 or 30 days. Every three years or so an intercalary month was inserted in order to keep the calendar in step with the seasons. Intercalation was not always practised simultaneously in China, Korea, Japan and Vietnam, but differences were usually slight. Days were sometimes noted from the start of each lunar month. However, a 60-day (sexagenary) cycle was also adopted. This cycle, which covered a little over two lunar months, was independent of any astronomical parameter. Its regular use, especially in China and Korea, materially assists in the conversion of dates to the Julian or Gregorian calendar. Table 2 in the paper by Willis and Stephenson (2000) presents a list of the cyclical days. We have devised a computer program to effect rapid date conversion from the Chinese calendar to the Julian or Gregorian calendar. As is common practice in the various oriental sunspot and auroral catalogues, the Julian calendar is used for all Western-style dates before AD 1582 October 5, whereas the Gregorian calendar is used for subsequent dates.

There is evidence that throughout East Asia the day began for astronomical purposes around dawn (Stephenson and Green, 2002), approximately 6 h after the beginning of the civil day. Consequently, auroral observations made both before and after midnight in East Asia (approximately 16:00 UT) are assigned the same Western-style date in the conversion from the Chinese calendar to either the Julian or Gregorian calendar. Stated alternatively, the Western-style dates presented in the various catalogues of oriental sunspot and auroral observations relate to approximate 24-h intervals in East Asia that extend from one dawn to the following dawn.

Most auroral records give only a very general time of night, if any indication at all. Occasionally the night watches (*keng*) are used. The interval from dusk (defined as about 35 min after sunset) to dawn (the same time before sunrise) was divided into five equal night watches. Near the equinoxes, the watches were equal to about 2.2 h but at the solstices they could range in length from about 1.7 h in summer to about 2.6 h in winter. The third watch was centred on midnight. Sometimes the double hours (*shih*) were utilised instead; these were twelve regular divisions of the day and night. The night-time hours were *yu* (17:00–19:00 LT); *hsu* (19:00–21:00 LT); *hai* (21:00–23:00 LT); *tzu* (23:00–01:00 LT); *ch'ou* (01:00–03:00 LT); *yin* (03:00–05:00 LT); and *mao* (05:00–07:00 LT).

Similarly, most sunspot records give no indication of the time of day, although in a few cases there is a clear indication that the observation was made close to sunrise or sunset. As the present investigation identifies a geomagnetic storm in terms of an auroral observation following (or in some instances preceding) a sunspot observation, with a "time delay" of several days, the shortest time interval that can be realistically considered in this study is just one day (24 h). Therefore, it is those precise sunspot and auroral observations, for which an exact date is known (year, month and day), that are crucially important in the identification of historical geomagnetic storms.

## 3 Databases of East Asian sunspot and auroral observations

Special sunspot and auroral databases have been constructed using the 273 entries in the combined sunspot catalogue and the 1155 entries in the combined auroral catalogue. The fields in the sunspot database are: the first date of the sunspot observation; the last date of observation (if noted); a comment (if necessary) on the accuracy of the sunspot record (i.e. inexact date, possible scribal error, possible date error and possible error in the duration of sunspot visibility); the country in which the sunspot observation was made; the number of sunspots seen; the number of days of continual visibility; and an abbreviated account of the description of the observation in oriental history. Similarly, the fields in the auroral database are: the first date of the auroral observation; the last date of observation; a comment (if necessary) on the accuracy of the auroral record (i.e. inexact date, possible scribal error and possible date error); the country in which the observation was made; the colour(s) of the display; the compass position(s) of the auroral luminosity in the sky; and an abbreviated account of the description of the display in oriental history. An alternative auroral database, which is rather more useful in certain circumstances, has also been implemented. In this alternative auroral database, all dates on which the aurora was seen in East Asia are included as separate records, in order to avoid the complication of auroral ranges; this change reduces the number of fields by one (the last date of observation) but increases the number of records significantly. It should be emphasised that in the present paper both the Julian calendar (dates before 1582 October 5) and the Gregorian calendar (dates from 1582 October 15) are employed (but all dates *within the databases* are expressed in the Gregorian calendar).

Not all of the database fields defined in this section are utilised in the present study. However, the goal has been to transfer to the sunspot and auroral databases all the scientific information (rather than just the purely historical information) included in the original sunspot and auroral catalogues. Moreover, single entries in the combined catalogues described in Sect. 2 have sometimes been divided into two entries in the corresponding databases. For example, it is particularly convenient to have two separate entries in the sunspot or auroral database if a single entry in the corresponding catalogue contains independent records from two different countries in East Asia. However, individual entries in these two databases are sometimes based on two, or more, separate records (not necessarily independent) from the same country.

The sunspot database contains a total of 286 entries, compared with 273 entries in the combined sunspot catalogue (see Sect. 2). The discrepancy between the number of entries in the sunspot catalogue and database arises from the fact that independent sunspot observations (e.g. observations from different countries on the same date) are always included as separate entries in the sunspot database. For each of the following countries, the corresponding contributions to the sunspot database are given in parentheses: China (240), Korea (42), Japan (1) and Vietnam (3). For future reference, the number of precise sunspot records, for which the year, month and day are all known *exactly* (and the historical text is not in any way dubious), is 186. For these precise sunspot records, which are all confined to the shorter interval AD 20–1918, the corresponding contributions by country are as follows: China (144), Korea (40), Japan (1) and Vietnam (1).

Similarly, the alternative auroral database (with separate entries for each individual night on which the aurora was observed in East Asia) contains a total of 1198 entries, compared with 1155 entries in the combined auroral catalogue (see Sect. 2). The discrepancy between the number of entries in the auroral catalogue and (alternative) database arises partly from the fact that independent auroral observations are always included as separate entries in the auroral database and partly from the avoidance of auroral ranges. For each of the following countries, the corresponding contributions to the auroral database are given in parentheses: China (467), Korea (574), Japan (157) and Vietnam (0). For future reference, the number of precise auroral records, for which the year, month and day are all known *exactly* (and the historical text is not in any way dubious), is 1036. For these precise auroral records, which are all confined to the shorter interval 139 BC–AD 1909, the corresponding contributions by country are as follows: China (323), Korea (567), Japan (146) and Vietnam (0).

For the purpose of this investigation, special software has been developed to facilitate the automatic identification of approximately coincident sunspot and auroral observations. An automatic procedure obviates the need for tedious manual comparisons of the sunspot and auroral catalogues. Using criteria formulated in the following section, particularly the criterion defined by Eq. (1), the sunspot and auroral databases have been searched for possible historical geomagnetic storms.

The software has been developed in a flexible manner, with several notable features. For example, the investigator can decide whether or not to include records that are potentially, but not definitely, inaccurate. In this context, potentially inaccurate records are those for which there are possible scribal errors, possible date errors, or possible duration-of-sunspot-visibility errors, as specified by particular fields in the sunspot and auroral databases. Each of these three possible sources of potential inaccuracy can be accepted or rejected individually. In addition, the investigator can decide whether or not to restrict any study to precise records, for which the year, month and day are all known *exactly*. Although it is possible (at least in principle) to include imprecise records, with inexact dates that lie within a specified lunar month, a specified season, a specified year, or a specified reign period, the inclusion of such imprecise records would introduce enormous uncertainties in the study of historical geomagnetic storms. The investigator can also decide whether to include or exclude records from each of the different countries of East Asia in turn. It should be noted that

a distinction is made in the database between records from South China and North China (sometimes two separate empires), although no such distinction is made in the present investigation. Finally, the software enables the investigator to modify and update the electronic sunspot and auroral databases, either by the incorporation of new records (which have yet to be discovered) or by the elimination of existing records (which may subsequently prove to be unreliable). In addition, the details of any record can be amended directly without the need to delete the record and then insert it again in its amended form.

This study is restricted to records from East Asia, for which the year, month and day are all specified *exactly*; records with possible dating errors or possible scribal errors are excluded. Some oriental records give the first and last dates on which a sunspot was (apparently) observed but do not state explicitly that the *same* sunspot was observed continually throughout the interval. On the basis of the criterion derived in Sect. 4.1, it would be logical to reject records that apparently claim a sunspot was seen continually for more than 10 days. However, the policy adopted in this paper is to include sunspot records for which the "first" and "last" dates are separated by more than 10 days, provided that the duration of visibility is not specified in a direct way. It may well be that, once having noticed a large sunspot group, the oriental observers scrutinised the Sun with extra care for several days afterwards. In the absence of cloud cover, they may have been able to track the same sunspot group, or possibly detect a new sunspot group, nearer to the west limb of the Sun than would be likely without such an earlier ("precursory") sunspot observation. This matter is discussed in greater detail in Appendices B–T, in which the sunspot and auroral records are discussed critically for each historical geomagnetic storm identified by the software.

## 4 Criteria used to identify historical geomagnetic storms

An historical geomagnetic storm is first defined in terms of an auroral observation that is associated with a particular sunspot observation, in the sense that the auroral observation occurred within several days of the sunspot observation. Indeed, the existence of approximately coincident sunspot and auroral observations is regarded as a necessary and sufficient condition to identify each geomagnetic storm. This is clearly a rather stringent criterion for the identification of historical geomagnetic storms because it depends on the existence of both solar and auroral records.

It is necessary to consider first the concept of *approximate temporal coincidence* in the context of the present investigation. In most cases, the historical sunspot records give no indication of the position of a sunspot (or sunspot group) on the solar disk (Yau and Stephenson, 1988; Beijing Observatory, 1988). Usually, it is merely stated that "within the Sun" there was a black "spot", "vapour" or "light". Occasionally, it is noted briefly that the sunspot was "right in" or "near to" the centre (or middle) of the Sun, or "on one (or the) side of" the Sun. Very occasionally, the term "north" or "south" is used to specify the position of a sunspot (or sunspot group). Moreover, as noted in Sect. 2, the oriental sunspot observations can usually be timed only to the nearest day. Therefore, it is important to discuss the necessary conditions for the oriental observers to have been able to detect sunspots with the unaided eye, as well as the solar–terrestrial conditions required for the occurrence of an historical geomagnetic storm.

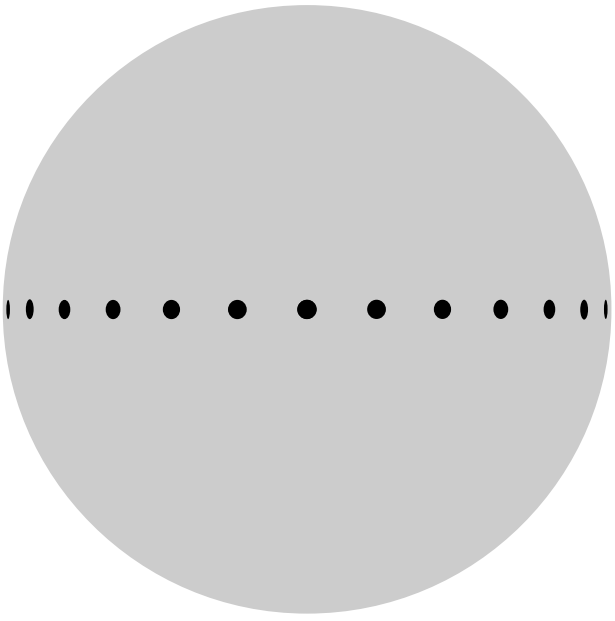

**Fig. 1.** Schematic illustration of the variation in the apparent (projected) area of a circular sunspot with an angular diameter of 1 arc min during its passage across the solar disk. The daily positions and areas of an idealised (purely umbral) sunspot on the solar equator are shown from 6 days before the sunspot reaches the central solar meridian to 6 days after it passes this meridian, as viewed from the Earth. The average equatorial synodic-solar-rotation period is assumed to be exactly 27 days, which corresponds to an apparent motion in heliographic longitude of 13.3° per day.

### 4.1 Criterion for the unaided-eye detection of sunspots

Figure 1 shows the apparent (projected) area of a circular sunspot with an angular diameter of 1 arc min during its passage across the solar disk, as viewed from the Earth. An angular diameter of 1 arc min (corresponding approximately to 500 millionths of the Sun's visible hemisphere) has often been cited as the canonical threshold for the detection of a sunspot with the unaided eye (see Willis et al., 1996a; and the references cited therein). The schematic nature of Fig. 1 is merely intended to illustrate the daily positions and areas of an *idealised* (purely umbral) sunspot on the solar equator, from 6 days before the sunspot reaches the central solar meridian to 6 days after it passes this meridian (i.e. for Days 0, ±1, ± 2, ±3, ±4, ±5 and ±6). The daily displacements of the sunspot have been calculated assuming that the

average annual value of the equatorial synodic-solar-rotation period is exactly 27 days, which corresponds to an average 13.3° per day (as viewed from the Earth).

At the positions ±4 days, ±5 days and ±6 days (away from the central solar meridian), the respective (longitudinal) foreshortening factors are 0.60 (cosine 53.3°), 0.40 (cosine 66.7°) and 0.17 (cosine 80.0°). In each case, the area of the elliptical projection of the circular sunspot is reduced by the same factor (see Fig. 1). It seems likely that the routine detection of sunspots with umbral and penumbral diameters of 15 and 41 arc s, respectively, is about the best that could have been achieved by the oriental observers (Willis et al., 1996a; see their Fig. 2). However, it has been claimed that "experienced" sunspot observers can detect sunspots with penumbral diameters of about 25 arc s under optimal viewing conditions (Mossman, 1989; MacRobert, 1989; Schaefer, 1991, 1993). The ratio of the areas of circular sunspots with diameters of 0.68 arc min (41 arc s) and 1.00 arc min is 0.47. Similarly, the ratio of the areas of circular sunspots with diameters of 0.42 arc min (25 arc s) and 1.00 arc min is 0.17. The ratios 0.47 and 0.17 are taken to be the (normalised) threshold visibility factors for "average" and "experienced" observers, respectively.

If these threshold visibility factors are compared with the foregoing foreshortening factors, it seems certain that the ancient East Asian observers would have been able to detect a circular sunspot with a penumbral diameter of 1 arc min at positions ±4 days away from the central solar meridian, since the foreshortening factor is larger than the threshold visibility factor for "average" observers ($0.60 > 0.47$). It is also just possible that they would have been able to detect this same sunspot at positions ±5 days away from the central solar meridian ($0.40 < 0.47$ for "average" observers but $0.40 > 0.17$ for "experienced" observers). However, it seems doubtful if the oriental observers would have been able to detect this sunspot at positions ±6 days away from the central solar meridian ($0.17 < 0.47$ for "average" observers), unless they can definitely be regarded as "experienced" sunspot observers ($0.17 = 0.17$ for "experienced" observers; coincidentally, the foreshortening factor is effectively equal to the threshold visibility factor). The extreme rarity of recorded sunspot sightings in East Asian history (averaging about one per decade) suggests that many oriental observers were not "experienced" observers by modern standards. Although the rate at which sunspots rotate (in both the northern and southern solar hemispheres) decreases monotonically with increasing heliographic latitude in the range 0° to 40° (Phillips, 1992; Beck, 1999; Brajša et al., 2002), it still seems unlikely that the oriental observers would have been able to see a sunspot with an angular diameter of 1 arc min at positions ±6 days away from the central solar meridian.

It is therefore assumed that, under suitable atmospheric viewing conditions, the oriental astronomers would have been able to see a sunspot continually with the unaided eye for an interval as long as 10 days, out of a possible 13.5 days (see also Willis et al., 1988). It must be emphasised, however, that this estimate is based solely on a circular sunspot with a diameter of 1 arc min; substantially larger sunspots might well be visible continually for an interval as long as 12 days. Conversely, a sunspot with a diameter slightly less than 1 arc min would be visible continually for an interval shorter than 10 days. Hence there is no unique value for the interval over which a sunspot can be seen continually with the unaided eye; 10 days is just a characteristic value for this interval of continual visibility in the case of sunspots large enough to be seen with the unaided eye.

From sunspot data acquired by the Royal Greenwich Observatory during the interval AD 1874–1954 (Royal Greenwich Observatory, 1955), it has been found that a sunspot as large as, or larger than, the one shown in Fig. 1 (which has an angular diameter of 1 arc min) would be expected on more than 800 days, on average, in each 11-year sunspot cycle (Eddy et al., 1989; see their Fig. 1). Since there are 273 sunspot records in the interval 165 BC–AD 1918 (Sect. 2), the ancient oriental observers recorded only about 0.2% of the number of sunspots expected on the basis of modern sunspot observations. This estimate would be reduced slightly by considering just the 186 precisely dated sunspot records in the shorter interval AD 20–1918 (Sect. 3) but increased slightly by allowing for those occasions when the ancient observers reported that a sunspot persisted for several days (see, for example, Appendices B, H, L and M). However, there can be no doubt that the East Asian sunspot record is far from impressive.

### 4.2 Criterion for historical geomagnetic storms

It has been concluded from modern measurements that intense geomagnetic storms and concomitant mid-latitude auroral displays are associated with energetic solar features such as flares, disappearing solar filaments (DSFs) and coronal mass ejections (CMEs). Indeed, CMEs (and their interplanetary counterparts, ICMEs) are believed to be the main source of the strong interplanetary disturbances and shocks that cause non-recurrent geomagnetic storms (e.g. Tsurutani and Gonzalez, 1997; Gonzalez et al., 1999, 2002; Wang et al., 2002; and references cited in these papers) and perhaps also the largest recurrent geomagnetic storms (e.g. Crooker and Cliver, 1994; Crooker, 2000; Webb et al., 2001). A number of investigations have been undertaken on the solar origin of CMEs and associated geomagnetic activity (e.g. Tsurutani and Gonzalez, 1997; Gonzalez et al., 1999, 2002; Plunkett et al., 2001; Wang et al., 2002; Vilmer et al., 2003). However, the precise mechanism by which an energetic solar feature produces a geomagnetic storm is still not fully understood, although it is known that the most intense storms are associated with strong and sustained southward interplanetary magnetic fields (e.g. Tsurutani and Gonzalez, 1997; Gonzalez et al., 1999, 2002; Plunkett et al., 2001; Webb et al., 2001).

Most of the front-side halo CMEs that generate geomagnetic storms originate from solar activity (or specific solar events) located within about ±40° or possibly ±50° (of heliographic longitude) of the central meridian, as viewed

from the Earth (Hudson et al., 1998; Webb et al., 2000; Cane et al., 2000; Berdichevsky et al., 2002; Cane and Richardson, 2003). This result implies that the location of the source of any CME that generates a geomagnetic storm lies within about ±3 days of the central meridian, although there is evidence for an asymmetric distribution of source regions with respect to heliographic longitude (Wang et al., 2002; Cane and Richardson, 2003). (Halo CMEs emanating from the far side of the Sun are automatically precluded from this study because they are not associated with a sunspot visible from Earth.) However, the source of a CME may not be at exactly the same heliographic longitude as an associated sunspot observed with the unaided eye, since a major active region on the Sun can extend over some 20°–30° of heliographic longitude (McIntosh, 1981; Schrijver and Zwaan, 2000; Thompson et al., 2000). In terms of solar rotation, this longitude range corresponds to about 2 days (13.3° per day), which is normally appreciably greater than the longitudinal extent of any individual sunspot within the major active region. A circular sunspot with an angular diameter of 1.0 arc min spans approximately 3.6° of heliographic longitude (see also McIntosh, 1981).

Thus the angular separation between the energetic solar feature and the observed sunspot could certainly correspond to about ±1 day (i.e. the energetic solar feature could be about 13° of heliographic longitude E or W of the sunspot). To allow for this possible longitudinal separation, it is assumed that the energetic solar feature producing an historical geomagnetic storm occurred when the sunspot (observed with the unaided eye) was within ±4 days of the central meridian. This wider interval also allows for the fact that the associated solar activity could be at a heliographic longitude as great as ±50° (rather than ±40°) for a small proportion of geomagnetic storms.

Allowance must also be made for the transit time of ejected solar plasma to travel from the Sun to the Earth. Some authors have derived typical transit times in the approximate range 3.0 to 5.5 days (Brueckner et al., 1998; Webb et al., 2000; Wang et al., 2002). These transit times are measured from the onset of an energetic solar feature to the peak of the main phase of the geomagnetic storm (as measured by either the $K_p$ index or the $D_{st}$ index). Other authors have derived typical transit times in the approximate range 1.0 to 5.0 days (Gopalswamy et al., 2000; Cane et al., 2000; González-Esparza et al., 2003). However, these latter transit times are measured from the onset of the solar feature to the arrival of ejected solar plasma at the orbit of the Earth and hence the occurrence of a storm-sudden-commencement (SSC). The time delay between the occurrence of the SSC and the peak of the main phase can easily be half a day, perhaps slightly longer (Taylor et al., 1994; Park et al., 2002). Therefore, to cover the most likely range of delay times, it is assumed here that the transit time of ejected solar plasma lies within the interval 1 to 6 days.

In view of all these various physical factors, as well as the inevitable limitations of historical data compared with modern data, it is difficult to provide a unique definition of an historical geomagnetic storm. The assumption made in this study is that an historical geomagnetic storm occurred if the time interval, $T$ (measured in days), between the observation of a sunspot and the associated auroral display satisfies the following condition:

$$-8 \leq T \leq +15. \quad (1)$$

This condition is based on the three preceding assumptions: (i) a sunspot could have been seen continually by the ancient East Asian observers if it was within ±5 days of the central solar meridian; (ii) the energetic solar feature producing the historical geomagnetic storm occurred when the associated sunspot was within ±4 days of the central meridian; and (iii) the transit time for ejected solar plasma to travel from the Sun to the Earth was within the range 1 to 6 days. The upper limit of this condition corresponds to the situation in which the sunspot was first seen on Day –5 (the presumed first possible day of detection with the unaided eye), the energetic solar feature occurred 4 days after central meridian passage of the sunspot and the transit time of the ejected solar plasma was 6 days (the maximum value). The lower limit of this condition corresponds to the situation in which the sunspot was first seen on Day +5 (the presumed last possible day of detection with the unaided eye), the energetic solar feature occurred four days before central meridian passage of the sunspot and the transit time of the ejected solar plasma was 1 day (the minimum value).

## 5 Historical geomagnetic storms identified by the strict criteria

The considerable number of auroral observations from East Asia is impressive. However, only a very small fraction of the sunspots potentially visible with the unaided eye can have actually been documented (Sect. 4.1). Nevertheless, the number of approximately coincident sunspot and auroral observations identified by Eq. (1) is significant and the relevant details are listed in Table 1. For clarity, this table presents – in separate rows – each date on which the aurora was seen in East Asia. Some of the compilers of the source auroral catalogues employ date ranges (similar to the sunspot date ranges), although the use of such date ranges is not universal. Consequently, not all of the entries in Table 1 refer to distinct geomagnetic storms. In some cases, the selection procedure for "approximate coincidences" results in neighbouring auroral observations being associated with the same sunspot observation. These neighbouring auroral observations are usually on consecutive (or almost consecutive) nights. This situation is to be expected for historical geomagnetic storms that were sufficiently intense to produce mid-latitude auroral displays. Such intense geomagnetic storms would be expected to have persisted for a few days, although cloud cover might have precluded uninterrupted auroral observations over a continuous sequence of nights (for example, an official Korean chronicle records auroral observations on the

nights of AD 1624 April 18, 19 and 21 but makes no mention of an aurora or other celestial event on the night of April 20).

Occasionally, however, non-neighbouring auroral observations are apparently associated with the same sunspot observation. For example, it follows from the entries in Table 1 that the auroral observations on both AD 1625 August 28 and September 16 are apparently associated with the same sunspot observation on September 2. Likewise, the auroral observations on both AD 1626 June 24 and July 10 are apparently associated with the same sunspot observation on June 29. Clearly, at least one member of each pair of these "approximate coincidences" is spurious, in the sense that two non-neighbouring auroral observations, separated by a time interval exceeding 13.5 days, cannot be linked physically to the same sunspot observation. The occurrence of such spurious "approximate coincidences" is an inevitable consequence of employing the 24-day acceptance interval $-8 \leq T \leq +15$. In general, additional information is required to eliminate these "ambiguities", which tend to take place at times when the oriental sunspot and auroral observations *both* occurred frequently. This matter is discussed further in the following section, in which European sunspot drawings are used to assess the reliabilities of some of the historical geomagnetic storms presented in Table 1.

Therefore, the 25 "approximate coincidences" in Table 1 correspond to 19 putative (apparently distinct) historical geomagnetic storms. It should be noted that if an historical geomagnetic storm is defined by the existence of *both* sunspot and auroral observations, no more than 17 of these 19 historical geomagnetic storms could have been genuine. If an historical geomagnetic storm is defined *solely* by the existence of an authentic auroral observation, however, all 19 historical geomagnetic storms could still prove to be genuine.

For consistency with modern observations, each historical geomagnetic storm is identified, or labelled, either by the single date of the auroral observation, or by the first date in a sequence of contiguous auroral observations. The East Asian sunspot and auroral records that define these storms are presented and evaluated in appendices at the end of this paper. Two different classification systems that are used to assess the reliability of these records are introduced in Appendix A. Then the actual sunspot and auroral records that define the 19 distinct historical geomagnetic storms identified in Table 1 are presented in Appendices B–T, which include assessments of the reliability of each historical record.

## 6 Discussion of the results

It should be noted that the 19 putative (apparently distinct) historical geomagnetic storms presented in Table 1 are confined to the interval AD 1135–1650, whereas the East Asian sunspot and auroral observations coexist at least throughout the interval 165 BC–AD 1910 (Sect. 2). The temporal distribution of the historical geomagnetic storms by century is as follows: 4 in the 12th; 2 in the 13th; 2 in the 14th; 0 in the 15th; 1 in the 16th; and 10 in the 17th (the last number is reduced to 8 if allowance is made for the spurious "approximate coincidences" discussed in the previous section). Therefore, all of the historical geomagnetic storms identified in this paper occurred after AD 1100, partly as a result of a general increase in the volume and dating accuracy of recorded information with the passage of time and partly because solar and auroral activity were both high in the twelfth century (Siscoe, 1980; Yau and Stephenson, 1988; Willis and Stephenson, 2001). The distribution of these storms by century is in approximate agreement with the number of days per century on which aurorae were recorded in both China *and* Europe (Siscoe, 1980; see his Fig. 5), although the numbers for China are essentially those derivable from the present auroral database and hence they do not provide independent confirmation of the centurial variation in the number of historical geomagnetic storms.

Moreover, the dates of the historical geomagnetic storms listed in Table 1 are in general agreement with the variations in solar activity that have been inferred from the $^{14}$C and $^{10}$Be records (Eddy, 1976, 1977; Siscoe, 1980; Beer, 2000; Usoskin et al., 2003). For example, the first six geomagnetic storms presented in Table 1 occurred during the Medieval Maximum (AD 1120–1280) in solar activity, whereas no storms occurred during the Oort Minimum (1010–1050), the Wolf Minimum (AD 1280–1340) or the Spörer Minimum (AD 1420–1530): just one storm occurred near the very beginning (AD 1648) of the Maunder Minimum (AD 1645–1715) and no storms occurred during the Dalton Minimum (AD 1795–1825). Likewise, none of the geomagnetic storms listed in Table 1 occurred during either of the two shorter minima (around 1765 and 1901–1913) noted by Silverman (1992) in a detailed discussion of the secular variation of the aurora for the past 500 years.

The failure of the present study to detect any historical geomagnetic storms after AD 1650 requires clarification. The surprising lack of storms in the eighteenth and nineteenth centuries results partly from a dearth of East Asian sunspot observations in this same time interval. Of the 286 records in the sunspot database (Sect. 3), 220 refer to observations up to the end of AD 1650. The remaining 66 records are distributed in time as follows: 11 in the interval AD 1651–1700; 13 in the interval AD 1701–1800; 34 in the interval AD 1801–1900; and 8 in the interval AD 1901–1918. There can be little doubt that the frequencies of East Asian records of sunspots and aurorae were very much affected by sociological factors: e.g. varying court attitudes to celestial omens, and loss of extant records as the result of wars and invasion. In Europe after about AD 1600, there was a marked increase in astronomical observation for scientific purposes; this was aided by the dissemination of the telescope. However, there was almost no parallel development in East Asia until as late as the twentieth century. Conservative attitudes were responsible for maintaining the traditional roles of court astronomers as observers and interpreters of portents.

Two of the great geomagnetic storms of the nineteenth century, namely those on AD 1859 September 2 and

**Table 1.** Chronological list of "approximate coincidences" between oriental sunspot and auroral observations, derived from the sunspot and auroral databases (Sect. 3) using the condition $-8 \leq T \leq +15$ to define historical geomagnetic storms (Sect. 4.2). Dates before AD 1582 October 5 are in the Julian calendar, whereas subsequent dates are in the Gregorian calendar. The country of origin of each observation, as recorded in the oriental histories, is denoted by a capital letter: C=China; J=Japan; and K=Korea. The "literary" reliabilities of the observations are classified in terms of the historical sources as follows: [DH]=a record of high reliability from a *dynastic history*; [OC]=a record of high reliability from an *official chronicle*; [LH]=a record of lesser reliability from a *local history*; [LC]=a record of lesser reliability from a *late compilation* (Appendix A). The "scientific" reliabilities of the observations are defined as follows: 1=certain; 2=very probable; 3=probable; 4=doubtful; and 5=unlikely (Appendix A). The abbreviation [NA] (=not available) is used to qualify the single Japanese auroral record (AD 1626 July 10) for which no reliability classification is available (Appendix R).

Notes. The superscript *a* signifies that the sunspot observation on AD 1185 February 10 was recorded in China, whereas the sunspot observation on February 11 (which does *not* satisfy the selection criterion defined in Sect. 4.2) was recorded in Korea; the superscript *b* signifies that the "scientific" reliability is borderline between [C1] and [C2]; and the superscript *c* signifies that the corresponding oriental record must be treated with extra caution, despite its apparent reliability, because it is based on a retrospective entry in an official chronicle (see Appendix L).

| No. | Sunspot Observation | Country | Reliability | Auroral Observation | Country | Reliability |
|---|---|---|---|---|---|---|
| 01 | AD 1137 Mar 1–Mar 10 | C | [DH] [C1] | AD 1137 Mar 4 | C | [DH] [C1] |
| 02 | AD 1185 Feb 10, 11[a] | C, K[a] | [DH], [DH] | AD 1185 Feb 2 | J | [J3] |
| 03 | AD 1185 Mar 27 | K | [DH] | AD 1185 Mar 26 | K | [DH] |
| 04 | AD 1193 Dec 3–Dec 12 | C | [DH] [C1] | AD 1193 Dec 5 | C | [DH] [C1][b] |
| 05 | AD 1193 Dec 3–Dec 12 | C | [DH] [C1] | AD 1193 Dec 6 | C | [DH] [C1][b] |
| 06 | AD 1202 Dec 19–Dec 31 | C | [DH] [C1] | AD 1202 Dec 19 | J | [J2] |
| 07 | AD 1204 Feb 21 | C | [DH] [C1] | AD 1204 Feb 21 | J | [J1] |
| 08 | AD 1204 Feb 21 | C | [DH] [C1] | AD 1204 Feb 22 | J | [J2] |
| 09 | AD 1204 Feb 21 | C | [DH] [C1] | AD 1204 Feb 23 | J | [J1] |
| 10 | AD 1370 Jan 28–Feb 3 | C | [OC] | AD 1370 Feb 11 | K | [DH] [OC] |
| 11 | AD 1370 Oct 21 | C | [OC] [C1] | AD 1370 Oct 27 | J | [J1] |
| 12 | AD 1556 Apr 17 | K | [OC] | AD 1556 Apr 13 | K | [OC] |
| 13 | AD 1618 May 22 | C | [LC] | AD 1618 May 17 | C | [DH] [OC] |
| 14 | AD 1620 Oct 15–Oct 24 | C | [OC][c] | AD 1620 Oct 19 | C | [OC] [LH] |
| 15 | AD 1620 Oct 15–Oct 24 | C | [OC][c] | AD 1620 Oct 20 | C | [LC] |
| 16 | AD 1624 Mar 17–Mar 20 | C | [DH] | AD 1624 Mar 21 | K | [OC] |
| 17 | AD 1624 Apr 15, Apr 16 | C | [LH] [LC], [DH] | AD 1624 Apr 18 | K | [OC] |
| 18 | AD 1624 Apr 15, Apr 16 | C | [LH] [LC], [DH] | AD 1624 Apr 19 | K | [OC] |
| 19 | AD 1624 Apr 15, Apr 16 | C | [LH] [LC], [DH] | AD 1624 Apr 21 | K | [OC] |
| 20 | AD 1625 Sep 2 | C | [LH] | AD 1625 Aug 28 | K | [OC] |
| 21 | AD 1625 Sep 2 | C | [LH] | AD 1625 Sep 16 | K | [OC] |
| 22 | AD 1626 Jun 29 | C | [LH] | AD 1626 Jun 24 | K | [OC] |
| 23 | AD 1626 Jun 29 | C | [LH] | AD 1626 Jul 10 | J | [NA] |
| 24 | AD 1638 Dec 9 | C | [DH] | AD 1638 Dec 23 | C | [LH] |
| 25 | AD 1648 Jan 16 | K | [OC] | AD 1648 Jan 24 | C | [DH] |

AD 1872 February 4, are certainly identified by auroral observations in *both* China and Japan but in neither case is there an associated East Asian sunspot observation. Similarly, one of the great geomagnetic storms in the first decade of the twentieth century, namely that on AD 1909 September 25, is identified by auroral observations in Japan (on the nights of both September 25 and 26) but once again there is no associated East Asian sunspot observation.

The magnitudes of these three great geomagnetic storms can be quantified by geomagnetic activity indices, namely the *Ak* (Helsinki) index and the *aa* index (Mayaud, 1980; Nevanlinna and Kataja, 1993). The daily values of the *Ak* index for the five-day interval centred on the great geomagnetic storm of AD 1859 September 2 are as follows: 22, 35, 32, 58, 75, (although it seems likely that these values of the Helsinki index underestimate the true strength of this

great geomagnetic storm). Likewise, the daily values of the *aa* index for the five-day interval centred on the great geomagnetic storm of AD 1872 February 4 are as follows (to the nearest integer value): 14, 12, 230, 54, 22. Similarly, the daily values of the *aa* index for the five-day interval centred on the great geomagnetic storm of AD 1909 September 25 are as follows: 10, 6, 329, 23, 16. Two of the great geomagnetic storms of the eighteenth century, namely those on AD 1730 February 15 and AD 1770 September 17, are also identified by auroral observations in *both* China and Japan but in neither case is there an associated East Asian sunspot observation or a quantitative measure of the level of geomagnetic activity.

On the basis of this limited evidence, it is tempting to speculate that a great geomagnetic storm ($aa \geq 50$) occurred whenever an aurora was observed in East Asia. However, some East Asian auroral observations are associated with relatively weak magnetic activity. For example, an auroral display was seen in China on AD 1859 August 4, 29 days before the great storm on AD 1859 September 2 (actually, dual storms commenced on August 28 and September 2); the daily values of the *Ak* index for the five-day interval centred on AD 1859 August 4 are as follows: 5, 5, 4, 4, 5. There are several other examples of aurorae being observed in East Asia under relatively quiet magnetic conditions. It is possible that the occurrence of aurorae in East Asia under quiet magnetic conditions is analogous to the occurrence of so-called "sporadic auroras" at low latitudes under quiet-to-moderate magnetic activity, as reported by Silverman (2003) for auroral data acquired exclusively in the United States during the interval AD 1880–1940 (with the exception of one event observed from Grahamstown, South Africa). However, this possibility requires further investigation before a firm conclusion can be reached. The complexity of the relationship between the level of magnetic activity (as quantified by geomagnetic indices) and the occurrence of auroral displays in East Asia entirely justifies the present decision to define intense historical geomagnetic storms strictly in terms of approximately co-incident auroral *and* sunspot observations, particularly since lists of great geomagnetic storms, and tables of geomagnetic activity indices, are available only from AD 1840 onwards (Royal Greenwich Observatory, 1955; Mayaud, 1980; Nevanlinna and Kataja, 1993).

As already indicated, one disadvantage of defining intense historical geomagnetic storms in terms of approximately coincident auroral *and* sunspot observations, however, is the relative paucity of East Asian sunspot observations. There are 1198 entries in the auroral database but only 286 entries in the sunspot database (Sect. 3). The corresponding numbers for precise records, for which the year, month and day are all known exactly, are 1036 and 186. The discrepancy between the numbers of sunspot and auroral observations arises partly from the fact that the detection of sunspots with the unaided eye is inherently more difficult than the detection of aurorae with the unaided eye. Sunspots can be detected with the unaided eye only under suitable atmospheric viewing conditions, when the glare of the Sun is greatly reduced – for example, when the Sun is low in the sky (near sunrise or sunset) or when dust, haze, mist, smoke or thin cloud prevails (Willis et al., 1980, 1988; Yau and Stephenson, 1988). Conversely, aurorae are spectacular, easily seen and visible for hours over wide geographic areas. Moreover, auroral luminosity can often be seen in the gaps between optically dense meteorological clouds, as inferred from some detailed descriptions of auroral displays in the oriental records (Yau et al., 1995).

Therefore, the definition of an historical geomagnetic storm in terms of approximately coincident sunspot and auroral observations is a very strict criterion that depends on a number of favourable atmospheric viewing conditions. It is clear that this technique can detect only a subset of the true number of historical geomagnetic storms (see also Sect. 4.1). Many storms must have been missed as a result of unfavourable viewing conditions for detecting either sunspots or aurorae, including extensive cloud cover. As a result, undue emphasis should not be placed on the centurial variation in the frequency of occurrence of historical geomagnetic storms, without first making some allowance for climatological changes over the same period – a topic that is well beyond the intended scope of this initial study. The great merit of the present investigation, however, is that it results in the identification of a number of historical geomagnetic storms before AD 1650, at a time when more modern scientific information is unavailable.

Quite apart from possible limitations resulting from the relative paucity of East Asian sunspot observations, another notable feature that should be mentioned is the very large number of Korean auroral records in the short interval AD 1624–1626, and also in the earlier interval AD 1510–1560. These follow a very repetitive style, in which the phenomenon observed is usually likened to either a "fire", a "vapour like a fire", a "flame" or a "vapour like a flame" (Yau et al., 1995), occurring predominantly in the southern sky (Zhang, 1985). In the context of the present study, the annual numbers of exactly dated Korean auroral observations (on separate days) in the interval AD 1623–1628 are as follows: 1 in 1623; 10 in 1624; 20 in 1625; 29 in 1626; 4 in 1627; and 1 in 1628 (Yau et al., 1995). As yet, no entirely convincing explanation has been given for the huge excess of Korean sightings around AD 1625 and in the longer interval AD 1510–1560 (Willis and Stephenson, 2000). Zhang (1985) has suggested that most of the Korean records referring simply to a "fire" or a "flame" actually describe stable auroral red arcs (SAR arcs) but this interpretation has been questioned by Kozyra et al. (1997) because of the low intensities of SAR arcs – typically several hundred Rayleighs (R). To be visible to the unaided eye, the SAR arcs allegedly observed by the Korean astronomers must have achieved intensities of at least 6–10 kR.

Although seven of the 25 approximate coincidences listed in Table 1 result from Korean auroral observations in the short interval AD 1624–1626, it is shown in the remainder of this section that three of these Korean auroral observations (AD 1625 August 28, September 16 and AD 1626

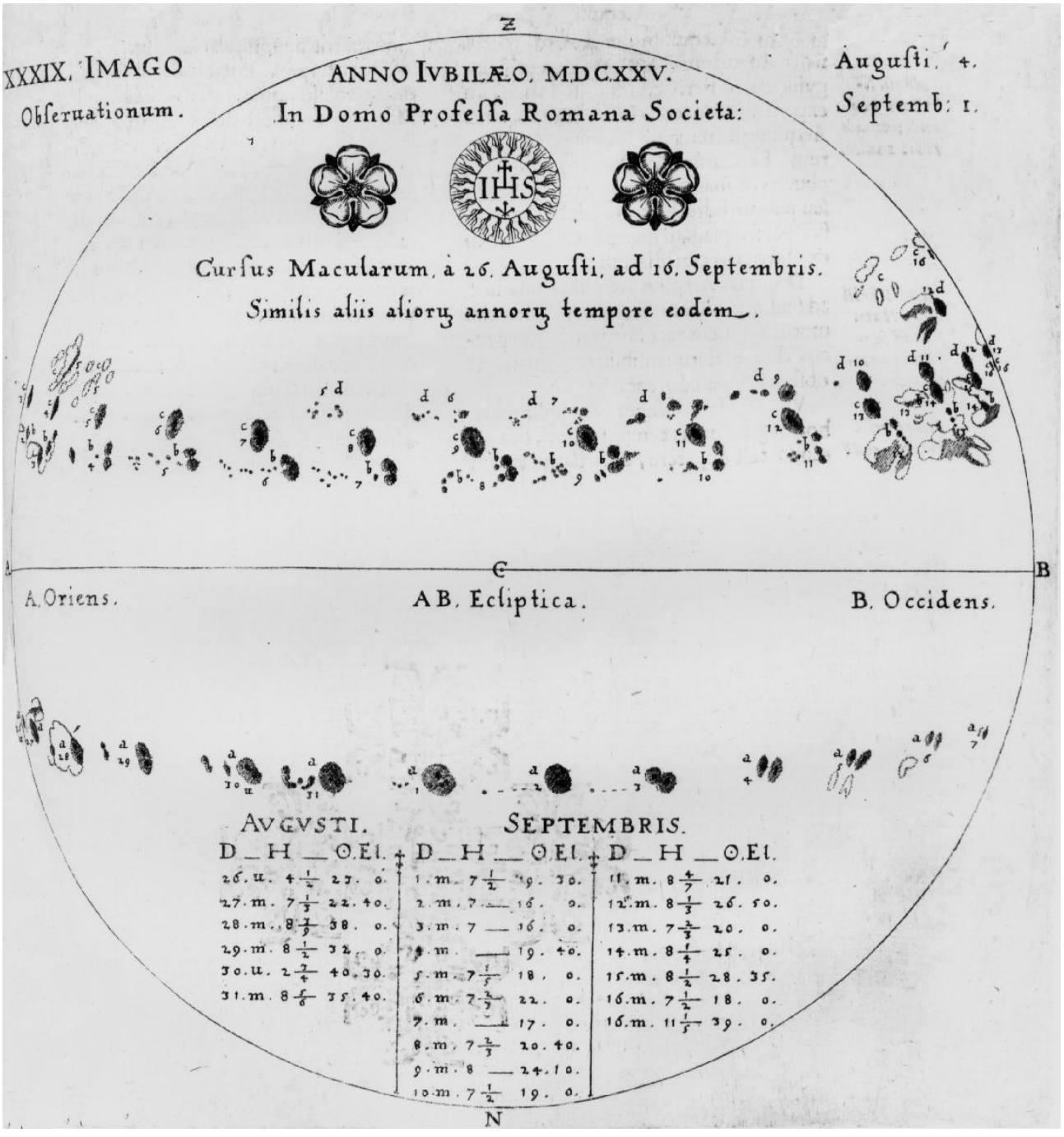


**Fig. 2.** The daily progression of sunspots across the solar disk during the interval AD 1625 August 26–September 16 (Scheiner, 1630). The sunspot in the southern half of the solar disk was close to the central meridian on September 2 and large enough to be seen without the aid of a telescope, which confirms the unaided-eye Chinese sunspot observation on the same date (see Table 1).

June 24) are compatible with European sunspot drawings (Scheiner, 1630). These European sunspot drawings show large sunspots near the central solar meridian a few days *before* each of these three Korean auroral observations (see Figs. 3, 2 and 4). The other four approximate coincidences in Table 1, resulting from Korean auroral observations in the short interval AD 1624–1626 (and for which no European sunspot drawings are available), only represent two distinct geomagnetic storms (AD 1624 March 21 and AD 1624 April 18; see Appendices M and N), which are separated by 28 days. The fact that these two geomagnetic storms are separated by about one synodic-solar-rotation period and are identified, respectively, by Chinese sunspot observations in the intervals AD 1624 March 17–20 and AD 1624 April 15–16 (i.e. a few days *before* the associated Korean auroral observations) suggests that the other four

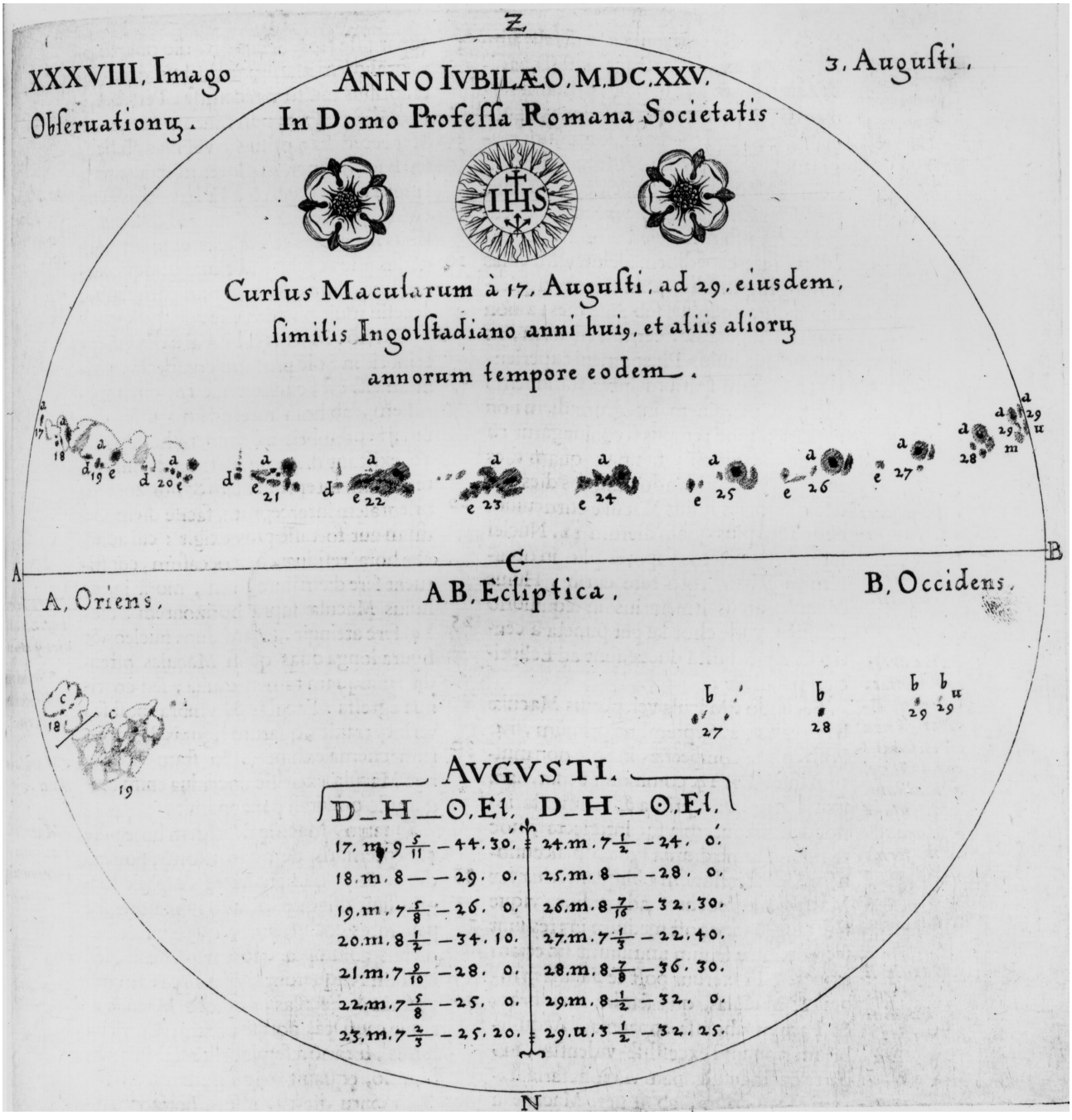


**Fig. 3.** The daily progression of sunspots across the solar disk during the interval AD 1625 August 17–29 (Scheiner, 1630). The complex sunspot group in the northern half of the solar disk that crossed the central meridian on August 23 (but was not observed in East Asia) is more likely to be associated with the Korean auroral observation on August 28 (see Table 1) than is the unaided-eye Chinese sunspot observation on September 2 (see Table 1).

Korean auroral observations (AD 1624 March 21 and AD 1624 April 18, 19 and 21) are also reliable. Moreover, three of these other four auroral observations occur on almost consecutive nights (AD 1624 April 18, 19 and 21), suggesting the existence of a particularly intense geomagnetic storm at this time (see Appendix N), which tends to corroborate the reliability of these three neighbouring Korean auroral observations.

With only a very few notable exceptions, there is no independent evidence that incontrovertibly establishes the veracity of the East Asian sunspot and auroral observations recorded during the interval 210 BC–AD 1918. The sunspot and auroral records identified by the selection criterion $-8 \leq T \leq +15$ (see Table 1) are discussed in Appendices B–T from the viewpoint of both the reliability of the relevant oriental history and the credibility of the scientific content of

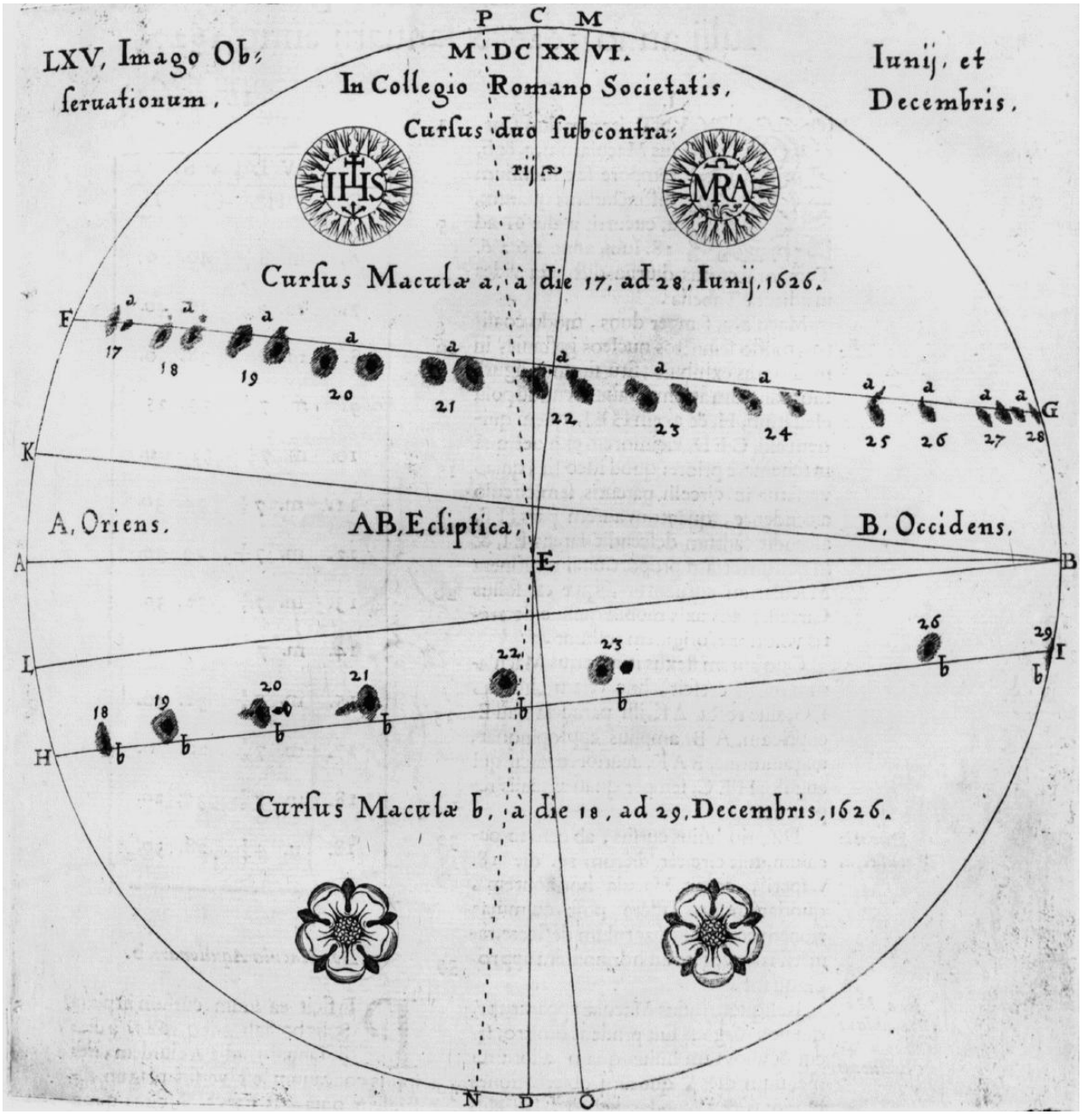


**Fig. 4.** The daily progression of sunspots across the solar disk during the interval AD 1626 June 17–28 (Scheiner, 1630). This figure indicates that the unaided-eye Chinese sunspot observation on AD 1626 June 29 (see Table 1) is apparently spurious because the pair of sunspots in the northern half of the solar disk would have already passed just beyond the west limb of the Sun by that time. However, this same pair of sunspots crossed the central meridian on June 22 and is therefore probably associated with the Korean auroral observation on June 24 (see Table 1).

the record, as defined in Appendix A. More generally, the present paper forms part of an ongoing critical assessment of the reliability and utility of the sunspot and auroral observations recorded in various histories from East Asia (Willis et al., 1996a, b; Stephenson and Willis, 1999; Willis and Stephenson, 2000, 2001).

Following the invention of the telescope in about AD 1610, however, systematic scientific observations start to become available from Europe. Indeed, Willis et al. (1996a) compared the oriental sunspot sightings from AD 1863 onwards with contemporaneous occidental white-light images of the Sun acquired by the Royal Greenwich Observatory. It was concluded from this earlier study that the dates of the oriental sunspot sightings quoted in the various histories are largely, but not invariably, correct for the interval AD 1863–1918. In the present paper, the sunspot drawings

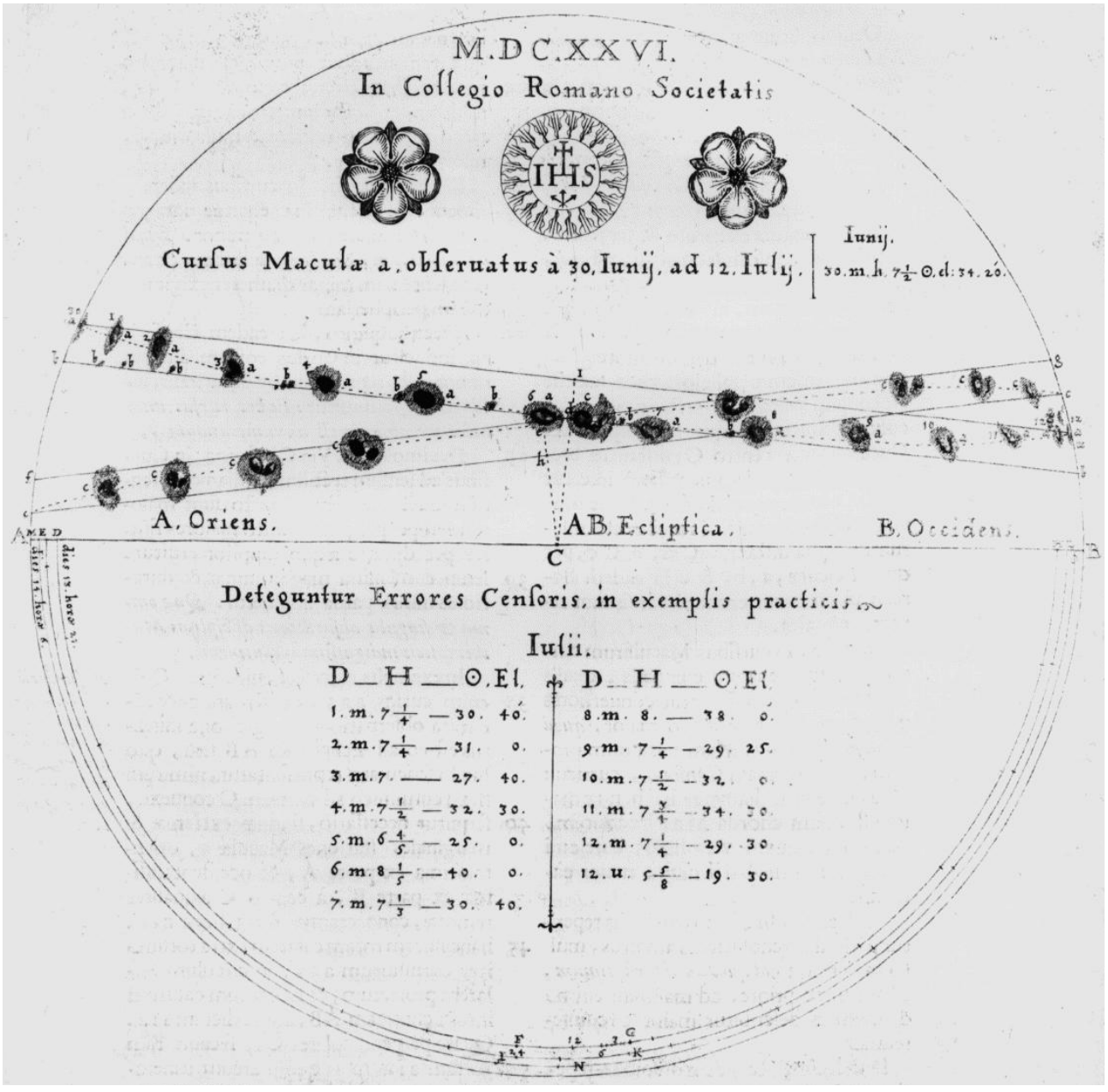


**Fig. 5.** The daily progression of sunspots across the solar disk (Curve a) during the interval AD 1626 June 30–July 12 (Scheiner, 1630). (Curve c refers to the interval AD 1625 December 22–1626 January 1.) The large sunspot in the northern half of the solar disk that crossed the central meridian on July 6 (Curve a) is much more likely to be associated with the Japanese auroral observation on July 10 (see Table 1) than is the apparently spurious unaided-eye Chinese sunspot observation on June 29 (see Table 1).

published in AD 1630 by the German astronomer Christoph Scheiner, SJ, are used to discuss the appropriateness and reliability of the oriental sunspot observations associated with the four putative historical geomagnetic storms that occurred (or commenced) on AD 1625 August 28, AD 1625 September 16, AD 1626 June 24 and AD 1626 July 10, respectively. All these dates are expressed in the Gregorian calendar, which was adopted by the Roman Catholic Church in AD 1582. Unfortunately, it seems unlikely that there are any sunspot drawings relevant to most of the remaining fifteen putative historical geomagnetic storms presented in Table 1. It is just possible, however, that further searches of historical books and documents will reveal sunspot drawings relevant to the geomagnetic storms of AD 1638 December 23 and AD 1648 January 24.

Figure 2 shows the motion of sunspots across the solar disk during the interval AD 1625 August 26–September 16 (Scheiner, 1630). It is clear from this figure that the sunspot in the southern half of the solar disk on September 2 was close to the central meridian and certainly large enough to be

seen with the unaided eye (see Willis et al., 1996a), which confirms the reliability of the unaided-eye Chinese sunspot observation on the same date (see Table 1). This confirmation is important because, as noted in Appendix O, the Chinese sunspot observation is from a local history and its precise translation is questionable. Nevertheless, if the large sunspot in the southern hemisphere crossed the central meridian on September 1 (Fig. 2), the energetic solar feature could not have occurred before August 28 and hence the transit time of the ejected solar plasma must have been less than a day.

However, Fig. 3 shows the motion of sunspots across the northern half of the solar disk during the earlier, but overlapping, interval AD 1625 August 17–29 (Scheiner, 1630). This figure shows that a complex sunspot group large enough to be seen with the unaided eye crossed the central meridian on August 23. It seems more probable that this complex sunspot group, which was apparently not seen by the oriental observers (perhaps because of cloud cover), was associated with the historical geomagnetic storm on August 28. Therefore, although it is highly likely that an historical geomagnetic storm actually occurred on AD 1625 August 28, since the Korean auroral observation was recorded in an official day-to-day chronicle (see Appendix O), it is unlikely that it was associated physically with the apparently authentic Chinese sunspot observation on September 2.

In Appendix P, the geomagnetic storm of AD 1625 September 16 is provisionally associated with the Chinese sunspot observation on September 2, although it is recognised that the conjectured time sequence of events is barely plausible because it relies on all three variables defined in Sect. 4.2 being near extremes of their acceptable ranges. Moreover, as noted in Appendices O and P, a sunspot observation on September 2 cannot be associated physically with auroral observations on both August 28 and September 16, since these two auroral observations are separated by 19 days.

As is clear from Fig. 2, however, one of the sunspots in the northern half of the solar disk on September 9 was close to the central meridian and large enough to be seen with the unaided eye. Hence it seems more probable that this large sunspot, which was apparently not seen by the oriental observers, was responsible for the historical geomagnetic storm on September 16. Therefore, although it is highly likely that an historical geomagnetic storm actually occurred on AD 1625 September 16, since the Korean auroral observation was recorded in an official chronicle (see Appendix P), it is unlikely that it was associated physically with the apparently authentic Chinese sunspot observation on September 2.

Figure 4 shows the motion of a pair of large sunspots across the northern half of the solar disk during the interval AD 1626 June 17–28 (Scheiner, 1630): the motion of the large sunspot in the southern half of the solar disk refers to the interval AD 1626 December 18–29. It is clear from this figure that the Chinese astronomers could not have seen a sunspot on June 29, since the pair of sunspots shown in Fig. 4 would have already passed just beyond the west limb of the Sun. This conclusion is consistent with the fact that the Chinese sunspot record has been extracted from a local history, whereas the Korean auroral record is from an official chronicle and hence is intrinsically more reliable (see Appendix Q). Therefore, the Korean auroral observation on June 24 cannot be associated physically with the apparently spurious Chinese sunspot observation on June 29. However, it is equally clear from Fig. 4 that the pair of sunspots in the northern half of the solar disk crossed the central meridian on June 22 and hence the historical geomagnetic storm of AD 1626 June 24 is probably associated with this particular pair of sunspots.

As already explained, the Chinese astronomers could not have seen a sunspot on June 29, since the pair of sunspots shown in Fig. 4 would have already passed beyond the west limb of the Sun. Moreover, a sunspot observation on June 29 cannot be associated meaningfully with auroral observations on both June 24 and July 10, since these two auroral observations are separated by 16 days. Therefore, the Japanese auroral observation on July 10 cannot possibly be associated physically with the apparently spurious Chinese sunspot observation on June 29.

However, Fig. 5 shows the motion of a large sunspot across the northern half of the solar disk (Curve a) during the interval AD 1626 June 30–July 12 (Scheiner, 1630). (N.B. Curve c shows another sunspot, observed during the interval AD 1625 December 22–1626 January 1.) It is clear from this figure that a sunspot large enough to be seen with the unaided eye crossed the central meridian on July 6. It seems more probable that this large sunspot, which was apparently not seen by the oriental observers, was responsible for the historical geomagnetic storm on July 10. Therefore, although it is highly likely that an historical geomagnetic storm actually occurred on AD 1626 July 10, it cannot possibly be associated physically with the apparently spurious Chinese sunspot observation on June 29.

## 7 Conclusions

This paper presents the first detailed attempt to identify historical geomagnetic storms using East Asian observations of both sunspots and aurorae. Careful examination of historical sunspot and auroral observations recorded during the interval 210 BC–AD 1918 has resulted in the identification of 19 alleged historical geomagnetic storms, which are listed in Table 1. By definition, these historical geomagnetic storms must have been intense if they produced mid-latitude auroral displays visible in China, Korea or Japan. Moreover, these 19 geomagnetic storms must be a very small subset of the true number of such events. The stringent criterion for an intense historical geomagnetic storm, namely the existence of approximately coincident East Asian observations of sunspots and aurorae, favours the identification of intense storms at times when sunspot and auroral observations were *both* frequent. Moreover, many sunspot and auroral observations must have been missed as a result of extensive cloud cover. All of the historical geomagnetic storms identified in

this paper occurred after AD 1100, partly as a result of a general increase in the volume of recorded information with the passage of time and partly because solar and auroral activity were apparently both high in the twelfth century.

Throughout the greater part of the two millennia prior to AD 1918, there is no independent evidence that incontrovertibly establishes the validity of the sunspot and auroral records from East Asia. Following the invention of the telescope in about AD 1610, however, systematic scientific observations start to become available from Europe. In this study, the sunspot drawings published by Scheiner (1630) are used to discuss the appropriateness and reliability of four of the 19 putative historical geomagnetic storms listed in Table 1. The European sunspot drawings presented in Figs. 2–5 cast doubt on certain of these storms, in the *strict* sense that the implied association between individual sunspot and auroral records (identified by the selection criterion $-8 \leq T \leq +15$) is imperfect or even invalid. This reservation applies only to those oriental sunspot records of lesser reliability, which are derived from local histories or late compilations. Even in these cases, however, the European telescopic sunspot drawings suggest that the relevant East Asian auroral observations are associated with a sunspot that was near the central solar meridian on a date when observers in China, Korea and Japan did not record any sunspot sightings. The European sunspot drawings are the most direct way of testing the validity of the East Asian sunspot sightings associated with the historical geomagnetic storms listed in Table 1. Telescopic sunspot drawings have the great advantage that they provide a clear indication of the size and complexity of a sunspot (or sunspot group) on a known date, as well as its exact position on the solar disk. Unfortunately, sunspot drawings do not exist for most of the 19 alleged geomagnetic storms discussed in Sect. 6 and are probably not even available for all 10 geomagnetic storms in the seventeenth century.

From AD 1840 onwards, however, more modern scientific information becomes available in the form of lists of great geomagnetic storms and tables of magnetic indices (*Ak* and *aa*). Unfortunately, the technique discussed in this paper does not identify any historical geomagnetic storms after AD 1648; therefore, direct comparisons with modern data cannot be made. Nevertheless, the more numerous East Asian auroral observations (if considered alone) correctly identify several of the truly great geomagnetic storms that have occurred during more recent times (AD 1859 September 2, AD 1872 February 4 and AD 1909 September 25). Further studies are planned, in which modern scientific information will be used to calibrate and interpret the historical data from East Asia.

## Appendix A: The relevant East Asian records and their associated reliabilities

The East Asian records that are selected from the sunspot and auroral databases (see Sect. 3), using the selection criterion $-8 \leq T \leq +15$ for historical geomagnetic storms (see Sect. 4.2), are presented in the following appendices. All sunspot and auroral records identified by this selection criterion for historical geomagnetic storms describe observations made during the interval AD 1100–1650. Each putative ("apparently distinct") historical geomagnetic storm is identified, or labelled, either by the single date of the auroral observation, or by the first date in a sequence of contiguous auroral observations (see Sect. 5). In the following appendices, the sunspot and auroral records listed in Table 1 are presented separately for each "apparently distinct" historical geomagnetic storm. As noted in Sect. 5, however, some of these "apparently distinct" geomagnetic storms are questionable in the sense that two non-neighbouring auroral observations, separated by more than 13.5 days, are apparently associated with the same sunspot observation. Such "ambiguities" arise as an inevitable consequence of the 24-day acceptance interval $-8 \leq T \leq +15$.

Throughout these appendices we have – with only a few specific exceptions – used the well-known Wade-Giles system of romanisation for Chinese words and names. The location of the Chinese capital has often changed down the centuries. The various records that are discussed in the following appendices originate from three separate capitals, as well as several provincial towns. In two instances, the name of the capital has remained unchanged to the present-day; here we have given the more familiar modern pinyin spelling (Beijing and Nanjing). However, we have used Wade–Giles romanisation for the name of the medieval capital Lin-an (now known as Hangzhou). In the case of the lesser-known provincial towns, we have kept to the Wade-Giles system. Since AD 918, there have been only two significant Korean capitals: Songdo (now Kaesong) and Hanyang (now Seoul). The imperial Japanese capital was Kyoto for the entire period from AD 784 to 1868. For each historical record, the place of observation is given immediately after the country of origin.

In Chinese and Korean dynastic histories, sunspot and auroral records may be found in the imperial annals, the astronomical treatises, or the "five phases" treatises. For the Ming Dynasty in China (AD 1367–1644), an important source is the *Ming Shih-lu* ("Veritable records of the Ming Dynasty"); this includes sections such as the *T'ai-tsu Shih-lu* and the *Hsi-ts'ung Shih-lu* (covering the reigns of Ming emperors T'ai-tsu and Hsi-ts'ung respectively). The *Yijo Sillok* ("Veritable records of the Yi Dynasty") has been our exclusive source for Korean records during the Yi Dynasty (AD 1392–1910). This compilation includes sections such as the *T'aejo Sillok*, *Myongjong Sillok* and *Injo Sillok* (dealing with the reigns of Yi kings T'aejo, Myongjong and Injo). For each Chinese and Korean record, the title of the relevant history (in italics) and the appropriate chapter number are given in parentheses (e.g. *Sung-shih*, 52). In the case of Japanese records, we have consulted only modern compilations, e.g. *Nihon Temmon Shiryou*, *Nihon Kishou Shiryou* and *Kinsei Nihon Temmon Shiryou*. These works are based on extensive searches of a wide variety of Japanese historical documents.

The following classification systems are introduced to assess the reliability of the oriental historical records. For the

Chinese and Korean records, the classifications [DH] and [OC] are used to signify a record of high reliability, which has been extracted either from a *dynastic history* or from an *official chronicle*, respectively; the classification [LH] is used to denote a record of lesser reliability that has been extracted from a *local history*; and the classification [LC] is used to denote a record of lesser reliability that has been extracted from a *late compilation*, for which the original official dynastic record is not available. The astronomical records in the dynastic histories and official chronicles are largely based on the observations of the Court Astronomers. However, the material in local histories and late compilations is of relatively dubious origin. The historical sources of the Japanese auroral records (there are no Japanese sunspot observations in Table 1) are much more diverse and in general these records do not originate from "official" histories, contrary to the situation for many of the Chinese and Korean auroral records. Indeed, there is no true Japanese equivalent of a dynastic history. In the work of Kanda (1934), the Central Meteorological Observatory and Imperial Marine Observatory (1939), and much later Osaki (1994), all sorts of sources were consulted: privately compiled histories, diaries of courtiers, temple records, etc. Hence the reliability of the Japanese auroral records is often more problematic.

In an attempt to make some assessment of the reliability of the Japanese (J) auroral records, the classifications [J1], [J2], [J3], [J4] and [J5] are used in this study, where the numbers 1, 2, 3, 4 and 5 are derived directly from the reliability scale employed by both Matsushita (1956) and Keimatsu (1976); namely, 1=certain, 2=very probable, 3=probable, 4=doubtful, and 5=unlikely. Both Matsushita (1956) and Keimatsu (1976) indicate that their numerical classification of the reliability of auroral records is based mainly on the characteristic properties of the luminous phenomena observed in the night sky, as described in the historical texts. These characteristic properties include: the time of occurrence; duration (distinction from meteors); position in the sky; colour; form; and movement (Matsushita also takes into account the number of independent observations). Fortunately, neither Matsushita (1956) nor Keimatsu (1976) classify any of the records corresponding to the Japanese auroral observations presented in Table 1 as "5=unlikely". However, for the Japanese auroral observations listed in this table, the "numerical credibilities" assigned by Keimatsu are at least one level higher (in the sense of greater credibility) than those assigned by Matsushita (apart from AD 1204 February 22). Moreover, Keimatsu (1976) does not consider any sunspot or auroral observations after AD 1600. Finally, it should be emphasised that this "scientific" or "credibility" classification system for the Japanese auroral records is quite different to the "literary" classification system introduced in the previous paragraph for the Chinese and Korean historical records.

However, it is possible to introduce completely analogous reliabilities [C1], [C2], [C3], [C4] and [C5], and [K1], [K2], [K3], [K4] and [K5], to represent the "numerical credibilities" of both the sunspot and auroral records from China (C), and Korea (K), respectively. In this case, the assignment of the numbers 1, 2, 3, 4 and 5 is necessarily determined solely from the numerical credibility scale employed by Keimatsu (1976), since Matsushita (1956) considered only Japanese auroral observations. For consistency and generality, it then seems sensible to use the (numerical) credibility scale published by Keimatsu (1976) to assess the reliability of the Japanese auroral records. In principle, therefore, the fifteen categories [C1], [C2], [C3], [C4], [C5], [J1], [J2], [J3], [J4], [J5], [K1], [K2], [K3], [K4] and [K5] represent an essentially uniform set of "measures" for classifying the credibilities of the sunspot and auroral records from China, Japan and Korea up to AD 1600. Difficulties still arise in classifying the credibilities of some oriental historical records before AD 1600, however, because not all of the sunspot and auroral observations listed in Table 1 are included in the summary catalogue published by Keimatsu (1976). Such "unclassifiable" cases are discussed individually in the appropriate appendices.

Whenever possible, the dual classification system ([DH], [OC], [LH], [LC]) and ([C1], [C2], [C3], [C4], [C5], [J1], [J2], [J3], [J4], [J5], [K1], [K2], [K3], [K4], [K5]) is used to consider the reliability of the sunspot and auroral observations of each of the putative ("apparently distinct") historical geomagnetic storms defined by the sunspot and auroral observations listed in Table 1 (at least up to AD 1600). In addition, a probable time sequence of events, which is compatible with the assumptions and criteria discussed in Sect. 4, is presented for each storm.

## Appendix B: The geomagnetic storm of AD 1137 March 4

The descriptions of the Chinese sunspot observations during the interval AD 1137 March 1–March 10 may be translated as follows:

[China, Lin-an] Shao-hsing reign period, 7th year, 2nd month, day *keng-tzu* (37) – March 1. "Within the Sun there was a black spot as large as a plum for 10 days; then it dispersed." (*Sung-shih*, 52)

(N.B. *Fu-chien T'ung-chih*, 177 records the following entry, commencing on the same day (March 1): "Within the Sun there was a black spot, like a granule; on day *hsin-ch'ou* (38)–March 2–it covered the Sun (!)" The source of this very early entry in a local history (of Fu-chien Province) is obscure.) Only the dates of the first and second days of the interval (March 1–March 10) are given explicitly; the text in *Sung-shih*, 52 merely states that the spot was visible for a decade (i.e. 10 days). However, the text in *Fu-chien T'ung-chih*, 177 asserts that the sunspot was seen on both March 1 and March 2. The reliability of the first Chinese sunspot observation, on March 1, is classified as [DH] in terms of the historical source and [C1] in terms of the credibility scale employed by Keimatsu (1976), as defined in Appendix A.

The description of the Chinese auroral observation on AD 1137 March 4 may be translated as follows:

[China, Lin-an] Shao-hsing reign period, 7th year, 2nd month, day *kuei-mao* (40). "It was again like this (following the entry of AD 1137 January 31)." (*Sung-shih*, 60)
For reference, the entry of AD 1137 January 31 may be translated as follows:

[China, Lin-an] Shao-hsing reign period, 7th year, 1st month, day *hsin-wei* (8). "At night, in the NE, there was a red vapour like fire appearing from the *Tzu-wei-kung* (the north circumpolar region)." (*Sung-shih*, 60)
The reliability of both these Chinese auroral observations is classified as [DH] in terms of the historical source and [C1] in terms of the credibility scale employed by Keimatsu (1976).

The fact that the sunspot was apparently visible for 10 days is consistent with the duration-of-visibility criterion defined in Sect. 4.1 and suggests that the sunspot crossed the central meridian on March 5 or March 6 (i.e. near the mid-point of the 10-day interval). Moreover, in terms of the discussion presented in Sect. 4.2, it seems likely that the energetic solar feature generating the historical geomagnetic storm of AD 1137 March 4 occurred sometime during the interval March 2–March 3. For example, if the Chinese observers first saw the sunspot (March 1) 5 days before it crossed the central meridian (March 6) and the energetic solar feature occurred 3 days before (March 3) the sunspot crossed the central meridian, it would have taken a further day for the ejected solar plasma to reach the Earth (March 4). If the sunspot crossed the central meridian a day earlier (March 5) and the energetic solar feature occurred 3 days previously (March 2), it would have taken two days for the ejected plasma to reach the Earth and the sunspot observation on March 10 would have been made on the last day of sunspot visibility. This time sequence of events is quite plausible in the sense that it is possible to change the date of occurrence of the energetic solar feature by a day (from March 3 to March 2) without violating any of the criteria defined in Sect. 4.2.

## Appendix C: The geomagnetic storm of AD 1185 February 2

The description of the Chinese and Korean sunspot observations on AD 1185 February 10 and February 11 may be translated as follows:

(i) [China, Lin-an] Shun-hsi reign period, 12th year, 1st month, day *kuei-szu* (30)–February 10. "Within the Sun there was produced a black spot as large as a date." (*Sung-shih*, 52)

(ii) [Korea, Songdo] King Myongjong, 15th year, 1st month, day *chia-wu* (31)–February 11. "On the Sun there was a black spot as large as a pear." (*Koryo-sa*, 47)
The reliability of the Chinese sunspot observation (February 10) is classified as [DH] from the historical source; the reliability of the Korean sunspot observation (February 11) is also classified as [DH] from the historical source. No other classification can be assigned because these sunspot observations are not in the list compiled by Keimatsu (1976).

The description of the Japanese auroral observation on AD 1185 February 2 may be translated as follows:

[Japan, Kyoto] Bunji reign period, 1st year, 1st month, 1st day. "This night there was a red vapour in the SE direction." (*Nihon Kishou Shiryou*, 13)
The reliability of this Japanese auroral observation is classified as [J3] in terms of the credibility scale employed by Keimatsu (1976).

The energetic solar feature generating the historical geomagnetic storm of AD 1185 February 2 probably occurred on February 1. For example, if the Chinese observers first saw the sunspot (February 10) 5 days after it crossed the central meridian (February 5) and the energetic solar feature occurred 4 days before (February 1) the sunspot crossed the central meridian, the ejected solar plasma would have taken a further day to reach the Earth. The Korean sunspot observation (February 11) is *not* identified by the selection criterion $-8 \leq T \leq +15$. Therefore, the time sequence of events is plausible only if the Korean sunspot observation actually occurred 6 days after central meridian passage or, alternatively, if the transit time of the ejected plasma was less than a day. However, it should be noted that this geomagnetic storm occurred almost two synodic-solar-rotation periods (i.e. almost 54 days) before the geomagnetic storm of AD 1185 March 26, which is discussed in the next appendix. The apparent existence of recurrent geomagnetic activity at this particular time increases the likelihood that a storm actually occurred on AD 1185 February 2.

## Appendix D: The geomagnetic storm of AD 1185 March 26

The description of the Korean sunspot observation on AD 1185 March 27 may be translated as follows:

[Korea, Songdo] King Myongjong, 15th year, 2nd month, day *wu-yin* (15). "On the Sun there was a black spot as large as a pear." (*Koryo-sa*, 47)
The reliability of this Korean sunspot observation is classified as [DH] in terms of the historical source. No other classification can be assigned because this sunspot observation is not in the list compiled by Keimatsu (1976).

The description of the Korean auroral observation on AD 1185 March 26 may be translated as follows:

[Korea, Songdo] King Myongjong, 15th year, 2nd month, day *ting-ch'ou* (14). "At night, on the E and W horizons, there were red colours like the shadows of fire." (*Koryo-sa*, 53)
The reliability of this Korean auroral observation is classified as [DH] in terms of the historical source. Similarly, no other classification can be assigned because this auroral observation is not in the list compiled by Keimatsu (1976).

The energetic solar feature generating the historical geomagnetic storm of AD 1185 March 26 probably occurred sometime during the interval March 23–March 25. For example, if the Korean observers saw the sunspot (March 27) 1 day after it crossed the central meridian (March 26) and

the energetic solar feature occurred 1 day before (March 25) it crossed the central meridian, it would have taken a further day for the ejected solar plasma to reach the Earth (March 26). This time sequence of events is entirely plausible, as are several others with minor variations in the precise details (e.g. 1-day or 2-day differences). In the discussion of all subsequent geomagnetic storms, the plausibility (or flexibility) of the time sequence of events will be noted briefly without further comment, unless this plausibility almost infringes one of the criteria presented in Sects. 4.1 and 4.2.

## Appendix E: The geomagnetic storm of AD 1193 December 5

The description of the Chinese sunspot observations during the interval AD 1193 December 3–December 12 may be translated as follows:

[China, Lin-an] Shao-hsi reign period, 4th year, 11th month, day *hsin-wei* (8) – December 3. "Within the Sun there was a black spot, until day *keng-ch'en* (17) – December 12 – when it dispersed." (*Sung-shih*, 36, 52)

Both dates (December 3 and December 12) are specified, but not duration in a direct way. The reliability of these Chinese sunspot observations, particularly on the first and last days (December 3 and December 12), is classified as [DH] in terms of the historical source and [C1] in terms of the credibility scale employed by Keimatsu (1976).

The description of the Chinese auroral observation on AD 1193 December 5 may be translated as follows:

[China, Lin-an] Shao-hsi reign period, 4th year, 11th month, day *kuei-yu* (10). "At night, there was a red cloud and a white vapour." (*Sung-shih*, 36)

The descriptions of the Chinese auroral observations on AD 1193 December 6 may be translated as follows:

(i) [China, Lin-an] Shao-hsi reign period, 4th year, 11th month, day *chia-hsu* (11). "At night, a red cloud and a white vapour were seen." (*Sung-shih*, 60)

(ii) [China, Lin-an] Shao-hsi reign period, 4th year, 11th month, day *chia-hsu* (11). "A red cloud was seen at night; it was divided by a white vapour." (*Sung-shih*, 64)

The auroral record on December 5 is only in the annals of the same history as the auroral record on December 6; the latter is in both the astronomical treatise and the five phases treatise of the same history as the former record. The reliability of both these Chinese auroral observations is classified as [DH] in terms of the historical source and borderline between [C1] and [C2] in terms of the credibility scale employed by Keimatsu (1976).

The fact that this sunspot was apparently visible for 10 days is completely consistent with the duration-of-visibility criterion defined in Sect. 4.1 and suggests that the sunspot crossed the central meridian on December 7 or December 8. It then seems likely that the energetic solar feature generating the historical geomagnetic storm of AD 1193 December 5 occurred on December 3, December 4 or just possibly on December 5. For example, if the Chinese observers first saw the sunspot (December 3) 4 days before it crossed the central meridian (December 7) and the energetic solar feature occurred 3 days before (December 4) the sunspot crossed the central meridian, it would have taken a further day for the ejected solar plasma to reach the Earth (December 5). If the energetic solar feature occurred 4 days before (December 3) the sunspot crossed the central meridian (December 7), it would have taken two days for the ejected plasma to reach the Earth. In both these cases, the sunspot observation on December 12 would have been made on the last day of sunspot visibility. If the sunspot crossed the central meridian a day later (December 8), however, either the energetic solar feature occurred 4 days before (December 4) the sunspot crossed the central meridian, or the energetic solar feature occurred a day later (December 5) and the transit time of the ejected plasma was less than a day. This time sequence of events is just plausible.

## Appendix F: The geomagnetic storm of AD 1202 December 19

The descriptions of the Chinese sunspot observations during the interval AD 1202 December 19–December 31 may be translated as follows:

[China, Lin-an] Chia-t'ai reign period, 2nd year, 12th month, day *chia-hsu* (11) – December 19. "Within the Sun there was produced a black spot as large as a date; on day *ping-hsu* (23) – December 31 – it then dispersed." (*Sung-shih*, 52)

(N.B. *Sung-shih*, 38 merely notes that on day *chia-hsu* (11) – December 19 – "within the Sun there was a black spot.")

Both dates (December 19 and December 31) are specified, but not duration in a direct way. Moreover, it is most unlikely that the ancient Chinese observers could have seen the same sunspot for 13 days (see Sect. 4.1); presumably the allusion is to two different sunspots. Nevertheless, the reliability of these Chinese sunspot observations, particularly the observations on the first and last days (December 19 and December 31), is classified as [DH] in terms of the historical source and [C1] in terms of the credibility scale employed by Keimatsu (1976). This particular sunspot record is the only one selected by the acceptance interval $-8 \leq T \leq +15$ for the situation in which the interval of visibility apparently exceeds the threshold of 10 days (see Sect. 4.1). It is accepted solely because the duration of visibility is not specified in a direct way and it may thus be inferred that the Chinese observers saw two different sunspots (see Sect. 3).

The description of the Japanese auroral observation on AD 1202 December 19 may be translated as follows:

[Japan, Kyoto] Kennin reign period, 2nd year, 11th month, 4th day. "At the hour *hsu* (19:00–21:00 LT), there was a red vapour." (*Nihon Temmon Shiryou*, 8; *Nihon Kishou Shiryou*, 13)

The reliability of this Japanese auroral observation is classified as [J2] in terms of the credibility scale employed by Keimatsu (1976).

Assuming that the Chinese observers actually saw different sunspots on December 19 and on December 31, it is easy to construct a plausible sequence of events for the historical geomagnetic storm of AD 1202 December 19. The energetic solar feature generating this historical geomagnetic storm probably occurred sometime during the interval December 16–December 18. The sunspot was probably reasonably close to the central meridian during this time interval, as it also was when it was actually observed by the Chinese observers (December 19). However, some uncertainty must remain over the identification of this historical geomagnetic storm, if only because the first and last dates of the sunspot observations were separated by 13 days.

## Appendix G: The geomagnetic storm of AD 1204 February 21

The description of the Chinese sunspot observation on AD 1204 February 21 may be translated as follows:

[China, Lin-an] Chia-t'ai reign period, 4th year, 1st month, day *kuei-wei* (20). "Within the sun there was a black spot as large as a date." (*Sung-shih*, 52)

(N.B. *Sung-shih*, 38 merely notes that on this same day "within the Sun there was a black spot.")

The reliability of this Chinese sunspot observation is classified as [DH] in terms of the historical source and [C1] in terms of the credibility scale employed by Keimatsu (1976).

The descriptions of the Japanese auroral observations on AD 1204 February 21 and February 22 may be translated as follows:

(i) [Japan, Kyoto] Genkyu reign period, 1st year, 1st month, 19th day. "After dusk, in the N and NE directions, there were red vapours. Their roots were like the Moon rising in the E. They were bright and white in colour. Their branches were flickering like the light from a funeral pyre at a distance. In four or five places they were white in colour and three or four of the stems were red. They were not clouds; if they were clouds, stars would not be seen. In the brighter part, it seemed as if the white and red lights were interchanging. They were very strange indeed and terrifying." (*Nihon Temmon Shiryou*, 8; *Nihon Kishou Shiryou*, 13)

(ii) [Japan, Kyoto] Genkyu reign period, 1st year, 1st month, 19th day. "At the hour *hsu* (19:00–21:00 LT), red clouds and white clouds were interchanging. They were seen from the NNW to the NNE. On the 20th and 21st days (i.e. the next two days), it was the same. From the NNE direction to the N direction, white clouds nullified them (the red clouds)." (*Nihon Temmon Shiryou*, 8; *Nihon Kishou Shiryou*, 13)

The description of the Japanese auroral observation on AD 1204 February 23 may be translated as follows:

[Japan, Kyoto] Genkyu reign period, 1st year, 1st month, 21st day. "After dark, in the N and NE directions, there were again red vapours. They were like funeral pyres burning beyond the distant mountains. It was most terrifying." (*Nihon Temmon Shiryou*, 8; *Nihon Kishou Shiryou*, 13)

The reliabilities of the Japanese auroral observations on February 21, February 22 and February 23 are classified as [J1], [J2] and [J1], respectively, in terms of the credibility scale employed by Keimatsu (1976).

The energetic solar feature generating the historical geomagnetic storm of AD 1204 February 21 probably occurred sometime during the interval February 18–February 20. For example, if the Chinese observers saw the sunspot (February 21) as it actually crossed the central meridian (February 21) and the energetic solar feature occurred between 1 and 3 days before (February 18–February 20) the sunspot crossed the central meridian, it would have taken between 1 and 3 days for the ejected solar plasma to reach the Earth (February 21). This time sequence of events is entirely plausible. Moreover, this historical geomagnetic storm is interesting in the sense that the aurora was seen by Japanese observers on three consecutive nights, which suggests that the geomagnetic storm was particularly intense.

## Appendix H: The geomagnetic storm of AD 1370 February 11

The description of the Chinese sunspot observations during the interval AD 1370 January 28–February 3 may be translated as follows:

[China, Nanjing] Hung-wu reign period, 3rd year, 1st month, day *ting-yu* (34)–February 3. "The Astronomical Bureau reported that from the 1st day (of the month) – January 28 – until today – February 3 – within the Sun there was a black spot." (*T'ai-tsu Shih-lu*, 48)

The reliability of this Chinese sunspot observation is classified as [OC] in terms of the historical source. No other classification can be assigned because this sunspot observation is not in the list compiled by Keimatsu (1976).

The descriptions of the Korean auroral observations on AD 1370 February 11 may be translated as follows:

(i) [Korea, Songdo] King Kongmin Wang, 19th year, 1st month, day *chia-ch'en* (41). "A violet vapour filled the NW sky. The shadows it cast were all in the S." (*Koryo-sa*, 53)

(ii) [Korea, Songdo] King Kongmin Wang, 19th year, 1st month, exact day unspecified. "This evening, to the NW of the capital, a violet vapour filled the sky. The shadows it cast were all in the S." (*T'aejo Sillok*, 1)

Although an exact date is not given in (ii), it is evident that the second description refers to the same event as noted in (i). The reliabilities of these two Korean auroral observations are classified as [DH] and [OC], respectively, in terms of the historical sources. No other classification can be assigned because this auroral observation is not in the list compiled by Keimatsu (1976).

The fact that the sunspot was visible for 7 days is consistent with the duration-of-visibility criterion defined in Sect. 4.1. The energetic solar feature generating the geomagnetic storm of AD 1370 February 11 probably occurred on February 6. For example, if the Chinese observers first saw the sunspot (January 28) 5 days before it crossed the

central meridian (February 2) and the energetic solar feature occurred 4 days after (February 6) the sunspot crossed the central meridian, it would still have taken 5 days for the ejected solar plasma to reach the Earth (February 11). This time sequence of events is only just plausible, since it relies on all three variables defined in Sect. 4.2 being near extremes of their acceptable ranges.

## Appendix I: The geomagnetic storm of AD 1370 October 27

The Chinese sunspot observation on AD 1370 October 21 may be translated as follows:

[China, Nanjing] Hung-wu reign period, 3rd year, 10th month, day *ting-szu* (54). "Within the Sun there was a black spot." (*T'ai-tsu Shih-lu*, 57)

(N.B. This record is duplicated in *Ming-shih*, 27; *Kuo-chueh*, 4 merely notes that on the stated day "within the Sun it was black".)

The reliability of this Chinese sunspot observation is classified as [OC] in terms of the historical source and [C1] in terms of the credibility scale employed by Keimatsu (1976).

The description of the Japanese auroral observation on AD 1370 October 27 may be translated as follows:

[Japan, Kyoto] Kentoku reign period, 1st year, 10th month, 8th day. "From the hour of *hsu* (19:00–21:00 LT) onwards, a red vapour was seen in the northern sky. It lasted until midnight. Its form was like a burning object. Everyone was puzzled. This was also seen last year." (*Nihon Temmon Shiryou*, 8; *Nihon Kishou Shiryou*, 13)

The reliability of this Japanese auroral observation is classified as [J1] in terms of the credibility scale employed by Keimatsu (1976).

The energetic solar feature generating the historical geomagnetic storm of AD 1370 October 27 probably occurred sometime during the approximate interval October 23–October 26. For example, if the Chinese observers saw the sunspot (October 21) 3 days before it crossed the central solar meridian (October 24) and the energetic solar feature occurred 1 to 2 days after (October 25–October 26) the sunspot crossed the central meridian, it would have taken a further 1 to 2 days for the ejected solar plasma to reach the Earth (October 27). This time sequence of events is entirely plausible.

## Appendix J: The geomagnetic storm of AD 1556 April 13

The description of the Korean sunspot observation on AD 1556 April 17 may be translated as follows:

[Korea, Hanyang] King Myongjong, 11th year, 3rd month, day *ting-mao* (4). "Within the Sun there was a black spot as large as a hen's egg. The sky was covered with a dense vapour." (*Myongjong Sillok*, 20)

The reliability of this Korean sunspot observation is classified as [OC] in terms of the historical source. No other classification can be assigned because this sunspot observation is not in the list compiled by Keimatsu (1976).

The description of the Korean auroral observation on AD 1556 April 13 may be translated as follows:

[Korea, Hanyang] King Myongjong, 11th year, 3rd month, day *kuei-hai* (60). "At night, in the SE and NW directions, there were like fire-vapours." (*Myongjong Sillok*, 20)

The reliability of this Korean auroral observation is classified as [OC] in terms of the historical source. No other classification can be assigned because this auroral observation is not in the list compiled by Keimatsu (1976).

The energetic solar feature generating the historical geomagnetic storm of AD 1556 April 13 probably occurred during the interval April 10–April 12. For example, if the Korean observers saw the sunspot (April 17) 4 days after it crossed the central meridian (April 13) and the energetic solar feature occurred 1 day before (April 12) the sunspot crossed the central meridian, the ejected solar plasma would have taken a further day to reach the Earth (April 13). This time sequence of events is entirely plausible.

## Appendix K: The geomagnetic storm of AD 1618 May 17

The description of the Chinese sunspot observation on AD 1618 May 22 may be translated as follows:

[China, Beijing] Wan-li reign period, 46th year, 4th month, day *ting-szu* (54). "Within the Sun there was a black ladle." (*Kuo-ch'ueh*, 83)

The reliability of this Chinese sunspot observation is classified as [LC] in terms of the historical source. No other classification can be assigned for this date, or any later date, because Keimatsu (1976) does not consider sunspot observations after AD 1600.

The descriptions of the Chinese auroral observations on AD 1618 May 17 may be translated as follows:

(i) [China, Beijing] T'ien-ming reign period, 3rd year, 4th month, day *jen-tzu* (49). "There were two bands of blue-black vapour stretching across the sky from W to E." (*Ch'ing-shih-kao*, 39)

(ii) [China, Beijing] T'ien-ming reign period, 3rd year, 4th month, day *jen-tzu* (49). "This evening, there were two bands of blue-black vapour stretching across the sky from W to E." (*Ch'ing-shih-lu*, 5)

The reliabilities of these two Chinese auroral observations are classified as [DH] and [OC], respectively, in terms of the historical sources. No other classification can be assigned for this date, or any later date, because Keimatsu (1976) does not consider auroral observations after AD 1600.

The energetic solar feature generating the historical geomagnetic storm of AD 1618 May 17 probably occurred sometime during the interval May 14–May 16. For example, if the Chinese observers saw the sunspot (May 22) 4 days after it crossed the central meridian (May 18) and the energetic solar feature occurred 2 days before (May 16) the sunspot crossed the central meridian, it would have taken a further

day for the ejected solar plasma to reach the Earth (May 17). This time sequence of events is again entirely plausible.

## Appendix L: The geomagnetic storm of AD 1620 October 19

The description of the Chinese sunspot observation during the interval AD 1620 October 15–October 24 may be translated as follows:

[China, Beijing] T'ai-ch'ang reign period, 1st year, 10th month, day *kuei-yu* (10) – November 23. "When Your Majesty ascended the throne during the last ten days (of the previous month)–October 15 to October 24–on the Sun there was a black vapour; it was agitating the Sun." (*Hsi-tsung Shih-lu*, 2)

Only an approximate date is given. A retrospective entry dated November 23 asserts that during the last decade of the previous month (October 15–October 24), when the Emperor ascended the throne, there was a black vapour on the Sun. Although the reliability of this Chinese sunspot observation is classified as [OC] in terms of the historical source, extra care is needed with the interpretation of this particular record.

There are two descriptions of Chinese auroral observations on AD 1620 October 19, which may be translated as follows:

(i) [China, Beijing] T'ai-chang reign period, 1st year, 9th month, day *wu-hsu* (35). "There was a red vapour shining in the sky; it was as if reddish-brown." (*Hsi-ts'ung Shih-lu*, 1)

(ii) [China, Chang-shan in Shan-tung Province] Wan-li reign period, 48th year, 9th month, 24th day. "A red vapour stretched across the sky." (*Chang-shan Hsien-chih*, 7)

The description of the Chinese auroral observation on AD 1620 October 20 may be translated as follows:

[China, Beijing] T'ai-chang reign period, 1st year, 9th month, day *chi-hai* (36). "At dawn there was a red vapour shining in the sky; it was as if reddish-brown. After a long time it faded away." (*Kuo-ch'ueh*, 84)

In terms of the literary sources, the reliability of the Chinese auroral observation at Beijing on October 19 is classified as [OC] and the reliability of the observation at Chang-shan on the same day is classified as [LH]; the corresponding reliability of the Chinese auroral observation at Beijing on October 20 is classified as [LC].

Clearly, neither the sunspot record nor the auroral record for this historical geomagnetic storm is of the very highest reliability. Nevertheless, if it were assumed that the Chinese observers saw a sunspot throughout the ten-day interval October 15–October 24, which is consistent with the duration-of-visibility criterion defined in Sect. 4.1, the sunspot would probably have crossed the central meridian on October 19 or October 20. It then seems likely that the energetic solar feature generating the historical geomagnetic storm of AD 1620 October 19 occurred sometime during the interval October 16–October 18. For example, if the Chinese observers first saw the sunspot (October 15) 5 days before it crossed the central meridian (October 20) and the energetic solar feature occurred 2 days before (October 18) the sunspot crossed the central meridian, it would have taken a further day for the ejected solar plasma to reach the Earth (October 19). This time sequence of events is entirely plausible.

## Appendix M: The geomagnetic storm of AD 1624 March 21

The description of the Chinese sunspot observation during the interval AD 1624 March 17–March 20 may be translated as follows:

[China, Beijing] T'ien-ch'i reign period, 4th year, 1st month, day *kuei-wei* (20). "The Sun was red and dim. There were two or three black spots moving about at its side. They gradually increased to about a hundred (*sic*), and lasted for four days." (*Ming-shih*, 27)

(N.B. This record is not found in *Ming-shih-lu*. However, *Kuo-ch'ueh* gives an abbreviated version of the above: "At the side of the Sun, there were black spots agitating one another for a total of four days." (*Kuo-ch'ueh*, 86))

Only the first date is given explicitly; the text states that two or three spots lasted for four days. The reliability of this Chinese sunspot observation is classified as [DH] in terms of the historical source.

The description of the Korean auroral observation on AD 1624 March 21 may be translated as follows:

[Korea, Hanyang] King Injo, 2nd year, 2nd month, day *ting-hai* (24). "At the first watch of the night, in the SE direction, there was a vapour like a flame." (*Injo Sillok*, 4)

The reliability of this Korean auroral observation is classified as [OC] in terms of the historical source.

The energetic solar event producing the historical geomagnetic storm of AD 1624 March 21 probably occurred during the interval March 18–March 20. For example, if the Chinese observers first saw the sunspot (March 17) 2 days before it crossed the central meridian (March 19) and the energetic solar feature occurred 1 day after (March 20) the sunspot crossed the central meridian, it would have taken a further day for the ejected solar plasma to reach the Earth (March 21). This time sequence of events is highly plausible.

## Appendix N: The geomagnetic storm of AD 1624 April 18

The descriptions of the Chinese sunspot observations on AD 1624 April 15 and April 16 may be translated as follows:

(i) [China, Che-chiang] T'ien-ch'i reign period, 4th year, 2nd month, 28th day – April 15. "The sky was of a dark colour. On the side of the Sun there was a black spot rocking to and fro." (*Che-chiang T'ung-chih*, 15)

(ii) [China, Beijing] T'ien-ch'i reign period, 4th year, 2nd month, 28th day – April 15. "On the side of the Sun there was seen a black Sun (*sic*) rocking to and fro." (*Ming-chi Pei-lueh*, 2)

(iii) [China, Beijing] T'ien-ch'i reign period, 4th year, 2nd month, day *kuei-ch'ou* (50) – April 16. "A black Sun (*sic*) was rocking to and fro beside the Sun." (*Ming-shih*, 27)

(N.B. This last record is not found in *Ming-shih-lu*. The interpretation of records (ii) and (iii) is rather obscure, but the fact that the observations are reported on separate dates suggests that the allusion is to a sunspot.)

The two dates (April 15 and April 16) of these Chinese sunspot observations are given in separate sources. The reliabilities of the first two observations (April 15) are classified as [LH] and [LC], respectively, whereas the corresponding reliability of the third observation (April 16) is classified as [DH]. Nevertheless, these sunspot observations are questionable because the original Chinese texts can be translated either as "on the side of the Sun" or as "beside the Sun".

The description of the Korean auroral observation on AD 1624 April 18 may be translated as follows:

[Korea, Hanyang] King Injo, 2nd year, 3rd month, day *i-mao*, (52), 1st day of the month. "Just before daybreak, in the E direction, there was a vapour like a flame. At night, in the S, NE, SE and SW directions, there were vapours like flames." (*Injo Sillok*, 5)

The description of the Korean auroral observation on AD 1624 April 19 may be translated as follows:

[Korea, Hanyang] King Injo, 2nd year, 3rd month, day *ping-ch'en* (53). "In the early evening, in the E direction, there was a vapour like a flame." (*Injo Sillok*, 5)

The description of the Korean auroral observation on AD 1624 April 21 may be translated as follows:

[Korea, Hanyang] King Injo, 2nd year, 3rd month, day *wu-wu* (55). "Just before daybreak, in the E direction, there was a vapour like a flame. At night, in the E direction, a red vapour shone brilliantly on the horizon. In the N and SW directions, there were vapours like flames." (*Injo Sillok*, 5)

There are no astronomical records, or any allusion to unfavourable weather, on the day corresponding to April 20. The reliabilities of the Korean auroral observations on all three dates (April 18, April 19 and April 21) are classified as [OC] in terms of the historical source.

Despite some reservations regarding the "literary" reliabilities of two of the Chinese sunspot observations, a time sequence comprising sunspot observations on April 15 and April 16, followed by auroral observations on April 18, April 19 and April 21, is highly plausible. The energetic solar feature generating the historical geomagnetic storm of AD 1624 April 18 probably occurred sometime during the interval April 15–April 17. For example, if the Chinese observers first saw the sunspot (April 15) 3 days before it crossed the central meridian (April 18) and the energetic solar feature occurred 1 day before (April 17) the sunspot crossed the central meridian, it would have taken a further day for the ejected solar plasma to reach the Earth (April 18). Moreover, this historical geomagnetic storm is interesting in the sense that the aurora was seen by Korean observers on three out of four consecutive nights, which suggests that the geomagnetic storm was particularly intense.

## Appendix O: The geomagnetic storm of AD 1625 August 28

The description of the Chinese sunspot observation on AD 1625 September 2 may be translated as follows:

[China, Che-chiang] T'ien-ch'i reign period, 5th year, 8th month, 1st day. "In the daytime, a star was seen on the side of the Sun." (*Chia-hsing Fu-chih*, 35)

(N.B. This was very probably a sunspot. It was not the planet Venus, which was 45° W of the Sun.)

The reliability of this Chinese sunspot observation is classified as [LH] in terms of the historical source. Moreover, this sunspot observation is questionable because the original Chinese text can be translated either as "a star was seen on the side of the Sun" or as "a star was seen beside the Sun". Nevertheless, the assertion that a star was seen "within" the Sun is fairly common in Chinese local histories at this period and it would be difficult to suggest an alternative to a sunspot. As noted in Appendix P, however, the sunspot observation on AD 1625 September 2 is notable in the sense that it is associated with two, widely separated, auroral observations on August 28 and September 16 (using the selection criterion $-8 \leq T \leq +15$). No more than one of these "approximate coincidences" can define a genuine historical geomagnetic storm, since the same sunspot cannot be associated physically with two auroral observations separated by 19 days (see Sect. 5).

The description of the Korean auroral observation on AD 1625 August 28 may be translated as follows:

[Korea, Hanyang] King Injo, 3rd year, 7th month, day *jen-shen* (9). "At night, in the NW and SW directions, there were vapours like flames." (*Injo Sillok*, 9)

The reliability of this Korean auroral observation is classified as [OC] in terms of the historical source.

The energetic solar feature generating the historical geomagnetic storm of AD 1625 August 28 probably occurred sometime during the interval August 25–August 27. For example, if the Chinese observers saw the sunspot (September 2) 4 days after it crossed the central meridian (August 29) and the energetic solar feature occurred 2 days before (August 27) the sunspot crossed the central meridian, it would then have taken just one day for the ejected solar plasma to reach the Earth (August 28). This time sequence is highly plausible. However, as shown in Sect. 6, careful European telescopic sunspot drawings (Figs. 2 and 3) suggest that the Korean auroral observation on August 28 is more likely to be associated with a complex sunspot group that was near the central meridian on August 23, which was apparently not observed in East Asia. Nevertheless, the Chinese sunspot observation on September 2 is confirmed by one of these European sunspot drawings (Fig. 2).

## Appendix P: The geomagnetic storm of AD 1625 September 16

The translation of the description of the Chinese sunspot observation on AD 1625 September 2 has already been presented in Appendix O, in which it is also stated that the reliability of this sunspot observation is classified as [LH] in terms of the historical source. This particular sunspot observation is notable in the sense that it is associated with two, widely separated, auroral observations (August 28 and September 16), using the selection criterion $-8 \leq T \leq +15$. No more than one of these "approximate coincidences" can be a genuine historical geomagnetic storm, since the same sunspot cannot be associated physically with two auroral observations separated by 19 days (see Sect. 5).

The description of the Korean auroral observation on AD 1625 September 16 may be translated as follows:

[Korea, Hanyang] King Injo, 3rd year, 8th month, day *hsin-mao* (28). "In the early evening, in the NE and NW directions, there were vapours like flames." (*Injo Sillok*, 9)

The reliability of this Korean auroral observation is classified as [OC] in terms of the historical source.

The energetic solar feature generating the historical geomagnetic storm of AD 1625 September 16 probably occurred on September 10 or September 11. Even if the Chinese observers saw the sunspot (September 2) 5 days before it crossed the central meridian (September 7) and the energetic solar feature occurred 3 or 4 days after (September 10 or September 11) the sunspot crossed the central meridian, it would still have taken a further 5 or 6 days for the ejected solar plasma to reach the Earth (September 16). This time sequence of events is barely plausible, since it relies on all three variables defined in Sect. 4.2 being near extremes of their acceptable ranges. Moreover, as shown in Sect. 6, a European telescopic sunspot drawing (Fig. 2) suggests that the Korean auroral observation on September 16 is more likely to be associated with a sunspot that was near the central meridian on September 9, which was apparently not observed in East Asia, rather than with the confirmed Chinese sunspot observation on September 2.

## Appendix Q: The geomagnetic storm of AD 1626 June 24

The description of the Chinese sunspot observation on AD 1626 June 29 may be translated as follows:

[China, Hsiang-yuan in Shan-hsi Province] T'ien-ch'i reign period, 6th year, 6th month, 6th day. "Within the Sun a ladle was seen." (*Hsiang-yuan Hsien-chih*, 8)

(N.B. *Shan-hsi T'ung-chih*, 163 and *Lu-an Fu-chih*, 15 give the same description as the previous record, but only an approximate date is given (month in the first source, season in the second).)

The reliability of this Chinese sunspot observation is classified as [LH] in terms of the historical source. As noted in Appendix R, however, the sunspot observation on AD 1626 June 29 is notable in the sense that it is associated with two, widely separated, auroral observations on June 24 and July 10 (using the selection criterion $-8 \leq T \leq +15$). Only one of these "approximate coincidences" can define a genuine historical geomagnetic storm, since the same sunspot cannot be associated physically with two auroral observations separated by 16 days (see Sect. 5).

The description of the Korean auroral observation of AD 1626 June 24 may be translated as follows:

[Korea, Hanyang] King Injo, 4th year, 6th month, day *jen-shen* (9), 1st day of the month. "At night, in the W, E and NE directions, there were vapours like flames." (*Injo Sillok*, 13)

The reliability of this Korean auroral observation is classified as [OC] in terms of the historical source.

The energetic solar feature generating the historical geomagnetic storm of AD 1626 June 24 probably occurred sometime during the interval June 21–June 23. For example, if the Chinese observers saw the sunspot (June 29) 4 days after it crossed the central meridian (June 25) and the energetic solar feature occurred 2 days before (June 23) the sunspot crossed the central meridian, it would have taken a further day for the ejected solar plasma to reach the Earth (June 24). This time sequence is quite plausible. However, as shown in Sect. 6, a European telescopic sunspot drawing (Fig. 4) indicates that no sunspot on the solar disk on AD 1626 June 29 would have been large enough to be seen by the Chinese observers with the unaided eye. The pair of large sunspots that crossed the central meridian on June 22 would have been beyond the west limb of the Sun by June 29. Therefore, the Chinese sunspot observation on June 29 is almost certainly spurious, possibly as a result of a scribal error in the date. This conclusion is consistent with the fact that the sunspot record has been extracted from a local history, which is intrinsically less reliable than a dynastic history or official chronicle. Indeed, the same European sunspot drawing suggests that the Korean auroral observation on June 24 is more likely to have been associated with the pair of large sunspots that crossed the central meridian on June 22, which was apparently not observed in East Asia.

## Appendix R: The geomagnetic storm of AD 1626 July 10

The translation of the description of the Chinese sunspot observation on AD 1626 June 29 has already been presented in Appendix Q, in which it is also stated that the reliability of this sunspot observation is classified as [LH] in terms of the historical source. This particular sunspot observation is also notable in the sense that it is associated with two, widely separated, auroral observations (June 24 and July 10), using the selection criterion $-8 \leq T \leq +15$. Once again, no more than one of these "approximate coincidences" can be a genuine historical magnetic storm, since the same sunspot cannot be associated physically with two auroral observations separated by 16 days (see Sect. 5).

The description of the Japanese auroral observation on AD 1626 July 10 may be translated as follows:

[Japan, Kyoto?] Kanei reign period, 3rd year, 5th month, 25th day, *ping-shen* (33). "It was clear; there was a shower of rain. Someone said that on the 17th day at dawn in the sky there were 'banner clouds' standing in the E and W." (*Kinsei Nihon Temmon Shiryou*, p. 569)

No reliability is available for this Japanese auroral observation because the date is after AD 1600.

It has been argued in the previous appendix that this oriental sunspot observation is almost certainly spurious, since a European telescopic sunspot drawing (Fig. 4) indicates that no sunspot on the solar disk on AD 1626 June 29 would have been large enough to have been seen by the East Asian observers with the unaided eye (see Sect. 6). Another European sunspot drawing (Fig. 5) suggests that the Japanese auroral observation on July 10 is more likely to have been associated with a large sunspot that crossed the central meridian on July 6, which was apparently not observed in East Asia.

## Appendix S: The geomagnetic storm of AD 1638 December 23

The description of the Chinese sunspot observation on AD 1638 December 9 may be translated as follows:

[China, Beijing] Ch'ung-cheng reign period, 11th year, 11th month, day *kuei-hai* (60). "Within the Sun there was a black spot, and there were black, blue and white vapours." (*Ming-shih*, 27)

(N.B. Although this record is not found in *Ming-shih-lu*, it is found in *Kan-su Hsin-t'ung-chih*, 2, except that the day is wrongly given as *kuei-szu* (30). There was no such day in the 11th month.)

The reliability of this Chinese sunspot observation is classified as [DH] in terms of the historical source.

The description of the Chinese auroral observation on AD 1638 December 23 may be translated as follows:

[China, Tung-cheng in An-hui Province] Ch'ung-cheng reign period, 11th year, 11th month, 19th day. "In the NE, there were several tens of bands of red vapour like swords and lances arranged in a line." (*Tung-cheng Hsu-hsiu Hsien-chih*, 23)

The reliability of this Chinese auroral observation is classified as [LH] in terms of the historical source.

The energetic solar feature generating the historical geomagnetic storm of AD 1638 December 23 probably occurred sometime during the interval December 17–December 18. For example, if the Chinese observers saw the sunspot (December 9) 5 days before it crossed the central meridian (December 14) and the energetic solar feature occurred 4 days after (December 18) the sunspot crossed the central meridian, it would still have taken a further 5 days for the ejected solar plasma to reach the Earth (December 23). This time sequence is barely plausible, since it relies on all three of the variables defined in Sect. 4.2 being near extremes of their acceptable ranges.

## Appendix T: The geomagnetic storm of AD 1648 January 24

The description of the Korean sunspot observation on AD 1648 January 16 may be translated as follows:

[Korea, Hanyang] King Injo, 25th year, 12th month, day *wu-tzu* (25). "Within the Sun there was a black spot." (*Injo Sillok*, 48)

The reliability of this Korean sunspot observation is classified as [OC] in terms of the historical source.

The description of the Chinese auroral observation on AD 1648 January 24 may be translated as follows:

[China, Beijing] Shun-chih reign period, 5th year, 12th month, 30th day. "At the first watch, there were hanging white cloths similar to coarse sackcloth. Four pieces of the cloth spread out vertically into approximately several tens of bands. The cold light reflected down made one's heart and eyes palpitate." (*Ch'ing-shih-kao*, 10)

The reliability of this Chinese auroral observation is classified as [DH] in terms of the historical source.

The energetic solar feature generating the historical geomagnetic storm of AD 1648 January 24 probably occurred sometime during the interval January 18–January 23. For example, if the Korean observers saw the sunspot (January 16) 4 days before it crossed the central meridian (January 20) and the energetic solar feature occurred 3 days after (January 23) the sunspot crossed the central meridian, it would have taken a further day for the ejected solar plasma to reach the Earth (January 24). This time sequence is quite plausible.

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