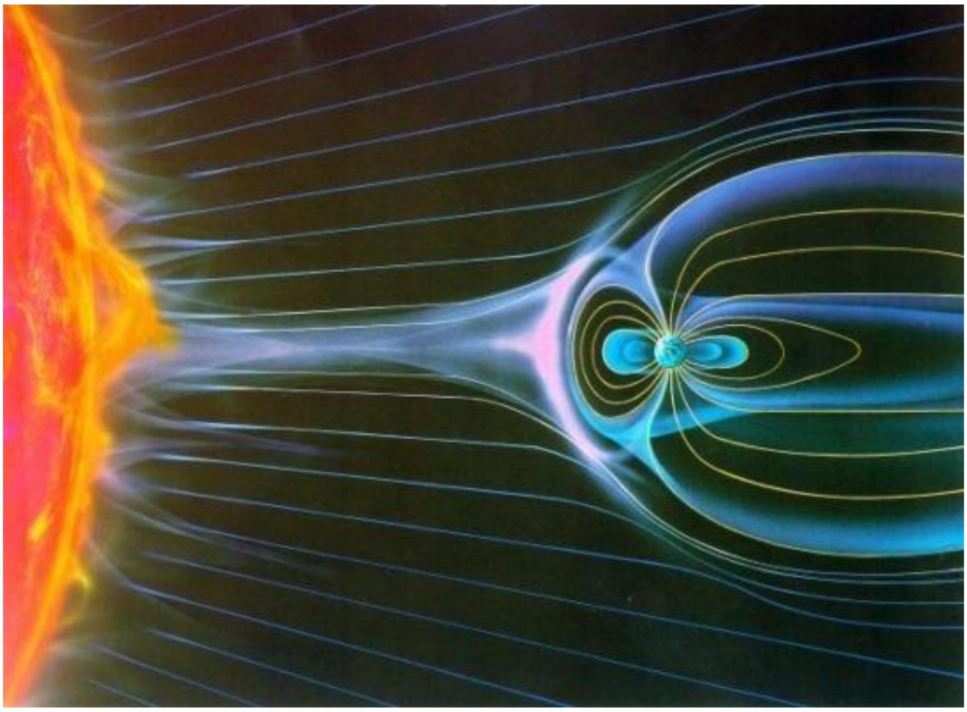
CHRONOLOGY & CATASTROPHISM
REVIEW 2016:3



Impact of the Solar Wind on the Earth's Magnetosphere. Credit: NASA

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A Geomagnetic Approach to Traditions of *Axes mundi*

Part II

Marinus Anthony van der Sluijs

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Variability of the Geomagnetic Field

Armed with a better grasp of the geometry of the 'traditional cosmos' as conveyed in historical and archaeological sources, the search is on for an appropriate physical explanation, starting from the critical examination given above of the 'intense-auroral' column proposed by Zysman and Peratt.

The study of traditional reflexes of auroral observations is closely linked to historical fluctuations in the geomagnetic field. Based on their duration, possible modifications of the geomagnetic field are grouped into two categories, comparable in timescales to 'weather' as opposed to 'climate'. Changes occurring on short timescales of less than 1 to 5 years are generally believed to result from factors external to the Earth, specifically responses of electrical currents in the ionosphere and magnetosphere to space weather, such as changes in the solar wind. All others represent the so-called 'secular variation' and are usually attributed to internal causes, notably fluid motions inside the Earth's core [1]. The first group is exemplified by geomagnetic storms and substorms seeing short-lived expansion of the auroral ovals, occasionally even to low latitudes. Crucial elements at play in secular variation are changes in the locations and strengths of all magnetic poles. The dipole strength and moment, along with the sizes of the magnetosphere and plasmasphere, oscillate on timescales from centuries to tens of thousands of years and perhaps longer [2].

Although the dipole is by far the most dominant feature, on average it accounts for no more than 80% to 90% of the Earth's magnetic field at the surface [3]. Locally, this may be as low as 70% [4]. Non-dipolar components – consisting of a group of other, minor poles – contribute to the intricate fabric of the field. At present, the non-dipole field (NDF) is on average stronger and more variable in the southern hemisphere than in the northern one [5]. It is because of its subtle distorting effect on the dipole field that the north and south magnetic poles do not exactly correspond with the geomagnetic poles, defined as the two points where the theoretical axis of the dipole field intersects the surface of the Earth [6].

How many magnetic poles does the Earth have? In 1972, the properties of dynamo fields were argued to consist of two 'families', which do not interact under stable circumstances: the 'dipole family', to which belong the dipole and perhaps also an octupole, comprising eight magnetic poles, and the 'quadrupole family', which includes the quadrupole, an axial configuration of four magnetic poles arranged at perpendicular angles to each other [7] (figure 1). The theory of spherical harmonics, on which this is based, may be a convenient mathematical tool for modelling the geomagnetic field, but modern geophysicists are well aware of the fictitious nature of the poles it defines. In reality, the non-dipole or 'multipole' part of the field manifests in the form of empirical anomalies in the dipole field. When separated out from the dipole, it is shown to comprise six to eight 'minor poles' [8] (figure 2). These can be modelled as 'lobes' or 'patches' with high flux or reverse flux in the liquid core deep below the Earth's surface, at the core-mantle boundary (CMB) [9]. Geometrically speaking, such 'flux lobes' are 'flaws' in a pure dipole field which must be due to the multipole component of the field. All of these minor poles are 'dip poles', where the orientation of the local magnetic field – the so-called inclination – would be vertical were it not for the dipole field. They pulsate, waxing and waning over time. Even though they rise to prominence when the dipole strength diminishes, "the dipole family appears to have dominated the quadrupole family for the Earth for the vast majority of the past 400 million years or so …" [10]

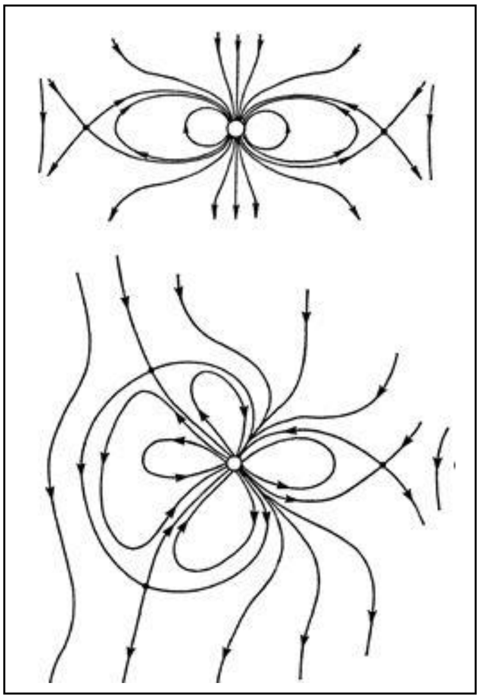

Figure 1: Theoretical field line configurations for a magnetic dipole (top) and quadrupole (bottom) field within a uniform external field.

Though it is usually much weaker than the dipole, "the non-dipole field

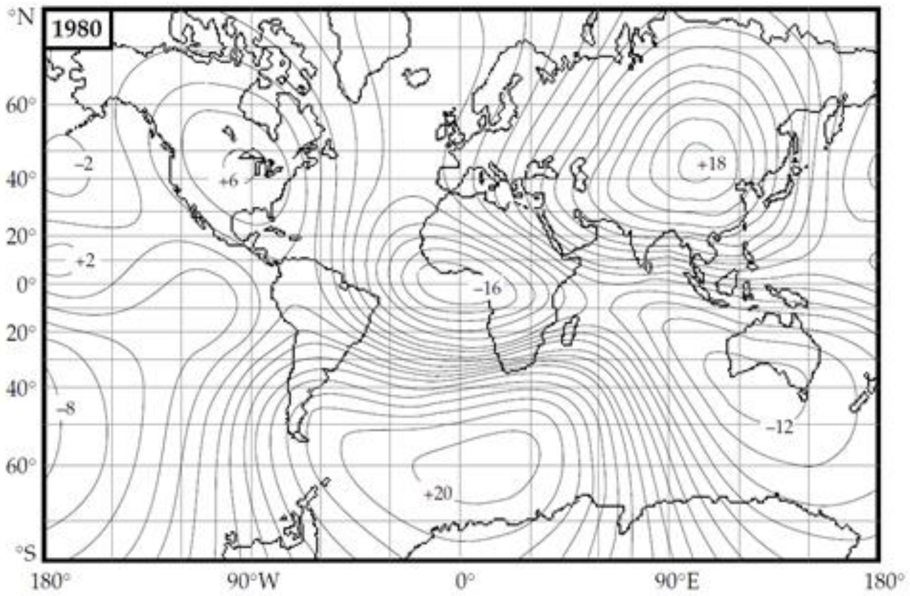

Figure 2: The vertical component of the non-dipole geomagnetic field for 1980.

is known from historical records to change more rapidly than the dipole field" [11], with a timescale measured in decades instead of centuries [12]. One analysis of the total geomagnetic field at the core-mantle boundary revealed four 'rapidly westward drifting flux spots' in the southern hemisphere and six 'static flux bundles' – positive ones under Canada, Siberia, the central Pacific Ocean and the Arabo-Persian Gulf and negative ones under Antarctica and south of Australia [13]. On the surface, the minor poles likewise form two categories: a standing part, which changes only in intensity, and a drifting part, which changes both in intensity and location – partly westward, partly eastward [14]. The strongest minor pole is the 'South Atlantic anomaly' (SAA), a positive drifting pole of reverse flux, which has waxed since 1780 and currently accounts for up to 80% of the total field in that area. Between 1945 and 1990, it drifted eastward by *c*. 25º of longitude. Another prominent focus is the 'Mongolian or Siberian anomaly' (45º N, 100º E), a positive standing pole over central Asia, which increased by 50% between 1829 and 1980. Two weaker positive foci are the standing 'North American anomaly', located in the eastern United States of America, which has waned since 1780, and the standing one in the central Pacific Ocean. Negative are the drifting 'Ivory Coast anomaly', to the east of Kenya in 1780, but, having drifted westward by *c*. 10º between 1945 and 1990, now to the south of Ivory Coast, and the standing 'South Australian anomaly', south of southern Australia [15]. Other small non-dipole anomalies do not show on all maps, due to different methods of calculating the positions. These include one focussed on the Seychelles (Indian Ocean) and one north of Iceland [16].

Because the incoming magnetic field lines from the polar funnels connect to the auroral rings associated with the dipole, but hardly to the minor poles, auroral effects are mostly limited to the north and south poles (figure 3). It cannot be assumed, however, that this is the case at all times. The historic paths of all magnetic poles, with their concomitant strengths, must be taken into account when linking past aurorae to human traditions and artefacts.

Historical descriptions of the aurora from higher latitudes, where it is a familiar phenomenon, are typically anodyne and, where they stray into mythology, remain restricted to simple superstitious beliefs. The same applies to reports from lower latitudes, where the aurora manifests sporadically due to equatorward expansion of the auroral ovals: generally, these bear no or only a superficial relationship to mythology, not involving elaborate narration. By contrast, the elaborate and internally consistent set of traditions associated worldwide with 'creation', including *axes mundi*, points to far more dramatic and less fleeting changes in the geomagnetic field, likely involving all of the above-mentioned variables.

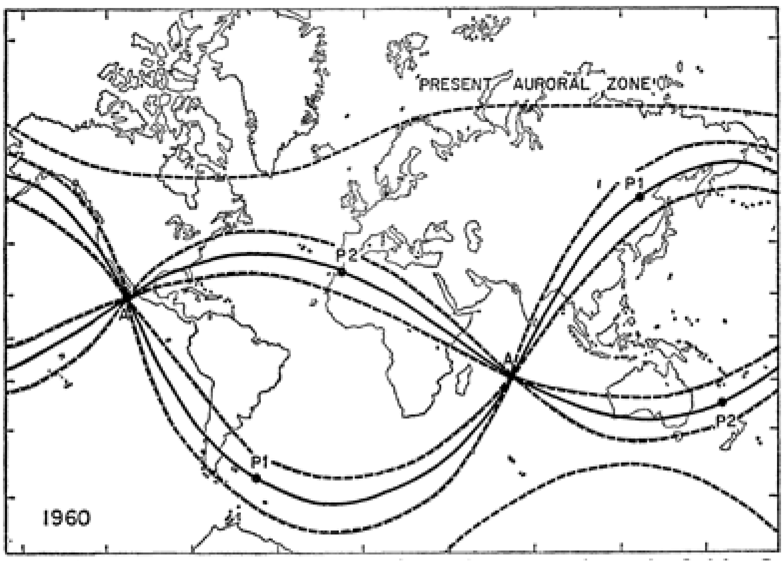

Figure 3: The auroral zones of the Earth's dipole and quadrupole fields for 1960.

Geomagnetic Reversals and Excursions

As seen, in many respects the *axes mundi* known from ancient human records bear a striking resemblance to the sight expected if the Earth's north and south magnetic poles were to experience a dramatic increase in the precipitation of charged particles: revealing the structure of the local magnetic field in visible light, the aurora would materialise as the familiar ring surrounding each pole, but with a funnel above it – a giant hollow column, perhaps formed of concentric circular 'curtains'. Following this line of thought, a solution to the geometric puzzle posed by the *axes mundi* may well lie in a past condition of extreme variability of the geomagnetic field over a longer span of time – that is to say, in archaeosecular variation (ASV) for contexts accessible by archaeologists and palaeosecular variation (PSV) for the earlier period studied by geologists, palaeontologists and palaeoclimatologists. Virtual geomagnetic poles (VGPs) are the positions of the geomagnetic poles as inferred from measurements obtained at individual locations.

Geomagnetic reversals involve a breakdown of the Earth's dipole field, followed by interaction between the impaired dipole and the robust non-dipole part of the field [17]. "The reversals begin with a decrease in dipole strength and a simultaneous motion of the poles to lower latitudes. By the time the poles reach equatorial latitudes the dipole field is smaller than the non-dipole components of the field, which do not change during a reversal. … The reversal ends with the poles reaching high latitudes and the field strength restored." [18] Whereas some poles, including those constituting the dipole, are expected to wander and change sign, others would remain stationary and not invert [19].

As first proposed in 1968, weakness of the dipole seems to be a prerequisite to geomagnetic reversals, often with values plummeting to as low as 25% of the usual value at the 'equator' of the transitional field. This enables "nondipole effects to dominate" [20], in the form of "several dip poles including some near the geographic equator", and "the effects of such reduction would be seen and felt globally." [21] Multiple reversals may occur "during an interval when the dipole intensity is low" [22], yet it must be realised that there also "appear to have been numerous times in the past when the dipole intensity has decreased without leading to a reversal. This is particularly so when, as in the recent past, the intensity has been above its long-term average value." [23] Furthermore, there are indications "that the dipole intensity increases after a reversal and then decreases in an approximately linear manner", as if the reversal provides a boost to the dipole field [24].

Reversals occur at long-term, seemingly irregular intervals ranging from anything between 100,000 and 50,000,000 years and are generally believed to last between 1000 and 10,000 years. "The interval in which the dipole swings across the equator and the non-dipole components dominate is very short, perhaps only a few hundred years." [25] During the transition, change need not occur at a steady pace: "… polarity transitions may be punctuated by episodes of extraordinarily rapid field change" [26]. The current *chron* or geomagnetic epoch is a 'normal' one, within which the dipole points south. Labelled the Brunhes chron, it is thought to have begun 780,000 years ago, succeeding the reverse Matuyama epoch [27]. A recent discovery is that this latest field reversal lasted "much less than a century", "a time interval comparable to the duration of an average human life" [28]. Yet as this happened long before *Homo sapiens sapiens* even attained anatomical modernity, true reversals will in the present study not be of any further concern with respect to the origins of myth.

The long intervals between reversals are punctuated by relatively short-term variations called *geomagnetic excursions*. These again involve a large non-dipole to dipole field ratio due to weakening of the dipole field, perhaps by a factor of 2 to 4 [29]. They are often accompanied by transient deviations of the north and south magnetic poles from the geocentric axial dipole with an amplitude in excess of 40º or 45º [30], of 90° [31], or simply "away from the normal range of geomagnetic secular variation" [32]. According to one hypothesis, they drift equatorward, but do not reverse completely and retreat to their original regions [33]. For this reason, excursions are often characterised as abortive reversals, but this is only appropriate in cases with substantial displacement of the dipole [34]. Some dissuade from referring to excursions "as either anomalous secular variation or as aborted reversals", defining them as "a short-duration … impulsive oscillation in the geomagnetic field direction with an amplitude that is at least three times greater than secular variation for the given time interval"; "when a reversed polarity is reached it is unstable" [35].

Waxing elements may either be an equatorial dipole or a non-dipole field, varying from case to case. Some excursions seem "consistent with a decrease in strength of the axial dipole, a substantial transitional equatorial dipole, and a reduced nondipole field relative to the axial dipole." [36] As long as the ratio of the non-dipole field to the dipole field is small, VGPs calculated from measurements obtained at geographically disparate locations "follow consistent paths for any given excursion" [37]. Other excursions are characterised by the preponderance of non-dipole geomagnetic components, "in which case VGP paths and the apparent polarity could vary around the globe." [38] In addition, there are excursions during which the geomagnetic field intensity increases [39]. Some specialists cautioned that excursions involving a strong non-dipole field do not necessarily extend through the entire geomagnetic field [40]. Yet according to a growing consensus, excursions "appear to be globally recorded and not local anomalies of the geomagnetic field." [41]

The duration of excursions is usually estimated to range from a few decades to 5000 years at the very most [42]. As with reversals, it is not impossible that some – or indeed many – events transpired rapidly throughout. Russian specialists distinguished between “prolonged” and fast “transitory” excursions [43]. The Laschamp excursion (40,000 BP) is the youngest excursion whose reality presently enjoys unanimous endorsement. A very fast rate was recently determined for it, of “half a degree in latitude per year during the transitional phase between the clear normal (N) polarity … and the clear reversed (R) polarity”. Fully reversed polarity lasted only 250 to 440 years, with a field decay down to 5% of earlier levels [44].

Reversals and excursions have important ramifications for climate and weather, although the exact mechanisms involved remain matters of intense debate. Limiting the discussion here to radiation hazards, Uffen observed that, during geomagnetic reversals, “the trapped corpuscular radiation” from the van Allen belts “may have spilled on to the Earth, and the solar wind would have been able to bathe the Earth” [45]. This condition, known as an ‘induced magnetosphere’, arises because a weaker magnetosphere will be less efficient in deflecting inflowing charged particles away from the Earth’s atmosphere: “If the present geomagnetic field were reduced to zero during a polarity transition, the increased radiation dose would amount to 10% at the equator and zero at the poles.” [46]

Geomagnetic Excursions and the Magnetosphere

How would such perturbations of the geomagnetic field affect the magnetosphere and hence the aurora? Surprisingly, down to 10% of the current strength the impaired dipole field remains dominant in the outer regions of the atmosphere, even if the non-dipole component is stronger at the surface. “The reason is that the dipolar component of the field decreases more slowly with distance from the earth than the others.” [47] Accordingly, the existence of a north-south pair of polar cusps must be maintained even for a very weak dipole field [48].

Even so, geophysicists believe that “the magnetosphere would likely have a very different structure during a reversal” than the familiar axial dipole [49]. A first effect involves shrinkage of the magnetosphere and the ring currents [50]. On the sun-facing side, the magnetopause may descend from its average normal position at about 65,000 km from the crust to a mere 10,000 km [51]. As the size of the plasmasphere varies more slowly with dipole strength than that of the magnetosphere, “the plasmasphere occupies a relatively larger fraction of the magnetosphere for small dipole strengths.” [52] Reversals and excursions might drive down the entire polar cusp structures with their field-aligned currents, normally towering thousands of kilometres higher above the Earth’s surface, towards lower altitudes and latitudes, perhaps revealing them in visible light to all living beings. Nevertheless, even the present non-dipole field is “capable of stopping the solar wind well above the atmosphere … so that the notion of a magnetosphere and associated auroral zones is valid.” [53]

A second outcome might be the formation of magnetospheric cusps and ring currents in specific localised regions associated with the minor poles, especially when the dipole strength drops below a critical level. The multipole field may become powerful enough for the Birkeland currents to reconnect to the minor poles, thus creating more than two polar cusps and auroral zones. One group noted that a multipolar field structure may predominate, at least near the Earth’s surface [54]. Theoreticians derived general equations for the magnetic field lines of axisymmetric (or zonal) and non-axisymmetric (or sectorial) magnetic multipoles, applicable to the Earth’s inner magnetosphere during geomagnetic reversals and large excursions [55]. They noted that, “in the case of a non-dipolar, axisymmetric multipole”, “variations in magnetic field strength result in some novel magnetospheric phenomena, including multiple belts of geomagnetically trapped radiation and concomitant multiple ring currents” [56]. On some occasions, “multiple magnetospheric cusps” can occur, described as “limited regions of space (‘funnels’) through which charged particles can gain relatively easy access to the inner magnetosphere”, “analogous to the northern and southern magnetospheric cusps (or clefts), which are an important feature of the contemporary ionospheric and magnetospheric system” [57]. In more recent years, they felt that “the actual existence of such idealized magnetospheres” during geomagnetic reversals and excursions “would necessarily imply multiple (n + 1) ‘magnetospheric cusps’ … as well as multiple (n) ‘ring currents’.” [58] In 1995, a computer simulation of a field reversal illustrated the complex field structure [59]. During the peak of the reversal, the minor poles were clearly visible above the Earth’s surface (figure 4): “At the core-mantle boundary, bundles of magnetic field lines emerge at high latitudes, but … there are two bundles in each hemisphere, and they are not actually at the poles. In fact, at the poles of the core-mantle boundary the field is relatively weak.” [60]

A miscellany of other deviations from the familiar appearance of the magnetosphere is predicted. “At the extreme end of the range … there should be rare events when the magnetopause is pushed briefly up against the plasmasphere by a shock wave.” [61] And a Russian team determined that a ‘reversal magnetosphere’ with the dipole still intact will probably have “the pole directed towards the Sun”, with an angle of less than 20º, so that “the magnetic pole finds itself in the equatorial region, shifting from one hemisphere to the other.” Under such conditions, “a funnel-shaped depression is formed in the cusp region in the frontal part of the magnetosphere”: “… an extensive and deep tunnel-like cusp is formed in the subsolar region, through which the solar plasma can effectively penetrate within the magnetosphere.

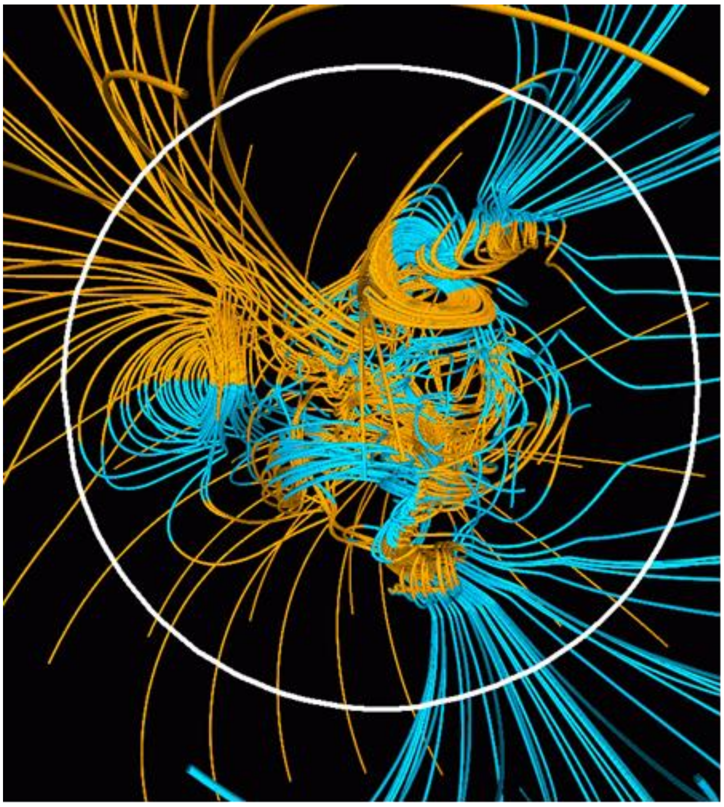

Figure 4: Computer simulation of the Earth's magnetic field during a polarity reversal (1990s). The white circle marks the Earth's surface.

Given the diurnal rotation of the Earth, such a situation, which promotes the pumping-in of solar plasma, will be repeated daily for several hours." For a quadrupolar field, a similar situation obtains when the inclination angle of the symmetry axis remains below 20º, but for a near-perpendicular angle "the quadrupole is almost axisymmetric with respect to the axis of rotation, and therefore diurnal rotation has practically no effect on the position of the funnel-shaped cusp." In such a situation, "conditions favorable for the effective pumping of solar plasma into the magnetosphere can be maintained for a very long (as much as 103 years) time (provided the pole stays in the equatorial zone for a time comparable to the reversal time)." Moreover, "the diurnal rotation of the region in which a magnetospheric 'hole' is possible will lead to periodic magnetospheric catastrophes, and the annual variations of the inclination angle of the equatorial plane with respect to the direction to the Sun produce an annual variation." [62]

Geomagnetic Excursions and Aurorae

The shape of the aurora is at all times determined by the structure of the geomagnetic field and will therefore be affected by distortions of it. Siscoe was one of the first scientists to offer a detailed picture of the correlation between geomagnetic reversals and the geographical extent of the aurora. According to him, "both the polar and equatorial borders to our planet's auroral zones can be predicted for an arbitrary strength of its dipole, the first from the outer boundaries of the plasma sheet and the second from the position of the plasmapause". Generally, the auroral zone, delineated by one of the ovals, "moves … equatorward for decreasing strengths"; "during times of significant magnetic disturbance, the latitudinal width of the auroral regions is greater for small dipole strengths." Thus, aurorae will be "more frequent and geographically more widespread" at times "when the earth's dipole is weak":

> At the low end of observed dipole strengths, the auroral zones occupy a latitudinal band through all of Europe. Moreover, the low end of the range can be associated with field reversals during which the magnetic poles move equatorward, bringing the auroral zones to even lower latitudes. … Such field shrinkage is associated with periods during which the polarity of the earth's dipole flips. [63]
>
> When the restriction of constant solar wind conditions is removed, it becomes evident that the changes in the size of the polar cap associated with solar wind variability, which in the present geomagnetic field are commonly of the order of 5º, will be magnified during weak dipole field epochs, thereby increasing the region in low latitudes subject to direct access by solar cosmic rays. [64]

As the dipole wanes, the secondary poles of the geomagnetic field come into play. Assuming that the strength of the non-dipole field as well as that of the solar wind is stable over long stretches of time [65] and treating the quadrupole field as dominant on the surface during a reversal, Siscoe's team found that the "auroral zones are much more extensive than at present":

> The quadrupole auroral zones are seen to cover a large part of the earth at any given time, in contrast to the present auroral zones. They extend from the tropics to midlatitudes in both hemispheres. The drift of the nondipolar components will sweep the auroral zones past any geographical point in this region at least one time in every several hundred years, the minimum duration of a reversal event. The points at the axis where auroral zones come together might be especially active. [66]

Siscoe conceded that the terrestrial reality during a geomagnetic reversal or excursion will be messier than the tidy model of a perfect quadrupole: "A picture of the magnetic field lines from the earth with the dipole component removed shows a complicated pattern asymmetric both in latitude and longitude. Since the field is in general weak and the pattern contains many poles (while the dipolar field, of course, contains only two) the total area over which particles gain access to the atmosphere should be quite large, and regular auroral displays over most of the earth seem guaranteed.” [67]

Modern authorities with impeccable credentials tend to come to similar conclusions:

> … removal of the Earth’s magnetic field would cause large increases in ionization at certain levels in the upper atmosphere. [68]
>
> Any major change in the configuration of the geomagnetic field during a polarity reversal (or even a large excursion) would inevitably lead to dramatic changes in geomagnetically trapped radiation, the geographical distribution of precipitating auroral particles and the geographical distribution of cosmic rays impinging on the Earth’s upper atmosphere. … a rich variety of auroral, ionospheric and magnetospheric phenomena. [69]
>
> Visual effects that would become apparent in the early stages of a polarity change might include changes in the aurora … More significant effects might come from the higher levels of ionizing radiation expected to reach the lower atmosphere in the densely populated low-latitude regions. [70]
>
> If the magnetosphere surrounding the Earth were to collapse, would we humans be entertained by spectacular aurora at equatorial latitudes? Or would we instead be forced to take refuge from the onslaught of the solar wind? [71]
>
> The magnetic poles reverse on long timescales (450,000 years on average), with the magnetic field decreasing significantly before reversing. This could result in significant auroral displays. [72]
>
> In the absence of a strong dipole field the solar wind would penetrate deeper into the atmosphere with consequent increased ionisation. Perhaps the entire sky would glow! [73]

Within the pervasive auroral glow which one might also call ‘airglow’, discrete auroral structure would be associated with all magnetic poles, including the minor poles. Depending on the local physical conditions, the aurorae related to the latter may take a variety of forms, which can be collectively dubbed *foci*. Presumably, the basic manifestations will be *rings*. One team of scientists included “multiple belts of geomagnetically trapped radiation and concomitant multiple ring currents, as well as multiple zones of auroral particle precipitation” among the “novel magnetospheric phenomena” one might expect “in the case of a non-dipolar, axisymmetric multipole” due to “variations in magnetic field strength” [74]. They noted that “the actual existence of such idealized magnetospheres” during geomagnetic reversals and excursions “would necessarily imply multiple (n + 1) ‘magnetospheric cusps’, and hence multiple (n +1) ‘auroral-precipitation regions’, as well as multiple (n) ‘ring currents’.” [75]

The current auroral ovals measure 4000 to 5000 km in diameter. Whether the diameters of the various auroral rings distributed over the globe during a geomagnetic reversal or excursion will be larger or smaller than that, in response to the weakness of the field, is moot and may depend on several, perhaps counteracting variables. If the diameter of the auroral zones of the dipole field is controlled by the geometry of the plasmasphere, a weak dipole may or may not imply enlarged auroral zones, as Siscoe asserted, but the minor poles may feature narrow auroral rings regardless of the plasmasphere [76]. Moreover, it will be argued below that the rings will contract when an increase in electrical current from the solar wind produces a pinch effect in the Birkeland current systems. This could result in auroral rings small enough to be perceived in their entirety from a vantage-point on the Earth’s surface. Furthermore, a diagram of the contemporary in- and outgoing currents above the magnetic poles suggests that auroral *half-circles* or *crescents* may also form instead of circles. *Patches* could be produced if the diameters of the cusps were small enough or the width of the auroral bands large enough.

One would perhaps intuitively expect that the aurorae sported by a diminished magnetosphere, less capable of deflecting cosmic rays or incoming charged particles, would not only be more geographically widespread, but also more common and perhaps more vigorous than at stable times. Due to ‘magnetic reconnection’ or partial merger of the magnetic field structure of the solar wind with that of the magnetosphere at their interface, “the palaeoearth would be affected by sub-storm disturbances much more frequently than the present Earth for 2,000 yr” or as long as the excursion lasts [77]. Paradoxically, however, one of Siscoe’s studies indicated the reverse: “The power into the magnetosphere is less for the same solar wind conditions, and auroras are weaker.” [78] Similarly, a French planetologist calculated that a weakening magnetosphere will be less efficient in accelerating incoming particles, so that the aurora will actually dwindle, but a permanent and total airglow, visible only on the nightside of the Earth, will result from the complete absence of a field [79]. During real excursions a remnant of the field will remain, so that some intermediate state may be expected. Moreover, these observations are probably offset by the effect of trapped reservoirs of particles: “The study shows that the upper atmosphere is much more extensively bombarded by magnetosheath and magnetospheric particles than at present. Although the magnetosphere is smaller at these times, recent observations by the Mariner 10 spacecraft in the small magnetosphere of Mercury show that large fluxes of quasitrapped energetic electrons will exist … to precipitate into the atmosphere.” [80]

It will be recalled that Peratt, preceded by Zysman, supported his notion of an 'intense-auroral' column by citing research according to which "oxygen plasma from the Earth's own ionosphere" is injected into the magnetosphere in overwhelming quantities "in magnetically disturbed times, when strong electric currents flow between the Earth and outer space". Other studies confirm that, at times, the magnetosphere is "dominated by oxygen plasma originating in the earth's own atmosphere." [81] During geomagnetic storms, oxygen ions dominate the ring current as well [82]. The "intermittent stream of oxygen atoms from Earth's atmosphere into outer space … under the influence of the aurora" is called the 'auroral wind' and is subject to ongoing investigation [83]. The ion escape is mainly driven by dynamic pressure from the solar wind. Geomagnetic reversals and excursions are recognised as occasions on which the oxygen loss is most pronounced, perhaps by 3 orders of magnitude compared to the present outflow rate [84]. It is thought that space weather events, such as 'corotating interaction regions' (CIRs), coronal mass ejections and other enhancements of the solar wind can drive up the escape rate of oxygen ions significantly further [85].

Because the light of the aurora is caused by the collision of atmospheric oxygen and nitrogen with inflowing electrons, an excessive outflow of oxygen into the Earth's magnetosphere will affect the appearance of the aurora [86], so that – as noted – it might reveal in visible light aspects of the discrete structure of the geomagnetic field which ordinarily subsist in darkness. Applying this knowledge to the study of geomagnetic reversals and excursions instead of the specific models of a single polar column espoused by Zysman and Peratt, the aurora could extend from the familiar north- and south-polar rings to the polar cusps above them, producing the visual effect of two *columns*, filamented and layered, just as it is structured today with the plasma in 'dark mode' instead of 'glow mode'. If the Russian findings mentioned above for the multipolar stage of an excursion were accurate, one would expect the aurora to trace a deep funnel-shaped cusp above the equator, visible for a few hours a day when the inclination angle of the symmetry axis remains small, but continuously when it approximates 90º.

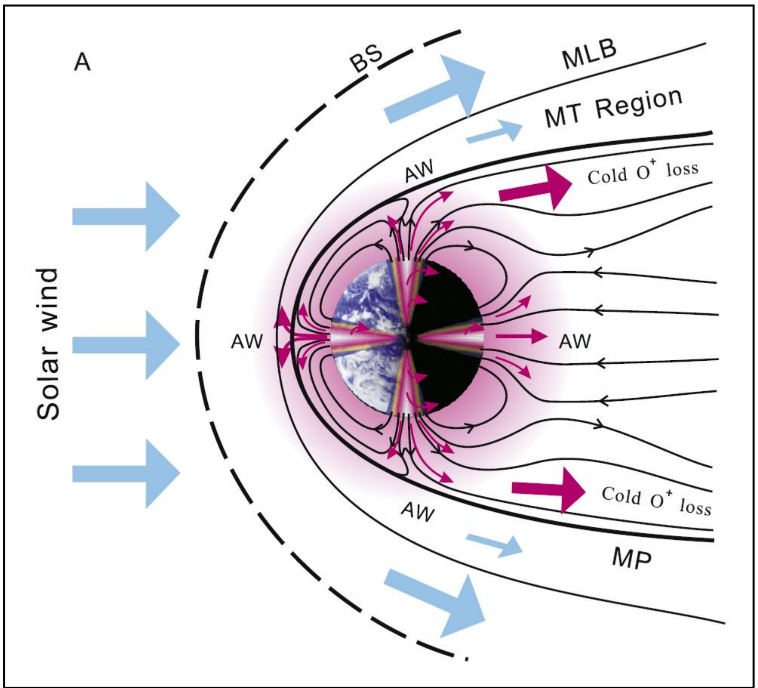

Figure 5: Hypothetical quadrupole field during a geomagnetic reversal showing four auroral zones as regions of oxygen loss and auroral wind (AW), bow shock (BS), magnetopause (MP) and momentum transfer (MT).

In addition to the two cusp regions of the dipole, the magnetospheric funnels formed above the minor poles would presumably also be exposed as visible columns. Looking at the multipolar stage of Glatzmaier & Roberts' computer simulation of a magnetic field reversal, it is possible to perceive the outlines of columns formed over some of the poles above surface level. And a Chinese team modelled a situation in which oxygen ions flow out of the atmosphere through four equidistant "auroral zones" aligned with the geomagnetic quadrupole before populating the entire magnetosphere, except further out towards the tail (figure 5). Although they were not concerned with events within human memory, there is no theoretical reason why their findings should not also apply to geologically recent occasions. Apart from the increased altitudinal profile of the aurora due to atmospheric oxygen loss, discrete magnetospheric structures such as plasmoids and magnetic flux ropes, which normally occur at higher altitudes and invisibly, may also descend and occasionally reveal themselves as they glow visibly.

How would the intense aurora relate to the Earth's diurnal rotation around its axis? If the minor poles are due to 'flux lobes' in the Earth's interior, they ought to corotate with the Earth in its daily cycle. The current auroral ovals at the poles of the dipole field partially participate in the Earth's axial rotation. Each oval "is not related to the rotation of a planet through gravity, but through the precession of the magnetic axis around the geographical axis." [87] The ovals perform an apparent minor revolution around their magnetic poles in the course of a day, such that they reach furthest toward the equator at 'magnetic midnight', about an hour before midnight [88]. How would they respond when magnetic poles are located much further away from the rotational poles than they do today? And what aurorae would the minor poles feature? Although this is uncharted territory in the study of Earth magnetism and pending simulations, a guess can be hazarded. For geomagnetic reversals and excursions, with a combination of multiple drifting and standing poles, three predictions can be made: that the various auroral foci distributed over the globe remain centred on the magnetic poles, which corotate with the Earth; that they exhibit more diurnal variation than the two current auroral ovals do, so that the foci will sometimes be entirely on the nightside and sometimes entirely on the dayside [89]; and that their associated columns, regardless of latitude, would be maintained throughout the diurnal cycle.

Geomagnetic Excursions and *Axes Mundi*

How do Peratt's Column and the search for the original *axes mundi* fit into the theory of geomagnetic excursions? The geomagnetic multipole enables a modification which helps to salvage the essence of Peratt's original hypothesis. As seen, the present polar funnels resemble the outer sheaths of Peratt's hypothetical column, but the correspondence is not precise and the appearance of a single stationary column is irreconcilable with the global visibility required by traditional cosmologies. Disregarding the question of the directionality of current flow, Peratt's Column may be treated as a simplistic approximation of a single auroral column. Within the framework of a geomagnetic excursion, any magnetic pole – whether part of the dipole or the multipole, standing or drifting – may be the focus of its own Peratt Column. The notion of a weak geomagnetic field featuring multiple prominent poles, some wandering and all corotating with the Earth, thus offers ample scope for a revised version of Peratt's ideas. This new model may be conveniently referred to as the 'polar columns' hypothesis.

Illuminated funnels above multiple and moving magnetic poles, including the "extensive and deep tunnel-like cusp" above the equator from the Russian experiment and the four quadrupolar "auroral zones" from the Chinese research, provide an attractive model for mythological *axes mundi*. Geomagnetic excursions apparently involve a chain of events that explains the worldwide visibility of one or more such columns: the north and south magnetic poles with their auroral rings, patches and columns wander equatorward and back and are temporarily superseded by multiple – perhaps four or five – other poles which may sport similar features. Thus, observers in many different parts of world will at one time or other have an opportunity to view a number of resplendent circles and columns, ranging from only one to as many as four or five.

Those able to perceive only one column could naturally interpret this towering feature in the natural environment as the 'middle' of the world, whether it appeared close to their zenith or on their horizon. Those who reported two or more columns – perhaps a sizeable minority – may have observed them at opposite ends of the horizon. And those who happened to live directly beneath a column could have concluded that it encompassed the entire world instead of occupying the middle or boundary; a view directly up into the column might have suggested a circular 'ocean', 'snake' or 'wall' at the base of the visible cosmos.

The majority of traditions, formulated from the perspective of witnesses on the surface of the Earth, present the *axes mundi* as stationary objects. This requires, as one would expect, that the poles corotated with the Earth in its diurnal cycle. Most locations on the Earth would have been provided with a fixed perspective on at least one plasma sheath for as long as the pole in question remained in one place. As the auroral rings, half-circles or patches displayed a greater diurnal variation than experienced today, the base of each column may have appeared to terrestrial observers to gently sway or rotate in the course of a day. The column, if not a disc surrounding it, may also have appeared to spin on its axis. Such dynamic behaviour, however, would not detract from the overall apparent immobility of each column.

A stationary position to a human observer is natural for magnetic poles belonging to the standing part of the geomagnetic field, but also places a constraint on the rapidity with which drifting poles and their attendant aurorae may have moved in the course of excursions. Supposing that a column would move at a constant rate of 0.08º of latitude or 8.88 km on the surface per year, equalling 4º or 444 km in a human lifespan of 50 years, a complete migration to the equator and back would last 2250 years. This figure corresponds to the upper limit of the estimated timescale of a 'classic' excursion, ranging from anything between perhaps 200 to 2000 years. When viewed at a considerable distance, the displacement might escape the attention of an individual observer. At the much higher historical rates of 0.18º-0.7º of latitude per year calculated for the westward or eastward drift of minor poles [90], which need not be constant at all, a human being would observe a drift of 9º-35º or 999-3885 km on the surface in 50 years. This might still just be about slow enough to sustain an impression of near-fixation should one of these drifting poles have hosted an intense aurora viewed from far away. Applying the rate of 0.5º of latitude per year recently determined for the Laschamp excursion (40,000 BP), as cited above, someone living for 50 years would see the features move over the considerable distance of 25º of latitude or 2775 km on the surface. Minor poles of both types may therefore have contributed to the mythological image of stationary columns. Bearing in mind that the migration rate of magnetic poles varies and traditions of visibly wandering *axes mundi* do exist, especially in association with the terminal stages of the sequence, it may be assumed that the event responsible for *axis mundi* mythology lasted decades to 1 or 2 millennia, mostly involving polar migrations that would be rapid on a geological timescale, but almost imperceptible to the many contemporary generations of human observers. Well exceeding 4 or 5 human generations, this would have been long enough to instil the memory of a veritable era – an 'age of the gods' or 'of creation' – but with an upper limit short enough to guarantee that human beings could perceive and pass on the entire series of events as an integrated narrative whole.

Today’s auroral ovals do not behave independently of each other, but act instantaneously in almost identical ways in response to the same external impulses and the same laws of physics. Likewise, the circles and columns manifesting above each magnetic pole during an excursion may have shared a similar morphology and have evolved synchronously, at least in general outline. The erstwhile appearance of a number of columns as opposed to a single column provides a promising tool to account for regional variation – in the form of differences in the geographic distribution of individual mythical motifs. For example, when some cultures report that the column was composed of 9 upper tiers, others of 13, and others of none, a potential solution is that three different columns were described, though all were part of the same overarching phenomenon – a geomagnetic excursion. Consequently, differences between traditions, including different patterns of geographic distribution, may prove indispensable in unravelling details of the physical background to creation lore.

The equatorward movement of the north and south magnetic poles and the temporary prevalence of the multipolar field thus hold the unique potential to explain the most salient recurrent themes in the mythology of *axes mundi*. Unlike any rival models involving a single column, the novel hypothesis of a geomagnetic excursion offers a straightforward and elegant solution to the paradoxical requirements of columns that are multiple while often appearing to be singular and that move while often seeming stationary to human eye-witnesses. It also resolves the conundrum of global visibility of a phenomenon that is otherwise largely confined to the circumpolar regions. No other known condition than a temporary enhancement of the multipole field could satisfy the criteria of augmented levels of auroral activity viewed above magnetic poles across so many latitudes. Radical weakening of the geomagnetic field emerges as the only key to penetrating the baffling body of *axis mundi* traditions.

Various other aspects of the global creation myth appear to fall into place. In addition to the rings and columns, the aurora could have illuminated parts of the finely threaded filamentary fabric surrounding magnetic poles, especially magnetic ropes, feeding into such mythological themes as a cosmic maze, a thicket and a spider web, of which the *axes mundi* represent threads. Arcs may have appeared in visible light as well, as they certainly abound in the structure of the geomagnetic field, especially in the vicinity of the minor poles, and the aurora simply follows the contours of this field. Traces of a transition from rings to hollow ionospheric sheaths may be detected in traditions of an enclosure – such as a cosmogonic ‘egg’, ‘womb’, ‘dragon’ or ‘chest’ – opening to give rise to a rapidly-growing form of *axis mundi*, often along with an outflow of light, ‘wind’, ‘water’ or mythical beings (§§46, 48-51, 56-60).

Furthermore, the rise and fall of *axes mundi* is intricately tied to the theme of a ‘low sky’ or a ‘collapsed sky’ which is eventually separated from the Earth. If even the mundane aurora occasionally descends to sufficiently low heights to suggest a ‘low sky’, the impression would certainly be strengthened if the effect acquired a global distribution. Moreover, on a weak geomagnetic field the solar wind – more strongly felt than usually – would drive the magnetopause down onto the sunward side of the ionosphere, compressing the entire atmosphere inside. In combination with induced changes in the chemistry of the atmosphere, this might cause the ionosphere to shrink and transform it and perhaps other regions of the atmosphere into a dusty plasma with increased electromagnetic activity – aurorae, megalightning, lightning. All this could leave people with the impression of an uncomfortably low-hanging and oppressive ‘sky’.

Just as temporary compression of the Earth’s ionosphere imbues the traditional theme of an originally ‘low sky’ with meaning, so the eventual recovery of the magnetosphere – its expansion and the restoration of the dipole field – offers an appealing model for the cross-cultural mythological nexus of the ‘separation of heaven and earth’ or the ‘elevation of the sky’. *Axes mundi* played an instrumental rôle in this process. At first, relatively short hollow pillars between the lower and upper boundaries of the compact ionosphere – the mesopause and the ionopause, respectively – would be seen ‘attempting to push up the sky’, but failing to lengthen as the ionosphere was restrained by the magnetopause. As the latter commenced to recede, eventually detaching itself from the ionosphere, the columns would appear to elongate. Human witnesses could have widely interpreted this process as the ‘lifting up of the sky’ by one, two or even more magnificent columns as they waxed. Auroral columns formed above two magnetic poles and seen from one location may be connected to the mythological theme of the raising of the sky by a double *axis mundi*, described as two trees or deities, often one in the north and the other in the south, or one in the west and the other in the east. This expansion might be expected to occur following the transitional multipolar stage of the excursion, as the dipole field recovers and directs the columns associated with the north and south magnetic poles back towards the Arctic and Antarctic regions.

The termination of the visible columns seems to have been sudden in most cases, mythologised as the fateful disconnection of *axes mundi*. From the perspective of human witnesses, this would have completed the ‘lifting up of the sky’. As seen, the latter process was sometimes presented in two to four stages, including the growth of the column itself (§§39-63) and its severance (§339). These can be related to respectively the short column, the expanding column, the severance of the column and the cutting of other ‘strings and strands’ attached to the column.

The hollow columns associated with the north and south magnetic poles would not really have vanished, but survived until today, linking the ionosphere and the magnetopause along the spreading field-aligned currents, albeit they reverted to 'dark mode', invisible to the human eye. The familiar circumpolar rings continued to exhibit auroral displays, but with the loss of highly discrete filamentation and almost exclusively at high latitudes.

In part III of this article, a possible role for the Sun in the dramatic events in the 'age of myth' will be considered.

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87. J. Lilensten, M. Barthélemy, C. Simon *et al.*, 'The Planeterrella, a Pedagogic Experiment in Planetology and Plasma Physics', *Acta Geophysica* 57(1), 2009, p. 234; *cf.* Jean Lilensten, pers. comm., 17-11-2013.
88. N. Bone, *The Aurora; Sun-Earth Interactions*, John Wiley & Sons, Chichester, 19962, p. 82.
89. *Cf.* Peter Olson, pers. comm., 24-1-2013; Gary Glatzmaier, pers. comm., 11-5-2012; 30-1-2013; Jean Lilensten, pers. comm., 31-5-2013; George Siscoe, pers. comm., 14-5-2012. Compare T. Saito *et al., op. cit.* [48].
90. W. Lowrie, *op. cit.* [3], p. 314; L. J. Pesonen *et al., op. cit.* [3], p. 65.

Figures: sources

1. G. L. Siscoe & N. U. Crooker, *op. cit.* [14], p. 3 Fig. 2.
2. W. Lowrie, *op. cit.* [3], p. 313 Fig. 5. 35 bottom.
3. G. L. Siscoe & N. U. Crooker, *op. cit.* [14], p. 6 Fig. 5c.
4. G. A. Glatzmaier, 'The Geodynamo' (no date), at www.es.ucsc.edu/~glatz/field.html, Fig. 3 centre. © Gary A. Glatzmaier.
5. Y. Wei *et al., op. cit.* [51], p. 96 Fig. 2 (A).

Reflections on the News

Dinosaur Tales

Palaeontologists in Argentina have announced the discovery, in March 2016 (http://phys.org//print375851809.html), of a major Jurassic fossil bed in Patagonia – four years after it was initially discovered by a farmer. The site spans 60,000 square km and has an amazing diversity of fossils. Most of them have been recently exposed by erosion and can be picked up from the surface or prized out with a trowel. This is why it was kept secret. The Jurassic landscape has been laid bare and consisted of thermal waters, lakes and stream, and lots of vegetation. The fossils, it is said, were preserved 'almost immediately' – within the course of a single day. You can even see worm holes, fungi spores and cyanobacteria in the soil. The site lies along a mountain range, the Deseado Massif, and is fairly remote.

A student at Imperial College in London, Alfio Alessandro Chiarenza, came upon a fossil bone in a drawer at the Museum of Geology and Palaeontology in Palermo, originally excavated from a sedimentary outcrop in Morocco rich in Jurassic remains (*PeerJ* 29 February 2016, https://peerj.com/articles/1754/). He was impressed by the size of the thigh bone. It belonged to an abelisaurus, a predatory carnivore with small front limbs and powerful muscular rear limbs. It is calculated that abelisaurus was 9 m in length and weighed one-and-a-half tons. It was found in the vicinity of other species of dinosaur. Scientists could not work out why so many different carnivores were living in the same neighbourhood but the young researchers cracked that one by pointing out the changing geology within the sedimentary deposit was heaped all together in a single dump, known colloquially as 'Stromer's Riddle', with origins in different places.

The Chinese are also excavating lots of dinosaurs at the moment in another huge deposit. The idea of swimming dinosaurs became quite popular in the literature after an initial suggestion, an idea derived from footprints left behind in soft sediments such as sand, silt and mud, which tend to show just the front or rear footfalls but not both front and rear at the same time. It became commonplace, when looking at dinosaur footprints, to infer they were swimming or wading with set of feet on the ground and the other doing a sort of doggy paddle. The Chinese, in a down-to-earth rethink are saying that dinosaur footprints reflect where the weight of the animal was greatest – on the rear (but sometimes on the front feet) and the lighter touch of the opposite feet did not make a deep indentation (*Scientific Reports*, February 2016, http://www.nature.com/articles/srep21138).

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