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AURORAE AND ARCHAEO-MAGNETISM FROM THE 1st MILLENNIUM B.C. CHINA, GREECE AND ITALY: A BRIEF OVERVIEW AND CRITICAL ASSESSMENT

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ABSTRACT

Auroral reports from ancient Chinese records and from Greece and Italy, from historical sources (Bamboo Annals, Tai ping yu lan, *Ch'un-ch'iu* period and Aristotle, Anaxagoras, Seneca, Pliny, Livy, respectively) in the 1st millennium B.C., are discussed in relation to the geomagnetic pole (GP) coordinates through archaeomagnetic inclination and declination data. It is shown that the expected auroral oval with its extension to a maximum of radius 30° around the GP occasionally reaches the Chinese / Southern Mediterranean mid latitudes and eastern longitudes: for China 35°-40° and 95°-125° respectively, and for Greece/Central Italy, 35°-40° and 10°-25° respectively; two distant regions where two great cultures flourished. Of the nine Chinese records those of 1000-900 B.C., 687 B.C., 193 B.C., 139 B.C., 32 B.C., 30 B.C. and 15 B.C. records are justified by a mid latitude geomagnetic pole which gives certain mid latitude aurorae. For the 166 B.C. and 154 B.C. available archaeomagnetic data the position of the VGP does not justify observation of aurorae. Archaeomagnetic data for Chinese accounts derived from South Korea, Japan and England reduced to mid China location are also used to determine GP at a reduced site of common latitude in China, but due attention and discussion of non-dipole magnetic sources and their calculated drift rates is made, to explain the unattainable observation of aurorae at central Chinese latitudes. Similarly, in southern Eastern Mediterranean area (Greece, Italy) 33 data are used and most are commensurable with the inclined GP towards mid latitudes, included within the auroral oval or at its southern maximum extension taking into account associated errors. Highly acceptable aurorae accounts and problematic ones are explained in terms of smooth or rapid, respectively, changes in the magnetic inclination and declination positions, reinforced by large age errors. Virtual Geomagnetic poles (VGP) for examined regions are ranging between 51° to 71° for latitude and between 1° to 123° for longitude for auroral observation dates of the 1st millennium B.C. to 1st century A.D.

KEYWORDS: geomagnetic field, virtual geomagnetic pole, Chinese dynasties, inclination, declination, coordinates, dates, ages, Mediterranean, Aurorae oval

1. INTRODUCTION

The reconstruction of the path of the geomagnetic pole can be corroborated using ancient historic descriptions of observations of the northern lights (aurorae, northern dawn). These lights have aroused the curiosity and wonder of people since the dawn of history.

Aurorae are caused when high-energy electrons pour down from the Earth's magnetosphere and collide with atoms. Red aurora occurs from 200 km to as high as 500 km altitude and is caused by the emission of 6300 Angstrom wavelength light from oxygen atoms. Green aurora occurs from about 100 km to 250 km altitude and is caused by the emission of 5577 Angstrom wavelength light from oxygen atoms. The light is emitted when the atoms return to their original unexcited state. At times of peaks in solar activity, there are more geomagnetic storms, and this increases the auroral activity observed on Earth and by astronauts from orbit.

Aurorae and geomagnetic activity are related to solar activity and both are linked to magnetospheric storms generated by interplanetary disturbances. In fact, the relationship between the solar-terrestrial parameters have been discussed elsewhere (Liritzis & Petropoulos, 1986, 1987; Crooker *et al.*, 1977; Mazawa, 1978; Rostoker *et al.*, 1967). The mechanism of aurora production and its physical relationship with other phenomena has been recognized and investigated (Feynman, 1983; Gussenhoven *et al.*, 1981; Hakamada & Akasofu, 1981; Feynman & Silverman, 1980; Siscoe, 1980; Russell, 1975).

Aurorae are observed in an approximately circular geographic zone (the auroral oval) with radius of approximately 22° almost centered on the geomagnetic poles, called the auroral zone. Historical observations of aurorae have been recorded mainly in China but in Europe and America as well (Hayakawa *et al.*, 2016; Willis & Stephenson, 2000; Wang & Siscoe 1995; Schove, 1962, 1983; Schove & Ho, 1958; Keimatsu 1970; Stothers, 1979a, b; Link, 1968; Loomis, 1866; Fritz, 1881; Rubenson, 1882; Dortous de Mairan, 1733 to mention a few), while auroral records related to sunspot variability has been shown by Siscoe (1980) and Korte & Stolze (2016).

From early times *e.g.*, since the 1st millennium B.C., auroral occurrences have been reported in Greece, Italy and China.

Observers in mid latitude countries of the northern hemisphere can see the northern lights only when the geomagnetic pole (precisely the magnetic pole) inclines towards their geographic longitude resulting in a high geomagnetic inclination or occasionally due to a great magnetic storm. The former suggestion was initiated by Keimatsu *et al.* (1968).

The inclination may be calculated from archaeomagnetic data for sites where the northern lights have been observed historically. Such calculations might question the validity of published inclination and declination (I, D) data or confirm large non-dipole differences between two distant regions, when pole positions are calculated.

In the past, three accounts of observed aurora were considered in: for Greece by Aristotle (384-322 B.C.), for Italy by Seneca (40-55 A.D.), in China at Hangzhou and at the same time in Prague, Czech (1138 A.D. 13th October) (Kawai & Hirooka, 1967; Fritz, 1873; Liritzis, 1988). In our work we calculate the pole positions mainly from Chinese, Greek and Italian archaeomagnetic directional data; for the Mediterranean cases they are revisited in the light of new archaeomagnetic data and mathematical equations, the Chinese accounts of the 1st millennium B.C. are included. Both incorporate observing positions of aurorae to corroborate due computations.

2. ARCHAEOMAGNETISM AND GEOMAGNETIC POLES

In common with many dating methods, the development of archaeomagnetic dating requires expertise from both natural sciences and archaeology. However, in archaeomagnetic dating, archaeological input is particularly crucial. The principles of the method are well-established (Linford, 2006; Clark *et al.*, 1988). The Earth's magnetic field in the past can be recorded by fired archaeological materials or sediments. The dates of materials can be obtained by comparing their geomagnetic record with a dated record of changes in the geomagnetic field over time, known as the secular variation (SV) record.

Whilst several databases of archaeomagnetic and palaeomagnetic data currently exist, such as GEOMAGIA50 (<https://geomagia.ucsd.edu>), the IAGA archaeomagnetic directional database (<http://www.ngdc.noaa.gov/geomag/paleo.shtml>), and the databases hosted by the Magnetics Information Consortium (<http://earthref.org/MAGIC/>), these are designed specifically for archaeomagnetists, palaeomagnetists, and modellers of the geomagnetic field.

Archaeomagnetic measurements have been made for various countries and data are available as data banks (see *e.g.* Creer *et al.*, 1983; <http://geomagia.gfz-potsdam.de/studies.php>; <http://dourbes.meteo.be/aarch.net/onlytxt/no.frame.html>) although not at the geographic sites exactly where the northern lights have been observed.

Through the correlation between archaeomagnetic data and aurorae sometimes we may question either the reliability of some published archaeomagnetic directions to allow for the particular differences in

latitude and longitude to be reassessed, or re-evaluate the attributed ages of measured materials.

Directions of magnetization may be represented by their corresponding virtual pole positions, calculated assuming a geocentric dipolar (but not axial) geomagnetic field. Any pole position that is calculated from a single observation of the direction of the geomagnetic field is called a *virtual geomagnetic pole* (abbreviated VGP). This is the position of the pole of a geocentric dipole that can account for the observed magnetic field direction at one location at one time point, which is the principle of the present work.

With this model, the inclination (I) and declination (D) for a particular geographic site of latitude (SITE_{lat}) and longitude (SITE_{long}) is directly related to the angular distance from the geomagnetic pole. If the location of the site is in geographic latitude and longitude, the latitude (VGP_{lat}) and longitude (VGP_{long}) of the pole, often called virtual poles (eq. (2a) and (3a) below), can be determined, involving the magnetic co-latitude (θ_m) and the angular great circle distance between observation site and VGP (Irving, 1964; Cox & Doell, 1960; Tauxe, 1993).

Any site-mean direction as I_m, D_m has an associated confidence limit α_{95} . This circular confidence limit about the site-mean direction is transformed (mapped by the dipole formula) into an ellipse of confidence about the calculated pole position. The semi-axis of the ellipse of confidence has an angular length along the site-to-pole great circle given by d_{θ_m} and d_m (eq. (1a) and (1b) below).

$$d_{\theta_m} = a_{95} \left(\frac{1+3 \cos^2 \theta_m}{2} \right) \quad (1a)$$

$$d_m = a_{95} \left(\frac{\sin \theta_m}{\cos I_m} \right) \quad (1b)$$

In fact, equations (2a) and (3a) below establish equivalent pole positions distributed over the earth's surface (from these equations errors are calculated). Thus "poles" may be formally computed from any observed field direction whether due entirely to a geocentric dipole or not, called the *Virtual Geomagnetic Poles (VGP)*. If non-dipole components are present, the virtual geomagnetic poles calculated at different localities will not, in general, coincide, and their scatter may be taken as a measure of the departure of the observed field from an ideal dipole field. In practice the position of VGPs from different latitudes and same time is presented an order of magnitude of signal noise to be expected for the determination of average poles by the archaeomagnetic meth-

od (Cox & Doell, 1960, Fig. 13). For determination of the geomagnetic pole position, globally distributed observations are required to "average out" the non-dipole field.

This is the position of the pole of a geocentric dipole that can account for the observed magnetic field direction at one location and at one point in time. As mentioned above a VGP can be calculated from an observation of the present geomagnetic field direction at a particular locality. If VGPs are determined from many globally distributed observations of the present geomagnetic field, these VGPs are scattered as 'signal noise' about the present geomagnetic pole. In paleomagnetism, a site-mean characteristic remanent magnetization (ChRM) direction is a record of the past geomagnetic field direction at the sampling site during the (ideally short) interval of time over which the ChRM was acquired (Note: The most important component of remanence is that acquired when a rock formed; this is called its *primary component* or *characteristic remanent magnetization*, ChRM). Thus, a pole position calculated from a single site-mean ChRM direction is a virtual geomagnetic pole.

The inclination and declination can be produced at a common site (center of China (35°N 105°E) or Beijing ~ (40°N, 116°E) for Chinese records; Rome ~ (42°N, 12.5°E) and Chalkidiki, North Greece ~ (41°N, 23.5°E) for Mediterranean records) from another location via the geomagnetic poles, with associated errors, using equations (5) and (6) respectively. The co-latitude (and its error) is computed using equation (4a) and (4b).

Alternatively, the quoted corrected I_5^C reduced to a common latitude (Beijing latitude (~40°N) for Chinese records; Rome (~42°N) and Chalkidiki, North Greece ~ (41°N) for Mediterranean records) calculated using the equation (7), is used on the assumption of an axial dipole field, which predicts $D = 0$ everywhere.

These calculations are given to a first approximation and correction of the present geomagnetic field directions in an area of no more than 750 x 750 km² shows differences of less than 1° in both I and D at a central location (Tarling, 1983). Clearly large errors (of a few degrees) will arise for extensions over wider areas, as the correction assumes that for any such region the geomagnetic pole corresponds to a geocentric dipole.

$$VGP_{lat} = \sin^{-1}(\sin(SITE_{lat}) \sin \theta_m + \cos(SITE_{lat}) \cos \theta_m \cos D) \quad (2a)$$

$$d(VGP_{lat}) = \sqrt{(\sin(SITE_{lat}) \cos I - \cos(SITE_{lat}) \sin I \cos D)^2 (dI)^2 + \frac{(\cos(SITE_{lat}) \cos I \sin D)^2 (dD)^2}{1 - (\sin(SITE_{lat}) \sin I + \cos(SITE_{lat}) \cos I \cos D)^2}} \quad (2b)$$

$$VGP_{long} = SITE_{long} + \sin^{-1} \left(\frac{\cos \theta_m \sin D}{\cos(VGP_{lat})} \right) \quad (3a)$$

$$d(VGP_{long}) = \sqrt{\frac{(\sin I \sin D)^2 (dI)^2 + (\cos I \cos D)^2 (dD)^2}{\cos^2(SITE_{lat}) - (\cos I \sin D)^2}} \quad (3b)$$

$$\tan I = \frac{2}{\tan \theta_m} = 2 \cot \theta_m \rightarrow \theta_m = \cot^{-1} \left(\frac{\tan I}{2} \right) \quad (4a)$$

$$d(\theta_m) = - \frac{dI}{2 \cos^2 I \left(1 + \left(\frac{\tan I}{2} \right)^2 \right)} \quad (4b)$$

$$I_c = \sin^{-1} \left(\sin(VGP_{lat}) \sin(SITE_{lat}) \pm \sqrt{\sin^2(VGP_{lat}) \sin^2(SITE_{lat}) - \sin^2(VGP_{lat}) + \cos^2(SITE_{lat}) - \cos^2(SITE_{lat}) \sin^2(VGP_{long} - SITE_{long}) \cos^2(VGP_{lat})} \right) \quad (5)$$

$$D_c = \sin^{-1} \left(\frac{\sin(VGP_{long} - SITE_{long}) \cos(VGP_{lat})}{\sqrt{1 - \sin^2 \theta_m}} \right) \quad (6)$$

$$I_s^c = \tan^{-1}(2 \tan(SITE_{lat})) \quad (7)$$

This is in fact the basic assumption of palaeomagnetism applied to geological formations. For determination of the geomagnetic pole position, globally distributed observations are required to “average out” the nondipole field. An observation of the magnetic field direction at a single location cannot be used because the observed direction could, in general, be affected by the non-dipole field. Thus, a pole position calculated based on a single observation at a particular location is not expected to coincide with the geomagnetic pole.

The non-dipolar components can certainly cause large errors in the determination of the actual pole. However, our computation corroborated by ancient auroral accounts offer further ways to estimate the reliability of some archaeomagnetic data. As scarce archaeomagnetic directional data were available for some periods, unavoidably we used the only ones and / or some distant locations reduced to the observation site, bearing in mind this deficiency, however.

Global geomagnetic field reconstructions spanning the past millennia rely on magnetic data sources including archaeomagnetic artefacts, young lava flows and sediment records (Constable *et al.*, 2000; Donadini *et al.*, 2010). Magnetization of ferro/ferrimagnetic materials occurs in the direction of the ambient magnetic field and is proportional to its strength when cooling below the Curie temperature; that is, the characteristic temperature above which an otherwise magnetic material loses its remanent magnetization. In fact, magnetic particles in sediments orient along the ambient field lines during deposition and become ultimately locked in the sediments during burial and diagenesis. Although the magnetization strength of sediments varies with the

concentration of ferro/ferrimagnetic minerals and post-depositional processes, relative variations of the geomagnetic field can be inferred following a suitable normalization of the data (e.g. Tauxe, 1993; Tauxe *et al.*, 2016; Xanthakis & Liritzis, 1991).

The analyzed auroral Chinese and southern Mediterranean records, their description and calculations pertaining to each case are discussed below.

3. GEOMAGNETIC, MAGNETIC AND QUASI-MAGNETIC POLE POSITIONS OVER THE PAST

The aurorae are formed around the magnetic poles which do not coincide with the geomagnetic and VGPs. A brief outline in the difference of these 'poles' and their movement is made here to understand any interpretation made below.

As a first-order approximation, the Earth's magnetic field can be modeled as a simple dipole (like a bar magnet), tilted about 9.6° with respect to the Earth's rotation axis (which defines the Geographic North and Geographic South Poles) and centered at the Earth's center. The North and South Geomagnetic Poles are the antipodal points where the axis of this theoretical dipole intersects the Earth's surface, thus unlike the magnetic poles they always have an equal degree of latitude and supplementary degrees of longitude respectively (2017: Lat. 80.5°N, 80.5°S; Long. 72.8°W, 107.2°E) (McElhinny *et al.*, 1996; Merrill, 2010)(Table 1).

If the Earth's magnetic field were a perfect dipole then the magnetic lines would be vertical at the Geomagnetic Poles, and they would coincide with the north and south magnetic poles. However, the approximation is imperfect, and so the *Magnetic* and *Geomagnetic Poles* lie some distance apart. Since the

Earth's magnetic field is not exactly symmetrical, the actual position of magnetic poles does not coincide with the geomagnetic poles. Thus, *the magnetic poles* so introduced are the points at which magnetic needles become vertical (called dip poles).

The North Magnetic Pole moves over time due to magnetic changes in the Earth's core. In the past these two poles have not a trendy variation, instead lati-

tudes and longitudes vary at an unpredictable manner. Geomagnetic field models can define geomagnetic poles, or geocentric dipole, which can be computed from the first three Gauss coefficients from a main field model, such as the World Magnetic Model (WMM) or International Geomagnetic Reference Field (IGRF). Calculated Geomagnetic poles are called *Virtual Geomagnetic Poles (VGP)*.

Table 1: The 2017 geomagnetic pole (GP) and magnetic pole (MP) coordinates for north and south poles in 2017

Year	GP Lat N	GP Lon N	GP Lat S	GP Lon S	MP Lat N	MP Lon N	MP Lat S	MP Lon S	Dipole moment 10 ²² Am ²
2017	80.5N	72.8W	80.5S	107.2E	86.5N	172.6W	64.2S	136.3E	7.72

To a first approximation the differences in magnetic poles and VGP coordinates during the last century (1900-2015) are $\Delta_{\text{lat}}=7^\circ$ and $\Delta_{\text{lon}}=30-80^\circ$ (<http://wdc.kugi.kyoto-u.ac.jp/index.html>).

Over the past 150 years the poles have moved westward at a rate of 0.05° to 0.1° per year, with little net north or south motion. The influence of the past geomagnetic dipole strength on aurora occurrence is not fully understood.

4. GEOMAGNETIC FIELD AND THE AURORAL VARIABILITY

Although geomagnetic pole positions cannot be observed, they are arguably of greater significance than the dip poles because the auroral ovals (approximate 5° latitude bands where the spectacular aurora is likely visible) are closely centered on the geomagnetic poles. They are usually displaced slightly to the night-side of the geomagnetic poles and greatly vary in size: bands of greatest activity occur between 15° and 25° from the geomagnetic poles. The locations of the auroral oval for quiet, moderate, and active conditions are a function of geomagnetic local time and geomagnetic latitude. The oval is mainly moving equatorward with increasing magnetic activity. Aurorae also appear fairly regularly poleward of these ovals.

The radius of the auroral oval, controlled by the fraction of the Earth's magnetic field that is open, is determined by a combination of the dayside reconnection rate and the intensity of the ring current. It is the rate at which closed magnetic flux is opened and the polar cap expands; the latter has been speculated to control the rate at which open flux is reclosed in the magnetotail (e.g. Nakai & Kamide, 2003; Milan et al., 2008, 2009a), by modifying the level of stretching of the tail field and hence its stability to the onset of nightside reconnection. The size of the polar cap is then determined by a competition between the opening and closing of magnetic flux, which is in turn the driving mechanism for the circulation of plasma

within the magnetosphere, now known as the Dungey cycle (Dungey, 1961).

During disturbed solar wind conditions, strong dayside coupling increases the size of the polar cap, moving the aurorae to mid latitudes, with a time-scale of a few hours. The intense magnetospheric convection which accompanies this leads to injection of plasma from the magnetotail into the inner magnetosphere to form the intensified ring current (e.g. Kozyra & Liemohn, 2003).

The oval radius (R) takes values close to 20° during undisturbed periods, but increases up to 30° during the main phases of the geomagnetic storms. There is clearly a close association between oval radius (R), ring current intensity as measured by the ring current intensity Sym-H index (H_{SYM}) and the dayside reconnection rate (Φ_{D}) and their quantification to the variation in oval radius (R) using regression analysis (Milan, 2009b).

At any rate the solar output described as solar wind reflects the solar activity (sunspots, flares, coronal mass ejections associated with charged particles such as electrons, protons, alpha particles of energies 1.5 - 10 KeV and magnetic fields) and higher solar activity generally results in enhanced auroral activity, but there is no simple direct relationship. A recent study based on solar cycles 17-23 (1933-2008 A.D.) identified between one and seven extreme geomagnetic storms with geomagnetic planetary index $K_p = 9$ per solar cycle, with an average of four (Pfoser & Eklund, 2011). Minor storms with $K_p \leq 5$ are frequent and occur at an average of more than 900 per solar cycle. There appears to be no appropriate way to scale the auroral oval reconstruction directly with solar activity estimates on decadal to centennial timescales. The scale of K_p varies from $K_p = 0$ (quiet), $K_p = 4$ (moderately disturbed) and $K_p = 9$ (strong geomagnetic storm). At any rate aurorae may appear mid-latitude at high K_p and low magnetic pole latitudes. There the enhanced ring current found during geomagnetic storms could alter the magnetic field

geometry of the near-Earth magnetotail, delaying sub-storm onset until the open flux content of the magnetosphere grows unusually large.

This would naturally explain the observation of aurora at mid latitudes during periods of intense geomagnetic disturbance, particularly geomagnetic storms.

In a comparison of the locations of three differently defined magnetic field poles for the time interval between 1600 and 2000 A.D. it is shown that the locations of the magnetic pole, where the inclination of the magnetic field lines is vertical at the Earth's surface, the geomagnetic pole locations, which are defined by the axis of the approximated dipolar field, and the positions of the magnetic poles described by quasi-dipole coordinates (Emmert *et al.*, 2010), which are considered relevant for processes in the ionosphere such as aurora formation, vary considerably in their coordinates (Korte & Stolze, 2016)

In fact, both the magnetic and the geomagnetic poles fell within a longitudinal wedge of 60° and were longitudinally separated by 5–10° (Korte & Manda, 2008). The location of the magnetic field pole in the quasi-dipole coordinates, which are relevant for auroral processes in the ionosphere, was closer to the geomagnetic than the magnetic pole. However, as a result of the inhomogeneous global distribution of available data sets, the uncertainties refer to: a) the geomagnetic data, b) their age information, and, c) the applied modelling approaches. But overall the available field reconstructions have limitations and uncertainties. These uncertainties are often difficult to assess for an individual geomagnetic field model.

Therefore, instead of considering reconstructions of past geomagnetic pole locations based on different data sets and modelling techniques, the ancient auroral records provides a good indication of the reliability of the reconstructions at a certain point in time.

In what follows, we accept the location of the geomagnetic pole to be a reasonable approximation for the center of the auroral oval. This is justified on the assumption that the dipole dominance of the geomagnetic field comparable to today's state existed over the past millennia. The Virtual Geomagnetic pole coordinates calculated from archaeomagnetic data are given in Tables 2-7.

Auroral reports can be used only cautiously, to corroborate the archaeomagnetic data for: 1) the reconstruction of the geomagnetic pole positions in the past, and, 2) archaeomagnetic dating.

As the auroral oval is formed around the pole, any shift of the geomagnetic pole, ideally, would result in a change in observational latitudes of aurorae. However, this is not always the case; a change in the pattern of observed occurrence of aurorae can be due

to several factors including, a change in the Earth's dipole field or a change in the solar wind driving the aurorae.

At our present stage of knowledge, it is not possible to identify unequivocally the solar wind parameters that might change to affect either the annual frequency or latitudinal distribution of auroral observations. The problem has been approached either through direct studies of aurorae or through the closely related geomagnetic activity; the latter, in turn, being related to some function of the solar wind velocity u , and the southward component of the interplanetary field, B_z (Liritzis & Petropoulos, 1987).

Two effects of change in the solar wind that could cause a change in auroral occurrence frequency at particular latitude are: a) changes in the number of geomagnetically disturbed days per year, and, b) changes in the position of aurorae for the same level of geomagnetic activity.

Siscoe and Siebert (2002) argued, that due to a phenomenon known as transpolar potential saturation, auroral activity might expand to lower latitudes in response to a stronger dipole moment. In any case variations in the dipole moment appear to play a minor role, compared to the dipole tilt, in the probability of mid-latitude aurora occurrence.

Auroral accounts and distributions in the Medieval and current epoch in Europe has been studied extensively (Feldstein & Starkov, 1968; Feynman & Silverman, 1980; see also references in the introduction). For the current epoch these studies have shown that the southward extension of the auroral oval edges is accompanied by increasing geomagnetic activity (R-index, geomagnetic storms) and the position and dynamics of the auroral oval was changed noticeably in a period as short as four years.

For the last 200 years such a change in auroral occurrence patterns was due to the solar wind or some underlying variability of the sun (see e.g. Kamide *et al.*, 1977; Svalgaard, 1977). For example, during the International Geophysical Year (IGY) 1957/58, when solar activity was maximum, aurorae was observed in mid latitudes and could be seen in Japan (Lat = 30° – 40° N) down to places of geomagnetic latitude 35° N (1957, July 5, 1120-1200 UT) (Japanese contribution IGY, Science Council of Japan, Tokyo, p. 44; In Beynon W.J.G (ed.) *Annals of the International Geophysics Year*, Pergamon Press, Oxford, XLVIII, 1970). One should, however, note that the low-mid latitude aurora is quite different from the mid-high-latitude aurora in the colour and display; the former being reddish and diffuse and of veil form while the latter tend to be very active and of long duration in time.

From all the above, we are aware that only simultaneous accounts in the Occident and the Orient

would be reasonably utilized to infer the position of geomagnetic pole axis because of the variability of auroral oval position with individual magnetic storms.

Since the loss of Prof. Keimatsu, in 1976, this work has only later been revived (Fukushima et al., 1985).

In our work we calculate the pole positions from archaeodirectional data and consequently the inclinations for three sites, and incorporate observing positions of aurorae to corroborate for such computations.

However, the calculation of past geomagnetic pole position is not an easy task for the following reasons:

a) geomagnetic pole positions (latitude and longitude) do not coincide with magnetic poles,

b) the VGPs assuming axial dipole symmetry is not representative of the magnetic poles,

c) the computed VGPs from archaeomagnetic inclination (I) and declination (D) are not securely attributed to a particular time period due to large age uncertainties. For example, from Table 2 for the dates 1100 B.C. \pm 170 and 1150 B.C. \pm 150 the inclination (I) varies between 50-60° and D also vary largely. The variation could be due to samples dated within a large span of 300 (\pm 150) years, knowing that rapid variations occur in intensity and inclination within short time intervals in the order of decades (Liritzis & Kovacheva, 1992; Liritzis 1989; Aitken et al., 1989; Xanthakis & Liritzis, 1989).

Along this rationale, any average value or large error bars depictions in graphs of archaeomagnetic direction versus time is no way conclusive, rather offers an interim report until greater accuracy data (magnetic and dating) are made. Narrow time intervals are needed and any conclusion of geomagnetic variation in the past, and particular time periods, must be cautiously considered.

Along these concepts the observed aurorae could reinforce those geomagnetic positions that allow such an observation, and exclude other values not as measurement errors but belonging to different times.

5. LOWER-MIDDLE-LATITUDE AURORAE

The ancient recorded descriptions may imply also the latitude of observation: for the *lower mid-latitude aurora* is quite different from the *mid-high-latitude aurora* in the color and display; the *former being reddish and diffuse and of veil form* while the latter tend to be very active and of long duration in time. Aurorae take on different appearances. They can look like an orange or red glow on the horizon -- *like a sunrise or sunset*. Sometimes they may be mistaken for fires in the distance, like the various indigenous people thought, amongst other legendary attributions (<https://www.northernlightscentre.ca/northernlights.html>; [*native-tales-about-the-northern-lights/*\). They can look like curtains or ribbons and move and undulate during the night.](http://goodnature.nathab.com/fifteen-</p>
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According to current knowledge (see e.g. Stormer, 1955; Kamide et al., 1977; Gussenhoven et al., 1981) the auroral form rays (narrow almost vertical columns of luminosity, field aligned) have a considerably greater vertical extent than normal aurora in the height distributions that varies from 100-600 km.

The longer extents e.g. 600 km (approx. 3° in latitude) are *observed in lower latitude (reddish, diffuse, veil form)* aurora near the sunspot maximum and are greater aurorae associated with atmospheric heating. *The diffused aurorae of the veil form* are also extensive to a diffused surface > 10° in extent.

The following descriptions fit the lower latitude aurorae appearances. reddish and diffuse (like rainbow) extended and of veil form: They are formed respectively: Blue and Violet: less than 120 kilometers (72 miles); Green: 120 to 180 km (72 to 108 miles); and Red: more than 180 km (108 miles) (Sandholt et al., 2004).

Low-latitude aurorae constitute a special and not frequent case. These aurorae can often be produced by massive solar flares, usually associated with huge Coronal Mass Ejection (CME). They are generally red and diffuse resulting primarily from an enhancement of the 630.0 nm atomic oxygen [OI] emission due to the bombardment by soft electrons (<100 eV). The typical altitude for a low-latitude aurora is 250-400 km (Silverman, 1998). They can be confused with fires or twilights due to their colour. As an example, we can cite the observation by A. Lang, Governor of the Saint Croix Island (17°44'32"North, now a part of the Virgin Islands), who reported a red aurora on 17 November 1848 and commented that the red glare ascended high above the hills, leading several persons to believe that a tremendous fire had occurred (Lang, 1849). This confusion is also described by J. Viera y Clavijo (1731-1813), writing about the aurora observed in Tenerife on 18 January 1770 (Viera, 1770).

6. THE 1ST MILLENNIUM B.C. AURORAL ACCOUNTS AND RELATED CRITICAL DISCUSSION

6.1 Chinese Auroral Records

Nine occurrences of aurorae are recorded in ancient Chinese sources during the 1st millennium B.C.: 980-970 B.C., 687 B.C., 193 B.C., 166 B.C., 154 B.C., 139 B.C., 32 B.C., 30 B.C. and 15 B.C..

The review by Wang & Siscoe (1995) contains also a total of eight possible references to auroral phenomena in the pre-Zhou dynasty i.e. earlier than 1046 B.C., referred to the 3rd millennium B.C.. Even if the dates of these events could be verified, they are

far too few to allow firm conclusions to be reached about the relative frequency of the aurora during that period compared to later periods. However, they represent potentially valuable additions to the scarce accounts of very ancient aurorae (Chou, 1979; Bagley, 1980; Wang & Siscoe, 1995). These third millennium B.C. aurorae, that forms another work in progress, yet the dates correspond to named Kings in the Chinese history (2674 to 2574, 2574-2490, 2490-2412, 2333- 2233, 2333-2183 B.C.) and preliminary work indicates that the observation was plausible, i.e. from samples from China dated in 2800 B.C. \pm 200 (I and D from Geomagia Data Base) the VGP position was calculated $58\pm 2^\circ\text{N}$, $121\pm 2^\circ\text{E}$. Despite the Chinese Kings seem to be unreal creatures, their association to aurora observations in the third millennium B.C. indicate the existence of sky observations related to solar activity that transformed into legends as time passed.

1) Chinese aurora record: 980-970 B.C.

Of the earliest recorded aurorae in history of mankind is in ancient China. Several Chinese literatures mentioned an aurora in the 10th century B.C.. The earliest ones are 5 resources of the Song Dynasty (960-1279 A.D.). Other records include one of Yuan Dynasty in the 13th -14th century, one of Ming Dynasty in the 17th century A.D., two of the Qing Dynasty (1644-1911). Three of them state that this record came from *zhu shu ji nian*, which are the *Tai ping yu lan* (太平御览) of the 10th century AD, the *Lu shi* (路史) of the 12th century AD and the *yu zhi tang tan hui* (玉芝堂谈荟) of the 17th century AD.

Tai ping yu lan is the earliest book among all of the above resources, and it is also the most authentic one because it was composed by a group of scholars under the demand of the second emperor of the Song Dynasty. It is the *Imperial Reader* or *Readings of the Taiping Era*, a massive Chinese leishu encyclopedia compiled by a number of officers under Li Fang from 977 to 983. It was commissioned by the imperial court of the Song dynasty during the first era of the reign of Emperor Taizong (Kurz, 2007). *Tai Ping yu lan* records in Volume 874:

竹书纪年曰：周昭王末年·夜清·五色光贯紫微·其年王南巡不返。

The *Bamboo Annals* mention: "in the last year of King Zhao of (western) Zhou, the night is clear, five-colored light penetrated *zi wei*. In this year the King inspected the south and did not return" (i.e. in the mid latitude).

Another name of The *Bamboo Annals* (*zhu shu ji nian*竹书纪年) is *ji zhong ji nian* (汲冢纪年) a chronological history book which recorded the history of Xia, Shang, Zhou, the Spring and Autumn Period, till the 20th year of Duke Xiang of Wei in 299 B.C. in the Warring States Period (475-221B.C.). This book made its first appearance in the 2nd year of Emperor Wu of Jin, 281 A.D., from a tomb of Warring States Period. It was written on bamboo strips thus got the name *Bamboo Annals*. Originally at burial the strips must have been strung together to form a book. When unearthed the strips were scattered and some of them lost. The scholars of that time worked carefully on them under the organization of the Jin government and made it a book again. After having been handed down for hundreds of years, this book lost again during the Song Dynasty, maybe around the 12th century. Several other books have cited part of its contents during its existing, *tai ping yu lan* being one of them. Thus, the earliest record of the 10th century B.C. aurora though from the Song Dynasty literature in fact originates from the 4th to 3rd century B.C. sources.

Other records of this aurora may all come from the *Tai ping yu lan*. The other two which state that it was from the *Bamboo Annals* with almost the same words as that of the *Tai ping yu lan*, the difference being that the *Tai ping yu lan* had a word 清 "clear" after the word 夜 "night", but the 2 other literatures used the word 有 "have" or "there is" instead of 清 "clear" in the same place.

Both are recorded as "a light of five colors penetrating the *zi wei*". "Zi wei" refers to the area around the north geographical pole. One recorded it happened in the first year of King Zhao of Western Zhou, and the other recorded in the last year of King Zhao. The light of five colors is a description that should be attributed to auroral oval formations.

Other literatures do not state where this record came from, but mixed this record with other affairs in the last year of King Zhao, they would have been collected from different literatures.

King Zhao is the 4th King of Western Zhou. Different literatures give different length of his reigning years. Xia-Shang-Zhou Chronology Project gives 995-977 B.C. as his reigning time, so in fact this aurora was in the 10th century B.C. (Li, 2002).

The *Bamboo Annals* does not mention the observing place, most likely observed in the capital but this is not sure. In any case, it is assumed to have been observed from within the Western Zhou region (Fig. 1). The Western Zhou capital is near Xi'an, the geographical coordinate being 34.2°N , 108.7°E .



Fig 1: a) Present China and the surrounding countries b) Western Zhou (in red) and Shang Dynasties (in green) regional territory

From burnt clay samples from China, South Korea and Japan dated around 1000 B.C. and 900 B.C. VGPs are calculated (Table 2). The mean VGP position calculated $(70 \pm 3)^\circ\text{N}$ and $(100 \pm 4)^\circ\text{E}$ from 1180 B.C. ± 90 and 899 B.C. ± 128 age data (Table 2/rows 1&2). The samples from Japan are not used for the mean VGP calculation due to the large inclination and declination errors which conclude to large VGP errors (Table 2/rows 3&4). The VGP positions calculated from 1150 B.C. ± 150 (China) and 1100 B.C. ± 170 (South Korea) age data are not used in the mean VGP calculation due to age errors (Table 2/rows 5-9). However, the mean VGP position from these ages is $(70 \pm 3)^\circ\text{N}$ and $(106 \pm 4)^\circ\text{E}$ and it is more prone justified for an aurora to be seen (Fig. 2). Thus, the record would be identified as mid latitude aurora and the auroral oval would be clearly seen by observers in north China. Though the average VGPs derives from two closely spaced in age data; within 10th century B.C. the overall average VGP from dates between 1180 and 899 B.C. provide a comparable VGP result.

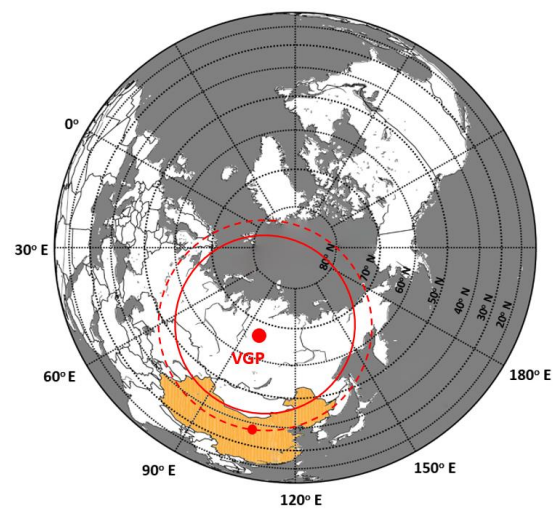


Fig 2: Virtual Geomagnetic Pole (VGP) position for aurorae observed in China 980-970 B.C. The red dot is the mean VGP position $(70 \pm 3)^\circ\text{N}$, $(100 \pm 4)^\circ\text{E}$. The solid inner red line defines the area of the auroral oval which radially extends up to 22° from the VGP (the VGP center represents the lower error span of the mean VGP). The outer red lines define the maximum radius of the auroral oval which extends up to 30° from the VGP. The red dot is the observation place Western Zhou capital near Xi'an.

Table 2: Calculated Virtual Geomagnetic Poles (VGPs) for the 1st millennium B.C. using measured data from China, Japan and South Korea

a/a	Archeological age (B.C.)	Reference	Site	Measured data ^{1,2}				Calculated values ³			Calculated reduced values ^{4,5}		
				SITE _{lat}	SITE _{long}	I	D	θ_m	VGP _{lat}	VGP _{long}	I _c	D _c	I _c ⁵
Aurora recorded in 950 B.C.													
1	1180 B.C. \pm 90	Wei et al. (1984)	China	34.5	107.8	57.3 \pm 2.7	355.3 \pm 5	52.1 \pm 2.9	72 \pm 3	98 \pm 4	56,7	351.3	54,0
2	899 B.C. \pm 128	Wei et al. (1984)	China	34.2	109	60 \pm 2	338.8 \pm 4	49.1 \pm 2.3	68 \pm 3	69 \pm 3	52.2	335.7	53.7
3	1090 B.C. \pm 170	Tanaka (1979)	Japan	35.2	139	57.1 \pm 21.4	343.1 \pm 39.4	52.3 \pm 22.7	69 \pm 23	109 \pm 30	60.7	356	54.7
4	950 B.C. \pm 290	Tanaka (1982)	Japan	35.2	139	57.1 \pm 21.4	343.1 \pm 39.4	52.3 \pm 22.7	69 \pm 23	109 \pm 30	60.7	356	54.7
5	1150 B.C. \pm 150	Cai et al. (2016)	China	36.71	117.11	56.9 \pm 5.4	347.4 \pm 9.9	52.5 \pm 5.7	72 \pm 6	92 \pm 8	55.9	347.9	56.2
6	1150 B.C. \pm 150		China	36.71	117.11	60.1 \pm 2.6	345.4 \pm 5.2	49 \pm 3	74 \pm 3	81 \pm 4	52.4	345.8	56.2
7	1150 B.C. \pm 150		China	36.71	117.11	52.4 \pm 1.1	2.8 \pm 1.8	57 \pm 1	70 \pm 1	121 \pm 1	60.2	3.5	56.2
8	1150 B.C. \pm 150		China	36.71	117.11	50.0 \pm 4.7	359.7 \pm 7.3	59.2 \pm 4.2	67 \pm 4	117 \pm 5	62.5	0.5	56.2
9	1100 B.C. \pm 170	Yu et al. (2010)	South Korea	36.64	126.49	49.4 \pm 3.5	354.1 \pm 5.4	59.7 \pm 3.1	67 \pm 3	119 \pm 3	63.4	2.4	56.1
Mean VGP (1st& 2ndrows)									70 \pm 3	100\pm4			

¹ latitude (SITE_{lat}) and longitude (SITE_{long}) of the site (in degrees)

² inclination (I) and declination (D) measured archaeomagnetically (in degrees)

³ Virtual geomagnetic pole latitude (VGP_{lat}), virtual geomagnetic pole longitude (VGP_{long}) and co-latitude (θ_m) calculated using the equations (2), (3) and (4) respectively

⁴inclination (I_c) and declination (D_c) that would be produced at a common site (40°N, 116°E (Beijing)) from another location via the geomagnetic poles using equations (5) and (6) respectively

⁵corrected inclination I_c⁵ using the equation (7)

2) 700-600 B.C. (Chinese aurora record: 687 B.C.)

In China of the Ch'unch'iu Period (722 – 481 B.C.) the 687 B.C. aurora is attributed a 'probable' reliability occurrence (Keimatsu, 1970; Stephenson & Yau, 1992). From measurements from China and South Korea dated in 620 B.C. \pm 150 and 745 B.C. \pm 80 respectively (Table 3/rows 1&2) the mean Virtual Geographical Pole position calculated $(68\pm 2)^{\circ}\text{N}$, $(110\pm 2)^{\circ}\text{E}$ denoting that an aurora would have been occurred and seen by a Chinese observer in northern China and quite likely by a Chinese observer in central China within errors in archaeomagnetic dates and directional data (Fig. 3a).

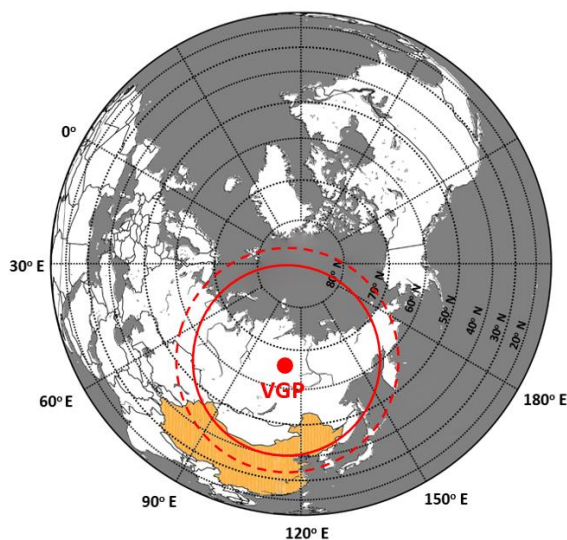


Fig. 3a: Virtual Geomagnetic Pole (VGP) for observed aurorae in China dated 687 B.C. The red dot is the mean VGP position $(68\pm 2)^{\circ}\text{N}$, $(110\pm 2)^{\circ}\text{E}$. The solid inner red line defines the area of the auroral oval which radially extends up to 22° from the VGP (the VGP center represents the lower error span of the mean VGP). The outer red lines define the maximum radius of the auroral oval which extends up to 30° from the VGP.

Another aurora-like record in Babylonian Calendars observed in B.C.E 652/651 "The 28th, a little rain. In the afternoon, a very red rainbow stretched in the east". Several accounts refer to this (Keimatsu, 1970). Taking into consideration the calculated VGP position an aurora could not be visible for a Babylonian observer. However, VGP was calculated once again from samples from Britain (Batt et al., 2017) dated from 700 to 600. It is derived that VGP latitude is constant during this period at $(73\pm 3)^{\circ}\text{N}$ while the VGP longitude moves from $(25\pm 8)^{\circ}\text{E}$ (in 700 B.C.) to $(17\pm 8)^{\circ}\text{E}$ (in 600 B.C.) denoting that the VGP position is moving westwards in time. In 687 B.C. the VGP position was calculated $(73\pm 3)^{\circ}\text{N}$, $(22\pm 8)^{\circ}\text{E}$. Thus, is quite likely that the VGP was at a proper position so

as the aurora would be visible at the same time by an observer in China and Babylonia. The phrase "stretched in the east" in Babylonian Calendars made us conclude that the VGP was closer to China than Babylonia with VGP_{long} at about 65°E (Fig. 3b).

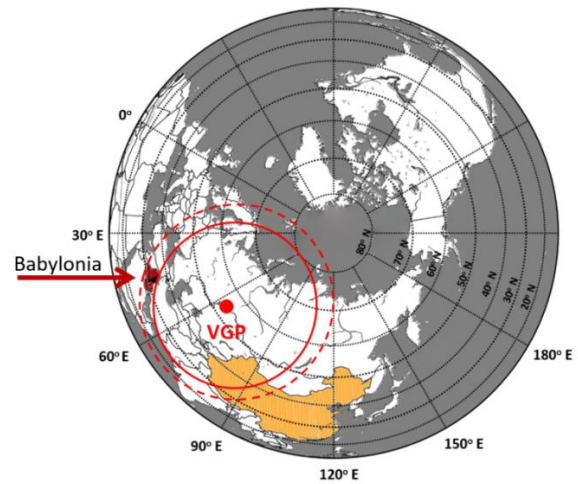


Fig. 3b: Virtual Geomagnetic Pole (VGP) dated around 690 B.C. The red dot is the suggested VGP position estimated at about $(55\pm 5)^{\circ}\text{N}$, $(65\pm 5)^{\circ}\text{E}$ so as aurora could be simultaneously seen by an observer in Babylonia and an observer in China. The solid inner red line defines the area of the auroral oval which radially extends up to 22° from the VGP (the VGP center represents the lower error span of the mean VGP). The outer red lines define the maximum radius of the auroral oval which extends up to 30° from the VGP.

Moreover, two more possible explanations are given; either, this is due to non-dipole fields that make magnetic field measurements at mid China (35°N , 98°E) and mid Babylonian territory (35°N , 40°E) to differ, or, the VGP rapidly changed within a short time thus the 30 years difference in observing aurorae (687 and ca. 651 B.C.) the magnetic pole could have been shifted and thus both ancient China and Babylonia observation sites could have been within the shifted auroral oval (Stephenson and Yau, 1992; Keimatsu, 1970).

3) Chinese aurora record: 193 B.C.

According to Hanshu (2017) (official Chinese text project, vol. 26) in 193 B.C. the heaven opened in northeast more than 10 zhang in width and over 20 zhang long. This means that in 193 B.C. people saw a sky phenomenon about 36 meters in width and over 72 meters long, equals to about 100 degrees in width and over 200 degrees long when referring to heavenly distance (see also Willis & Stephenson, 2000; Yau et al., 1995). It is known that 1 zhang is about 3.6 meters; when referring to heavenly distance 1 zhang is equals to about 10 degrees (Wu & Liu, 1989). From sample from China dated in 206 B.C. \pm 10 (Table 3/row 3) the VGP position calculated $(51\pm 1)^{\circ}\text{N}$,

(101±1)°E. The VGP calculation is very accurate due to the low age error (only 10 years) and much more accurate than the VGP position (67.8, 336.7) Batt et al. (1998) calculated. Although the exact observation place is not recorded the aurora would have been easily seen by a Chinese observer. The record is a certain mid latitude effect and could be identified as an auroral oval. It is noted that the approximate geographical coordinates of the appropriate eight oriental capitals in eight China, Korea and Japan vary between 30°15' N, 120°10' E for Lin-an to 43°59'N, 119°20' E for Shang-ching (Table 4) or latitude 30° - 43° and longitude 103° - 136°.

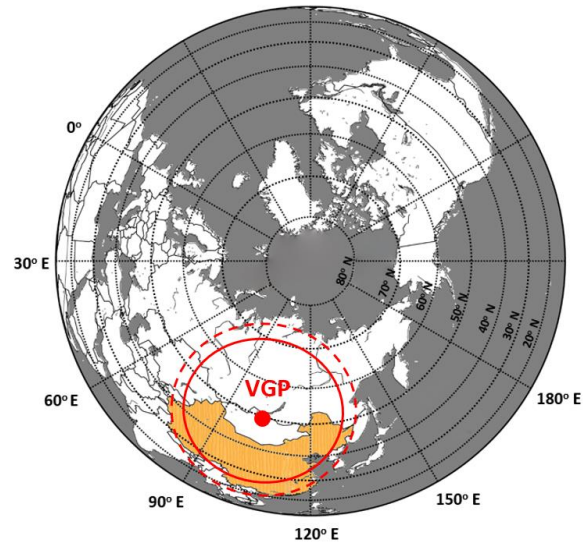


Fig. 4: Virtual Geomagnetic Pole (VGP) position for aurorae observed in China dated 193 B.C. The red dot is the mean VGP position (51±1)°N, (101±1)°E. The solid inner red line defines the area of the auroral oval which radially extends up to 22° from the VGP (the VGP center represents the lower error span of the mean VGP). The outer red lines define the maximum radius of the auroral oval which extends up to 30° from the VGP.

Table 4

Geographic coordinates of the appropriate oriental capitals (or regions)

Capital or region	Country	Geographic Coordinates	
Honshu (Kyoto) ^a	Japan	35°00'N	136°00'E
Kan-su Province ^a	China	37°00'N	103°00'E
Lin-an	China	30°15'N	120°10'E
Pien	China	34°47'N	114°20'E
Shang-ching	China	43°59'N	119°20'E
Shang-hsi Province ^a	China	36°00'N	111°00'E
Shang-tung Province ^a	China	36°00'N	118°00'E
Songdo	Korea	37°58'N	126°34'E

a: Denotes approximate coordinates (given to the nearest degree) (Willis & Stephenson, 2000)

Table 3: Calculated Virtual Geomagnetic Poles (VGPs) for the 1st millennium B.C. using measured data from China, South Korea and England

a/a	Archeo-logical age (B.C.)	Reference	Site	Measured data ^{1,2}				Calculated values ³			Calculated reduced values ^{4,5}		
				SITE _{lat}	SITE _{lo_{ng}}	I	D	θ_m	VGP _{lat}	VGP _{lo_{ng}}	I _c	D _c	I _c ^c
Aurora recorded in 687 B.C.													
1	620 ± 150	Batt et al. (1998)	China	35.1	109	56.2±0.8	3±1.4	53.2±0.8	72±1	115 ± 1	58.3	359.3	54.6
2	745 ± 80	Yu et. al. (2010)	South Korea	36.64	126.5	49.5±2.9	341.7±4.5	59.7±2.6	64±2	105±3	65	350.7	56.1
Aurora recorded in 193 B.C.													
3	206± 10	Batt et al. (1998)	China	34.3	109.25	33.2±2.4	343±2.9	71.9±0.1	51±1	101±1	74.5	328.4	53.8
Aurora recorded in 166 B.C.													
4	175± 75	Aitken & Hawley (1967)	England	51.8	358.6	72.3±3.1	357.5±10.2	32.5±2.5	71±5	352±14	48.4	340.9	68.5
Aurora recorded in 154 B.C.													
5	150 ± 50	Aitken & Hawley (1966)	England	51.4	357.7	65.4±4.3	349.9±10.3	42.5±2.8	79±6	316±12	50.4	354.8	68.2
6	150 ± 50	Clark et. al. (1988)	England	50.6	357.6	68.8±0.7	359.9±1.9	37.8±0.5	77±1	357±2	45.1	345.8	67.7

¹ latitude (SITE_{lat}) and longitude (SITE_{lo_{ng}}) of the site (in degrees)

² inclination(I) and declination (D) measured archaeomagnetically (in degrees)

³ Virtual geomagnetic pole latitude (VGP_{lat}), virtual geomagnetic pole longitude (VGP_{lo_{ng}}) and co-latitude (θ_m) calculated using the equations (2), (3) and (4) respectively

⁴inclination (I_c) and declination (D_c) that would be produced at a common site (40°N, 116°E (Beijing)) from another location via the geomagnetic poles using equations (5) and (6) respectively

⁵corrected inclination I_c^c using the equation (7)

4) Chinese aurora record: 166 B.C.

According to ancient text, in 166 B.C. in the north-east of Chang'an (Capital of Han), there was qi of spirit in five colors, as if a man wearing an official cap. There are no data recorded in Geomagia Data Base close to 166 B.C. from samples from China or around China. Thus, a recorded sample from Europe and especially from England dated in 175 B.C. \pm 75 (Table 3/row 4) was used for the calculation of the VGP position. The VGP position calculated $(71\pm 5)^{\circ}\text{N}$, $(352\pm 14)^{\circ}\text{E}$ denoting a celestial position above Greenland very close to the north geographical pole. For this purpose the reduced inclination and declination (reduced to China) were used and the VGP position recalculated $(76\pm 2)^{\circ}\text{N}$, $(316\pm 4)^{\circ}\text{E}$. Although the latter coordinates are closer to China an aurora having its center at the recalculated VGP position could not be seen in China even if the observer is in the north China. The age error is not low so as to conclude that an auroral observation could not have been recorded. Thus, it is concluded that the VGP position had constantly changed at that period due to short-term variation on directional data of the geomagnetic field, well documented at any rate (Xanthakis & Liritzis, 1989; Liritzis & Kovacheva, 1992).

5) Chinese aurora record: 154 B.C.

According to Hanshu (vol. 26) in 154 B.C. in the north it has been recorded something red like a mat in the sky, more than 10 zhang long (36 meters long, equals to about 100 degrees when referring to heavenly distance), it might be called red qi, or splitting of heaven. Chinese carpets made in this period are red; the phenomenon recorded is like a flying carpet in the sky.

From data from England the mean VGP position calculated $(78\pm 4)^{\circ}\text{N}$ and $(337\pm 7)^{\circ}\text{E}$ from 150 B.C. \pm 50 age data (Table 3/rows 5&6) denoting a magnetic pole position above Greenland very close to the north geographical pole. The high latitude calculated VGPs cast doubt if the phenomenon was aurora. Keimatsu (1970, Part I) assigns the sky records in 158 B.C. and 155 B.C. (*Hanshu*, vol. 26) as *probable* to *doubtful* aurora occurrences.

6) Chinese aurora record: 139 B.C.

According to *Hanshu* (vol. 6) in 11 June, 139 B.C., there was something like as if the sun was rising in the night. The 139 B.C. aurora is attributed to a 'probable' reliability occurrence (Keimatsu 1970). From measurements from China and South Korea dated in 100 B.C. \pm 100 and 91 B.C. \pm 115 VGP position was calculated (Table 4/rows 1-3). The sample from South Korea is not used for the mean VGP cal-

culatation due to its high inclination which results in a large VGP (Table 4/rows 1).

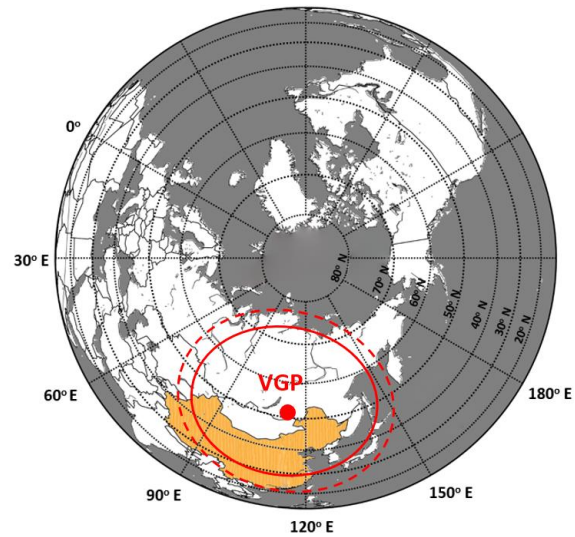


Fig 5: Virtual Geomagnetic Pole (VGP) position for aurorae observed in China around dated around 140 B.C.. The red dot is the mean VGP position $(53\pm 1)^{\circ}\text{N}$, $(113\pm 1)^{\circ}\text{E}$. The solid inner red line defines the area of the auroral oval which radially extends up to 22° from the VGP (the VGP center represents the lower error span of the mean VGP). The outer red lines define the maximum radius of the auroral oval which extends up to 30° from the VGP.

From measurements from China the mean VGP position was calculated $(53\pm 1)^{\circ}\text{N}$, $(113\pm 1)^{\circ}\text{E}$ denoting that the aurora would have been occurred and seen by a Chinese observer in China. The record is certainly a mid latitude effect and could be identified as an auroral oval (Fig. 5). Our VGPs are more representative for the 139 B.C. aurora description compared to the VGP positions $(73.4^{\circ}\text{N}$, 289.1°E) and $(73.4^{\circ}\text{N}$, 284.5°E) other researchers calculated (Wei et al. 1981; 1984); the latter VGPs denote a celestial position above North-East Canada very close to the north geographical pole.

7) Chinese aurora records: 32 B.C., 30 B.C. and 15 B.C.

Aurora records in 32 B.C., 30 B.C. and 15 B.C. had occurred within a very small time span. According to *Hanshu* (vol. 27) in 13 May 32 B.C., in the night, there was something like fire in the northwest (similar to Seneca's description for Italy (see below 6.2.5 paragraph); in 27 March, 15 B.C. (vol. 26) in the night, there was red color in the east looking like a tree. The latter's size was about the embrace of 3 or 4 people stretching their arms and it's about 2 or 3 zhang long (7.2 or 10.8 meters long, equals to about 20 or 30 degrees when referring to heavenly distance). In the south there was one about 4 or 5 persons embraced (6.9 or 9.2 meters long, equals to about 30 or 40 degrees when referring to heavenly

distance) and they all moved down more than 10 zhang (about 36 meters long, equals to about 100 degrees when referring to heavenly distance), extinguished before reaching the ground (Keimatsu et al., 1968). Moreover, in the 7th month (10 August-8 September) 30 B.C., in the night, there was qi in yellow and white, more than 10 zhang long (about 36 meters long, equals to about 100 degrees when referring to heavenly distance) and its brightness lighted the ground. It might be called *splitting of heaven*, or *heaven's sword* (Keimatsu, 1970, Part I) assigns a probable occurrence for the 32 B.C. aurora record and a certain occurrence for the 15 B.C. aurora record. It is noted that, the red formations observed in 32 B.C. aurora should be attributed to a geomagnetic storm. According to ancient text, the 15 B.C. aurora was observed in Chang'an, the capital of the Former Han Dynasty (202 B.C.-8 A.D.) (see also Keimatsu, 1970; Keimatsu et al., 1968). Chang'an was an ancient capital of more than ten dynasties in Chinese history, today known as Xi'an ($34^{\circ}16'N$ $108^{\circ}54'E$), the capital of Shaanxi Province, China. Due to the lack of Chinese data for that period the only one sample from China dated in 7 ± 213 A.D. was used for VGP calculation despite the high age error (Table 4/row 7). The VGP calculation was also reached from data from England reduced to China dated around 20 B.C. (Table 4/rows 4-6). The VGPs and its errors calculated from samples from England are larger than the VGP and its error calculated from the sample from China despite the large age error of the latter.

So, the most representative value for the VGP position is $(61 \pm 3)^{\circ}N$, $(123 \pm 3)^{\circ}E$. The record would be identified as mid latitude aurora and the auroral oval would be clearly seen by observers in central and north China, including the observation recorded Chang'an city (Fig. 6).

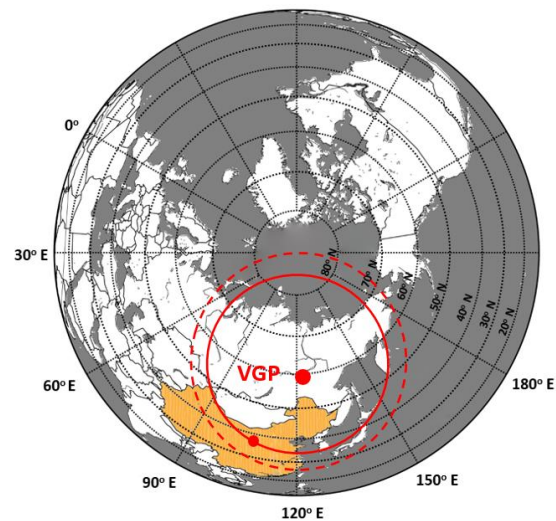


Fig 6: Virtual Geomagnetic Pole (VGP) position for aurorae observed in China, 32, 30 and 15 B.C. The red dot is the mean VGP position $(61 \pm 3)^{\circ}N$, $(123 \pm 3)^{\circ}E$. The solid inner red line defines the area of the auroral oval which radially extends up to 22° from the VGP (the VGP center represents the lower error span of the mean VGP). The outer red lines define the maximum radius of the auroral oval which extends up to 30° from the VGP. The red dot is the observation place, Chang'an.

Table 4: Calculated Virtual Geomagnetic Poles (VGPs) for the 1st millennium B.C. using measured data from China, South Korea and England.

a/a	Archeological age	Reference	Site	Measured data ^{1,2}				Calculated values ³			Calculated reduced values ^{4,5}			
				SITE _I _{at}	SITE _I _o _{ng}	I	D	θ_m	VGP _{lat}	VGP _{lo} _{ng}	I _c	D _c	I _c ^c	
Aurora recorded in 139 B.C.														
1	100 B.C. ± 100	Yu et al. (2010)	South Korea	37.24	127.17	55.6±4.8	1.7±8.5	53.9±2.5	73±5	131±6	55.9	7.1	56.7	
2	91 B.C. ± 115	Wei et al. (1984)	China	34.7	112.7	33.2±2.2	1.0±2.6	71.9±0.9	53±1	113±1	77	354.6	54.2	
3	91 B.C. ± 115	Wei et al. (1981)	China	34.7	112.5	33.2±2.2	1.0±2.6	71.9±0.9	53±1	113±1	77	354.2	54.2	
Mean VGP (2nd and 3rd rows)										53±1	113±1			
Aurorae recorded in 32, 30 & 15 B.C.														
4	25 B.C. ± 85	Clark (1983)	England	52.9	356.40	71.0±9.6	344.2±29.5	34.6±7.5	68±17	319±42	59	350.1	69.3	
5	15 B.C. ± 50	Clark et al. (1988)	England	51.13	359.43	66.1±5.8	352.1±14.3	41.5±3.9	79±8	327±17	49.2	352.5	68	
6	15 B.C. ± 50	Clark et al. (1988)	England	51.13	359.43	65.3±3.4	351.4±8.1	42.6±2.2	80±5	322±10	49.1	354	68.0	
7	7 AD ± 213	Wei et al. (1981)	China	37.7	113.6	41.1±3.7	11.4±4.9	66.4±1.6	61±3	123±3	69	8.4	57.1	

¹ latitude (SITE_{lat}) and longitude (SITE_{long}) of the site (in degrees)

² inclination (I) and declination (D) measured archaeomagnetically (in degrees)

³ Virtual geomagnetic pole latitude (VGP_{lat}), virtual geomagnetic pole longitude (VGP_{long}) and co-latitude (θ_m) calculated using the equations (2), (3) and (4) respectively

⁴ inclination (I_c) and declination (D_c) that would be produced at a common site (40°N, 116°E (Beijing)) from another location via the geomagnetic poles using equations (5) and (6) respectively

⁵corrected inclination I_c^c using the equation (7)

6.2 Aurorae from South-East Mediterranean area (Greece and Italy)

Early astronomy in Greece has been well documented regarding celestial and meteorological phenomena (Hannah, 2015). The accounts of possibly aurora in ancient Greece / Italy are those of: (a) Aristotle (384-322 B.C.) in his work 'Meteorology I', describes various types of aurorae, saying, "Sometimes on a clear night a number of spectra can be seen taking shape in the sky, such as 'chasms', 'trenches', and blood red colours . . . the upper air condenses and takes fire and that its combustion sometimes produces the appearance of a burning fire, sometimes of 'torches', or stars in motion. . .". (b) Seneca (55AD-40 AD), who speaks of a light, "Sometimes so low in the horizon that it gives the effect of a fire in a distance. . .", c) Another notion quoted by Plutarch (Sympos., VIII 3' 3. 122 A) regarding nature is the solar wind, which Anaxagoras called <tilas> (= tiny traces and pieces of matter moving always inside light rays), saying that the wind moves from the sun through oscillatory and wavy motion. This wind, Anaxagoras says, occasionally produces sounds and motion. It may well be the aurora, which produces such phenomena, mainly in northern latitudes, where the charged particles (trapped electrons and protons) from the solar wind are more intense and the magnetic field stronger than around the equator, and as a result, the resulted ionization and excitation of the nitrogen and oxygen atoms is higher and this causes the creation of colourful moving curtains, but also produce natural radio signals (sounds) which have been described them as distant noise and sputter. Researchers suspect there are several mechanisms behind the formation of these auroral sounds. These sounds are so soft that one has to listen very carefully to hear them and to distinguish them from the ambient noise (https://pwg.gsfc.nasa.gov/polar/EPO/auroral_poster/aurora_all.pdf).

Seneca the younger wrote about aurorae in the first book of his *Naturales Quaestiones*, classifying them, for instance as *pithaei* (barrel-like); *chasmata* (chasm); *pogoniae* (bearded); *cyparissae* (like cypress trees), and describing their manifold colors. He wrote about whether they were above or below the clouds, and recalled that under Tiberius, an aurora formed above the port city of Ostia that was so intense and red that a cohort of the army, stationed nearby for fire duty, galloped to the rescue. It has been suggested that Pliny the Elder depicted the aurora borealis in his *Natural History*, when he refers to *trabes*, *chasma*, falling red flames and daylight in the night.

For South-East Mediterranean area (central Italy and north Greece, 41-42°N and 12-24°E) the aurorae occurrences are grouped in four periods as follows:

467 B.C., 380-340 B.C., ca. 225 B.C., 100-200 B.C. and 40-55 A.D.. The catalogue provides a geographical homogeneity and uniformity taken from reliable ancient sources, as they were regarded of significant religious and war affairs matters. Also, they were checked by authorities because the rites necessary to expiate them were costly and time-consuming (Pliny the Elder *Natural History*; Livy in the *annalistic History of Rome*, (27B.C.-17AD); Stothers, 1979, Table 1) (<http://www.masseiana.org/pliny.htm#BOOK%20I%20II>). This practice was followed in ancient China too. The data from Greece (Aristotle) and Italy (Seneca) are reassessed from earlier publication (Liritzis, 1989) for inclusion to the larger record here.

6.2.1 Aurora recorded by Anaxagoras in Greece: 467 B.C.

Archaeomagnetic data mainly from Italian materials but one for Greece as well were used for the calculation of the VGP position (Table 5). The mean VGP position calculated (78 ± 3)°N and (36 ± 6)°E from 550 B.C. \pm 50 and 550 B.C. \pm 25 age data (Table 5/rows 1&2). The data from Italy and Greece (Table 5/rows 4, 6, 7) are not used due to the high VGPs within its errors denoting that mean VGP position is almost at the northern geographical pole. In this case an aurora could not be observed. The VGP position calculated from 525 B.C. \pm 25 (Table 5/row 5) is excluded due to large inclination and declination errors which result in a large VGP error (Errors of the order of higher than 15% in I and D which result in much higher errors in error propagation for the calculation of the VGPs should not be quoted in publications). The VGP position calculated from 525 B.C. \pm 50 (Table 5/row 3) is also excluded due to high errors in inclination and declination. However, the VGP was re-calculated using the reduced I_c and D_c because almost all the samples are from Italy and not from Greece (except the last one/Table 5/row 7) where the aurora was recorded. The new VGPs are listed in Table 5 in brackets. The new mean VGP is (65 ± 2)°N and (18 ± 2)°E which was calculated from 525 B.C. \pm 25 and 475 B.C. \pm 75 age data (Table 5/rows 4, 6, 7). The other data from Italy are excluded due to the high VGPs or / and its errors. The auroral oval would be clearly seen by an observer in the South-East Mediterranean and naturally from Greece (Fig. 7). Thus, the record would be characterized as a mid latitude aurora. It is noted that the corrected inclinations I_c^s are close to most calculated reduced inclinations I_c because the reduced declinations D_c are around zero.

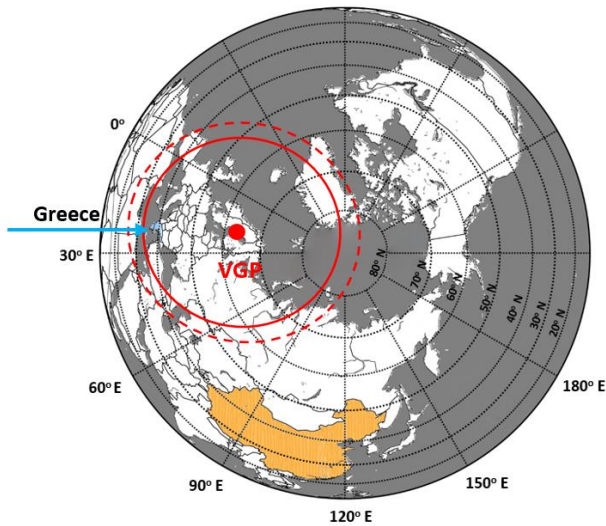


Fig 7: Virtual Geomagnetic Pole (VGP) position for aurorae observed in Greece 467 B.C. The red dot is the mean VGP position $(65\pm 2)^{\circ}\text{N}$, $(18\pm 2)^{\circ}\text{E}$. The solid inner red line defines the area of the auroral oval which radially extends up to 22° from the VGP (the VGP center represents the lower error span of the mean VGP). The outer red lines define the maximum radius of the auroral oval which extends up to 30° from the VGP.

6.2.2 Aurora recorded by Aristotle in Greece: 380-340 B.C.

Nine archaeomagnetic data from Greece, four from Italy, one from Ukraine and another one from Bulgaria as well were used for the calculation of the VGP position (Table 6). VGPs were calculated using all the data listed in Table 6. However, the samples from Greece dated in $385 \text{ B.C.} \pm 15$, $350 \text{ B.C.} \pm 50$ and $325 \text{ B.C.} \pm 25$ (Table 6/rows 3, 8, 14 & 15) are only used for the mean VGP calculation because the VGPs calculated from most of the data resulted in near the pole VGP positions possibly due to presence of non-dipole fields. The mean VGP position is $(74\pm 3)^{\circ}\text{N}$, $(9\pm 4)^{\circ}\text{E}$. The auroral oval would be only seen by an observer in north Greece during a strong geomag-

netic storm though the area of observation is at the border of auroral oval (Fig. 8). In addition, the different VGPs listed in Table 6 seem to rapidly change within a short time span of given archaeological ages. However, the VGP was re-calculated using the reduced inclination I_c and declination D_c as the available samples derive from different European countries and non-dipole field effects are an expected to have an effect. The new VGPs are listed in Table 6 in brackets are $(68\pm 2)^{\circ}\text{N}$ and $(3\pm 2)^{\circ}\text{E}$. The auroral oval would be clearly seen by an observer in the South-East Mediterranean region and north of Greece. This would be characterized as a mid latitude aurora. It is noted that the corrected inclinations I_s^c are close to most calculated reduced inclinations I_c because the reduced declinations are around zero within the attached errors.

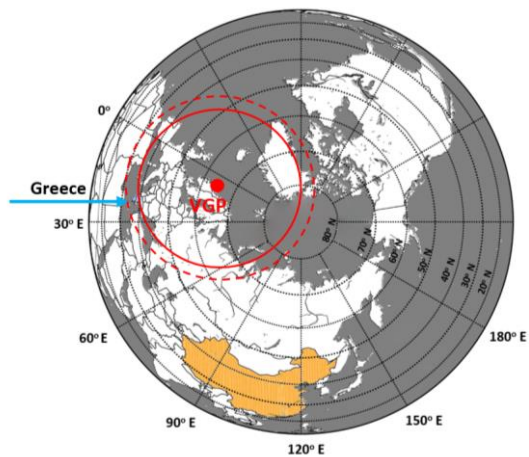


Fig 8: Virtual Geomagnetic Pole (VGP) position for aurorae observed in Greece in 380-340 B.C. The red dot is the mean VGP position $(68\pm 2)^{\circ}\text{N}$, $(3\pm 2)^{\circ}\text{E}$. The solid inner red line defines the area of the auroral oval which radially extends up to 22° from the VGP (the VGP center represents the lower error span of the mean VGP). The outer red lines define the maximum radius of the auroral oval which extends up to 30° from the VGP.

Table 5: Calculated Virtual Geomagnetic Poles (VGPs) for the 1st millennium B.C. using measured data from Italy, Greece England.

a/a	Archeo-logical age (B.C.)	Reference	Site	Measured data ^{1,2}				Calculated values ³			Calculated reduced values ^{4,5}		
				SITE _{lat}	SITE _{long}	I	D	θ_m	VGP _{lat}	VGP _{long}	I _c	D _c	I _c ^c
Aurora recorded by Anaxagoras, Greece (ca. 510-428 BC)													
467 B.C., North Greece													
1	550 ± 50	Tema et al. (2006)	Italy	46.03	13.14	71.1±2.4	6.5±7.4	34.4±1.9	77±4 (79±2)	38±9 (25±3)	53.1	3.9	64.3
2	550 ± 25	Evans & Hoye (2005)	Italy	37.85	15.3	60.3±1.7	5.6±3.4	48.8±1.0	78±2 (71±2)	34±3 (21±2)	52.4	3.2	57.2
3	550 ± 50	La Torre et al. (1998)	Italy	41.25	14.17	53.7±5.8	353.3±9.8	55.8±2.9	75±6 (74±6)	0±7 (350±8)	54.5	349.2	60.3
4	525 ± 25	Evans & Mareschal (1987)	Italy	40.4	16.8	66.4±1.8	0.6±4.5	41.1±1.2	89±3 (64±1)	48±4 (17±1)	41.8	0.5	59.6
5	525 ± 25	Tema et al. (2006)	Italy	45.97	13.2	74.8±11.7	359.9±44.6	28.5±10.5	73±19 (84±13)	13±56 (351±20)	58.0	356.4	64.2
6	525 ± 25	Evans & Hoye (2005)	Italy	40.42	16.75	66.4±1.8	0.6±4.5	41.1±1.2	89±3 (64±1)	49±4 (17±1)	41.8	0.5	59.6
7	475 ± 75	Evans (2006)	Greece	40.65	24.49	63.7±3.9	355.3±8.8	44.7±2.5	85±6 (67±3)	345±8 (19±3)	45.1	355.4	59.8
Mean VGP (1st and 2nd row)													
Mean VGP (calculated from I_c and D_c) (4, 6, 7 rows)													
									78±3 (65±2)	36±6 (18±2)			

¹ latitude (SITE_{lat}) and longitude (SITE_{long}) of the site (in degrees)

² inclination (I) and declination (D) measured archaeomagnetically (in degrees)

³ Virtual geomagnetic pole latitude (VGP_{lat}), virtual geomagnetic pole longitude (VGP_{long}) and co-latitude (θ_m) calculated using the equations (2), (3) and (4) respectively. The VGPs in brackets are calculated using as inclination and declination the reduced ones I_c and D_c

⁴inclination (I_c) and declination (D_c) that would be produced at a common site (41°N, 23.5°E (Chalkidiki, North Greece, though Anaxagoras born at Clazomenae Asia Minor and moved between Asia Minor to Athens and exiled and died at Lampsacus in Troad 40°20'48"N, 26°41'57"E)) from another location via the geomagnetic poles using equations (5) and (6) respectively

⁵corrected inclination I_c^c using the equation (7)

Table 6: Calculated Virtual Geomagnetic Poles (VGPs) for the 1st millennium B.C. using measured data from Europe.

a/a	Archeological age (B.C.)	Reference	Site	Measured data ^{1,2}				Calculated values ³			Calculated reduced values ^{4,5}		
				SITE _{lat}	SITE _{long}	I	D	θ_m	VGP _{lat}	VGP _{long}	I _c	D _c	I _c ^c
Aurora recorded by Aristotle's (384-322 B.C.) 380-340 B.C., North Greece													
1	400-300 B.C.	Kovacheva (1980)	Bulgaria	45	15.8	65±2	-6±3	43±1.3	85±3 (68±1)	309±5 (2±2)	42.1	353.7	63.4
2	400-300 B.C.	Zagny (1981)	Ukraine	~47	~30	70	-8	36.1	78±0 (79±0)	359±0 (14±0)	52.0	353.5	65
3	385 ± 15	Evans (2006)	Greece	35.32	25.2	58.4±2.7	351.5±5.2	50.9±1.5	73±3 (72±3)	6±4 (10±4)	56.7	352.2	54.8
4	375 ± 25	Evans & Hoye (2005) and Evans&Mareschal (1987)	Italy	37.8	12.5	61.3±2.2	352.2±4.6	47.6±1.3	79±3 (66±2)	345±4 (353±2)	49.4	349.5	57.2
5	365 ± 35	Evans (2006)	Greece	37.92	22.92	60.1±1.6	352.8±3.2	49±1	63±2 (60±1)	328±3 (346±2)	51.2	325.5	57.3
6	350 ± 50	Spatharas et al. (2011)	Greece	40.45	21.16	59.5±2.8	340.2±5.5	49.7±1.6	73±3 (67±2)	331±5 (353±3)	49.6	339.5	59.6
7	350 ± 50	Evans & Hoye (2005)	Italy	40.4	16.79	63.4±2.9	3.2±6.5	45±1.8	85±4 (68±2)	43±6 (14±3)	45.9	2.4	59.6
8	350 ± 50	Evans&Mareschal (1988)	Greece	35.32	25.6	58.8±3.3	352.4±6.4	50.5±1.8	74±4 (72±3)	8±5 (13±4)	56.3	353.3	54.8
9	350 ± 50	Evans&Mareschal (1988)	Greece	37.92	24.92	60.1±1.6	352.8±3.2	49±0.9	63±2 (61±1)	330±3 (347±2)	52.1	326.5	57.3
10	338 ± 12	Evans & Hoye (2005)	Italy	40.42	16.75	62±2.7	347±5.8	46.8±1.6	79±4 (65±2)	325±5 (356±2)	46.1	345.9	59.6
11	337 ± 12	Evans&Mareschal (1987)	Italy	40.4	16.8	62±2.7	347±5.8	46.8±1.6	79±4 (65±2)	325±5 (356±2)	46.2	345.9	59.6
12	325 ± 25	De Marco et al. (2008)	Greece	40.59	23.79	60.6±4.1	347.2±8.4	48.4±2.4	78±5 (69±3)	339±7 (6±4)	48.9	347.3	59.7
13	325 ± 25	De Marco et al. (2008)	Greece	40.59	23.79	66.6±3.6	343.5±9.1	40.9±2.5	78±7 (63±3)	300±9 (10±3)	41.3	343.5	59.7
14	325 ± 25	Evans (2006)	Greece	37.5	21.61	56.4±2.5	354.8±4.5	53±1.3	74±3 (74±3)	10±3 (8±3)	56.4	354.0	56.9
15	325 ± 25	Evans&Mareschal (1988)	Greece	37.92	24.92	57.2±1.1	353.6±2	52.2±0.6	75±1 (71±1)	10±2 (13±1)	55.4	354.2	57.3
Mean VGP (3rd, 8th, 14th and 15th rows)									74±3 (68±2)	9±4 (3±2)			
Mean VGP (calculated from I_c and D_c)													

¹ latitude (SITE_{lat}) and longitude (SITE_{long}) of the site (in degrees)

² inclination (I) and declination (D) measured archaeomagnetically (in degrees)

³ Virtual geomagnetic pole latitude (VGP_{lat}), virtual geomagnetic pole longitude (VGP_{long}) and co-latitude (θ_m) calculated using the equations (2), (3) and (4) respectively. The VGPs in brackets are calculated using as inclination and declination the reduced ones I_c and D_c

⁴inclination (I_c) and declination (D_c) that would be produced at a common site (41°N, 23.5°E (Chalkidiki, North Greece)) from another location via the geomagnetic poles using equations (5) and (6) respectively

⁵corrected inclination I_c^c using the equation (7)

6.2.3 Aurora recorded in Central Italy: ca. 225 B.C.

Archaeomagnetic data from Greece dated around 250 B.C. were used for the VGP calculation (Table 7/rows 1-2). The sample dated in 250 B.C. \pm 50 (Table 7/row 1) is excluded for the mean VGP calculation because its position does not correspond to observations from mid latitude European sites. Thus, the most representative VGP position is $(71\pm 5)^\circ\text{N}$, $(1\pm 6)^\circ\text{E}$ (Table 7/row 2). The auroral oval would be clearly seen by an observer in south Europe (Fig. 9) and the record would be characterized as a certain mid latitude aurora.

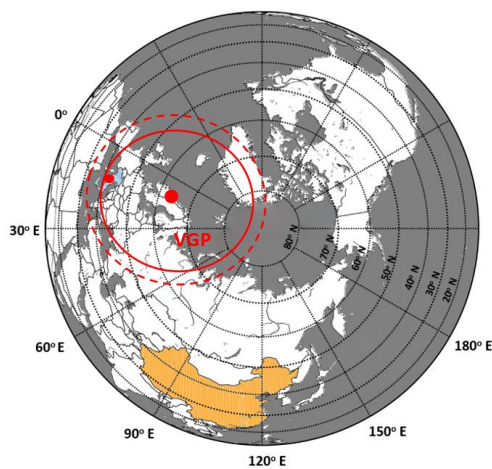


Fig. 8: Virtual Geomagnetic Pole (VGP) position for aurorae observed in Italy ca.225 B.C. The red dot is the mean VGP position $(71\pm 5)^\circ\text{N}$, $(1\pm 6)^\circ\text{E}$. The solid inner red line defines the area of the auroral oval which radially extends up to 22° from the VGP (the VGP center represents the lower error span of the mean VGP). The outer red lines define the maximum radius of the auroral oval which extends up to 30° from the VGP. The red dot is the observation place, central Italy.

6.2.4 Aurora recorded in Central Italy: 200-100 B.C.

Archaeomagnetic data from Greece and Italy dated around 200-100 B.C. were used for the VGP calculation (Table 7/rows 3-7). The mean VGP calculated from samples from Italy dated in 150 B.C. \pm 50 (Table 7/rows 5&6); the VGPs calculated from samples from Greece are excluded both due to large age errors and distant longitude (Table 7/rows 3&4). The VGP position for sample dated in 100 B.C. \pm 50 (Table 7/rows 7) is also excluded because its time span is not clearly referred within the period 200-100 B.C.. This is also verified from its VGP latitude is too close to the north geographical pole; the VGP longitude corresponds to positions far away from the European skyscape in direction towards the east. The mean VGP position is $(79\pm 2)^\circ\text{N}$, $(11\pm 3)^\circ\text{E}$ (Table 7/rows 5&6). The VGP latitude is close enough to the north

geographical pole and an aurora observation could be possible within the limit of auroral oval and the associated VGP errors and during a strong geomagnetic storm. Thus, the occurrence is not likely to be a mid latitude aurora and further archaeomagnetic data and measurements should be taken so as safely conclusions to be drawn for the VGP position for 200-100 B.C.

6.2.5 Aurora recorded by Seneca: 40-55 A.D.

Archaeomagnetic data from Greece, Bulgaria and France dated around the 1st century A.D. were used for the VGP calculation (Table 7/rows 8-11). The mean VGP calculated from samples from Greece dated in 0 ± 100 and $65 \text{ A.D.} \pm 134$ (Table 7/rows 10&11). The VGP calculated from sample from France is excluded both because its latitude is too close to the north geographical pole and its longitude corresponds to positions far away from the European skyscape in a direction towards the west (Table 7/row 8). The VGP calculated from sample from Bulgaria is also excluded; VGP latitude is at the north geographical pole and its longitude corresponds to positions of east-European sky in a direction towards the east (Table 7/row 9). The VGPs calculated from samples from Bulgaria and France are not used in mean VGP calculation, as they denote existence of non-dipole fields around the beginning of the 1st century A.D.. The mean VGP position is $(65\pm 2)^\circ\text{N}$, $(12\pm 2)^\circ\text{E}$ (Table 7/rows 10&11) is characterized as a certain mid latitude aurora that would be observed in central Italy.

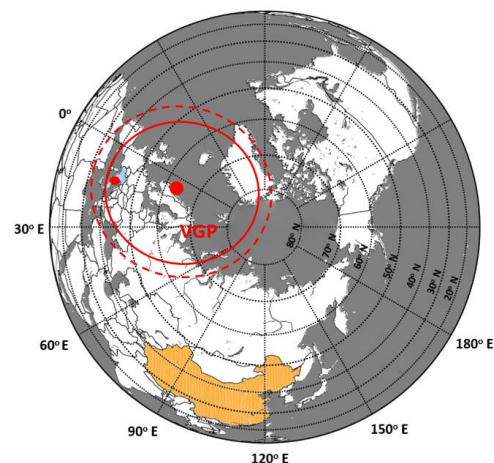


Fig. 9: Virtual Geomagnetic Pole (VGP) position for aurorae observed in Italy 40-55 A.D. The red dot is the mean VGP position $(65\pm 2)^\circ\text{N}$, $(12\pm 2)^\circ\text{E}$. The solid inner red line defines the area of the auroral oval which radially extends up to 22° from the VGP (the VGP center represents the lower error span of the mean VGP). The outer red lines define the maximum radius of the auroral oval which extends up to 30° from the VGP. The red dot is the observation place, central Italy.

Table 7: Calculated Virtual Geomagnetic Poles (VGPs) for the 1st millennium B.C. and 1st century A.D. using measured data from Europe.

a/a	Archeological age	Reference	Site	Measured data ^{1,2}				Calculated values ³			Calculated reduced values ^{4,5}		
				SITE _{lat}	SITE _{long}	I	D	θ_m	VGP _{lat}	VGP _{long}	I _c	D _c	I _c ⁵
Aurora recorded in ca. 225, Central Italy													
1	250 B.C. ± 50	De Marco et al. (2008)	Greece	40.79	22.05	57.4±1.7	349.5±3.2	52.2±0.9	77±2	-7±3	54.3	-7.2	59.9
2	250 B.C. ± 50	Spatharas et al. (2011)	Greece	40	21.9	52.6±5.3	348.1±8.7	56.8±2.6	71±5	1±6	60	-6.6	59.2
Aurora recorded in 200-100 B.C., Central Italy													
3	200 B.C. ± 130	Evans (2006)	Greece	40.7	22.33	62.5±3.6	354.8±7.8	46.2±2.2	83±5	-11±7	48	-3.8	59.8
4	200 B.C. ± 130	Evans (2006)	Greece	40.8	22	60.8±2.2	355.3±4.5	48.2±1.3	82±3	-1±4	49.9	-2.8	59.9
5	150 B.C. ± 50	Evans & Hoye (2005)	Italy	40.4	16.7	57.9±1.7	358.3±3.2	51.4±0.9	79±2	11±3	53.1	-0.4	59.6
6	150 B.C. ± 50	Evans & Hoye (2005)	Italy	40.39	16.72	57.9±1.7	358.3±3.2	51.4±0.9	79±2	11±3	53.1	-0.4	59.6
7	100 B.C. ± 50	Evans & Hoye (2005)	Italy	41.32	15.63	63±1.7	4.8±3.7	45.5±1.1	85±2	54±3	46	5.1	60.4
Mean VGP (5th and 6th rows)									79±2	11±3			
Aurora recorded by Seneca (40-55 A.D.)													
8	40 B.C.-40 A.D.	Thellier (1981)	France	48.48	2.5	67±2	-3.6±4	40.3±1.4	81±3	-16±6	49.3	-5.4	66.1
9	0-100 A.D.	Kovacheva (1980)	Bulgaria	43.7	23.1	66.3±2	-	41.3±1.4	88±3	23±5	44.4	0.6	62.4
10	0 ± 100	De Marco et al. (2008)	Greece	37.08	25.15	47.6±2.7	344.6±4	61.3±1.2	64±2	8±2	67.9	-3.9	56.5
11	65 A.D. ± 134	Evans & Mareschal (1988)	Greece	37.38	25.29	47.1±2.5	352.1±3.7	61.7±1.1	65±2	16±2	66.7	3.4	56.8
Mean VGP (10th and 11th rows)									65±2	12±2			

¹ latitude (SITE_{lat}) and longitude (SITE_{long}) of the site (in degrees)

² inclination (I) and declination (D) measured archaeomagnetically (in degrees)

³ Virtual geomagnetic pole latitude (VGP_{lat}), virtual geomagnetic pole longitude (VGP_{long}) and co-latitude (θ_m) calculated using the equations (2), (3) and (4) respectively

⁴ inclination (I_c) and declination (D_c) that would be produced at a common site (42°N, 12.5°E (Rome)) from another location via the geomagnetic poles using equations (5) and (6) respectively

⁵ corrected inclination I_c⁵ using the equation (7)

6.3 Repercussions and implications

The computed VGP data per auroral event are worth of close inspection (Tables 2-7). For the 980-970 B.C. aurora in China the different computed VGP coordinates may be explained as due to the large age error, and that during this probable age span the geomagnetic intensity varied between 50-85 μT or 85-130 ZAm^2 its virtual axial dipole moment. Drastic short-term changes in intensity reflect changes in directional inclination (I) and declination (D).

The two Chinese VGPs of 1 and 2 row (Table 1) with narrower age errors are used for the drawing the auroral oval map (Fig. 2). The two similar VGPs in rows 5 and 6 come from a higher age error bar but they coincide with the chosen 1 and 2 row values.

Interestingly enough, the reduced I_s^c to common Beijing latitude under the assumption of an axial dipole field, which predicts $D = 0$ provided satisfactory commensurability.

The Chinese VGP for the 687 B.C. aurora permits lower latitude aurora to be seen and the auroral oval of the Korean VGP is within the lower error limit that could allow mid latitude aurora to be observed (Table 3/rows 1&2).

The 193 B.C. Chinese reported aurora could be justified from the position of the VGP as well despite lack the exact location of observation.

The fifteen VGPs from Greece, Italy, Bulgaria and Ukraine (reduced to Greece) for Aristotle's time and the corresponding similar period in central Italy are all converging to mid latitude supporting the validity of aurorae observation, taking into account non-dipole field effects and drastic changes in magnetic pole position within a century.

The allegedly referred ca. 225 B.C. and 100-200 B.C. aurorae in higher latitudes of central Italian observing sites could be valid within the limit of auroral oval and the associated errors in the computation of VGPs from the directional data.

In Britain at around 0-200 B.C. the declination (D) has a locus around $0 \pm 30^\circ$ (Batt et al., 2017), and the corrected I_s^c , as well as, the reduced inclination (I_c) and declination (D_c), for China, have reasonable values. Similarly, in Italy 0-200 B.C. the declination (D) is zero plus minus 10° , similarly those supposed to have been observed on 32, 30 and 15 B.C.. Though for a northern Chinese observing site and taking into account attached error bars for I, D, this might have been possible. At any rate according to Keimatsu (1970) the reliability of those possible occurrences (included also 172, 158, 155, 139, 134-128, 119, 112, 79 B.C.) is *probable* (criterion 3) to *doubtful* (criterion 4).

A further point of support of the present investigation derives from an aurorae observation reported

independently by Chinese astronomers in Hangzhou, China and by European observers in Prague in 1138 A.D. (Liritzis, 1989).

In the abovementioned assessment, the reported auroral occurrences are supported by calculated VGP yet sometimes not for the allegedly reported location of observation.

The explanation has threefold reasons:

a) the VGP is in higher latitudes than the magnetic poles, around which essentially forms the auroral oval, quite plausible, to justify a difference of at least 10° e.g. between 70° - 80° in 139 B.C. - 1 B.C. China.

b) there exist age uncertainties in the measured inclination (I) and declination (D) of sample for the calculated VGP. The latter is reinforced from the observed rapid variation of geomagnetic field intensity within short time intervals and magnetic pole (MP) position within short time intervals (see Liritzis, 1987; Aitken et al., 1989). But also of the I, D as well, exhibit rapid variations with periodicities of a few hundred or with a short time intervals of a few years to some decades (Xanthakis & Liritzis, 1989; see also Table 1 above).

c) the emergence of non-dipole sources prevents the calculated axial geomagnetic pole position. The latter has been observed in the construction of archaeomagnetic intensity reference curves from the World (see GEOMAGIA50 data base). It has been noticed earlier that the archaeointensity peaks time lag of 600 years (1500 B.C. for Greece and 900 B.C. for N. East) moving eastwards while for the latter 900 B.C. peak is moving westwards giving rise to the high Greek intensity at ca. 500 B.C.. With a $\sim 8^\circ$ longitudinal difference Greece and Near East the drift rate is ~ 0.02 long/yr. In Britain same intensity peak appears in 500-650 B.C.. In eastern Asia the intensity peak within an error bar is between 1000-1300 B.C. or ca. 250-300 years difference from the Greek spike i.e. 0.36° long/year (Liritzis & Lagios 1993, Xanthakis & Liritzis 1989; Liritzis 1989) and verified later (Cai et al., 2017; Stillinger et al., 2015).

In fact, the drift rate between European and Eastern Asia (China, Japan, India) intensity curves has been earlier estimated between 0.1-0.4 long/year (Aitken et al., 1989). Such drifting sources may be related to a differential velocity change between outer core and mantle precession. Inevitably, given the poor definition of some of the maxima, these rates are no more than rough estimates, yet in right order of magnitude compared with historical magnetic data. Such local non-dipole sources do not produce similar VGP for some regions e.g. from eastern Chinese and European data sets in particular periods in the past.

Due to the drift of the non-dipole field as well as the local development of magnetic anomalies the

average reduced inclination (I_c) and declination (D_c) are considered as most reliable when deduced from regions nearest to those of interest. In cases of missing data then distant regions were included their directional data being reduced to the country of auroral observation. The reduced to a common latitude computed I_c and D_c are within the errors commensurable to the respective VGP coordinates, while the corrected inclination (assuming $D=0$) in certain documented cases proved valuable.

Last but not least in regions of marked earthquake activity zones a shift from tilting, bedding etc. of stable burnt structures if not accounted for may induce errors (Liritzis, 1995).

To reiterate the different latitude and longitude of the magnetic pole position compared to the geomagnetic or VGP pole has to be taken into account that brings in the issue of cautious consideration of the obtained ancient pole positions and mid latitude aurorae observations.

7. CONCLUSION

The aurorae borealis spectacular phenomenon caught the curiosity and sensation of humanity, and in some ancient cultures it was recorded and described accordingly. A brief tutorial of aurorae and archaeomagnetism is presented marking essential differences in magnetic poles, geomagnetic poles and VGPs, while critically assessing northern lights accounts by ancient observers. Calculated VGPs from measured directional data in literature are computed also from reduced data on common latitude. The circular (oval) formation of northern lights

around the earth's magnetic pole could be seen in mid latitudes. The recording of some early aurorae records from China, Greece and Italy during the 1st millennium B.C. has been studied in relation to archaeomagnetic values of inclination and declination of baked clay fabric (ceramics, kilns). The virtual geomagnetic pole (VGP) theoretically calculated and its associated aurorae critically discussed with the observed accounts of these lights concluded that in almost all cases the observation was true. Several thorns in the attribution of archaeomagnetic data to a mid latitude magnetic pole positions are discussed. The aim is to support and reinforce the accuracy of archaeomagnetic data; but in other cases the archaeomagnetic measurements could be questioned, yet the aurorae accounts are meticulously evaluated attaching a probability scale. In several cases more measurements are needed, but with lower age errors attached and increased reliability in the directional data from statistical and systematic errors. The aurorae observation enhances also the commensurability or small differences between magnetic poles and calculated VGPs. Both in China and Italy narrower age errors are needed and in Greece the possible effects on directional measurements of seismic activity should be revisited. Last but not least such an appraisal contributes greatly to the appreciation of the abilities of historical societies to make accurate observation to their sky that without doubt is extremely useful scientific information to study the past astronomical and terrestrial phenomena.

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