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External forcing of the geomagnetic field? Implications for the cosmic ray flux—climate variability

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Abstract

Data on the relation of past climate variations and changes in the geomagnetic field can contribute to the research on a cosmic ray–climate link. This paper presents a synthesis of geological and astrophysical results about the link of magnetic field variations and Earth's climate and external forcing. On millennial timescales, geomagnetic intensity lows are apparently in phase with times of low solar magnetic activity and climate cooling. Reconstructions of quaternary continental climate systems indicate colder and dryer conditions during and after geomagnetic reversals. In the Milankovitch frequency band geomagnetic field reversals can occur in conjunction with minima in the carbonate content related to the 100 ka eccentricity cycle of the Earth's orbit. A quasi 100 ka cyclicity (in phase with orbital eccentricity) is discussed in the literature for both geomagnetic intensity and solar magnetic activity. On mega-cycle periods external forcing seems to play a role in the appearance of superchrons of the geomagnetic field. When applying current spiral arm models superchrons developed during times when the solar system was located between spiral arms. This suggests that the galactic environment may force the geomagnetic field to switch from its reversing mode into superchron stages probably via modulations of the Sun. Interestingly, there is a link to the structuring of magnetic fields in our galaxy. While the galactic magnetic fields between spiral arms are homogenous, the passage of the solar system through turbulent magnetic fields along the spiral arms parallels high geomagnetic reversal rates. Occurring in conjunction with a low intrinsic cosmic ray flux the superchrons probably lowered the cosmic ray flux at Earth even further. This may also have played a role in the evolution of life on Earth and the timing of some mass extinction events.

Keywords: Geomagnetic reversals; Superchrons; Orbital forcing; Solar activity; Cosmic ray flux; Spiral arms; Carbonate cycles; Palaeoclimatic change

1. Introduction

Space weather influences the climate on Earth by variations in the cosmic ray flux (CRF). In order to improve our knowledge of this kind of external forcing, multi-disciplinary syntheses of astrophysical, geophysical and geological data are crucial. The investigation of phenomena in the geological record which are related to CRF variations can play a key role for the understanding of the processes of the cosmic ray–climate link which are still controversially discussed. This study aims at stimulating such synthetic research between sciences by discussing the role of magnetic fields in shaping Earth's climate. Three magnetic fields are known so far to have the potential to cause variations in the CRF: the galactic magnetic fields which control the distribution of cosmic rays in the Milky Way (Binney and Tremaine, 1988; Shaviv, 2002, 2003), the interplanetary magnetic field produced by the Sun (Hoyt and Schatten, 1997; van Geel et al., 1999; Beer et al., 2000; Wagner et al., 2001), and the Earth's magnetic field (van Geel et al., 1999; Wagner et al., 2000a, b).

One of the most important issues in the research on a cosmic ray–climate connection is the search for the physical mechanisms. The way galactic and solar cosmic rays affect the cloud formation by tropospheric ion

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production comprises an area of intensive research (e.g. Ney, 1959; Friis-Christensen and Lassen, 1991; Svensmark and Friis-Christensen, 1997; Tinsley, 1996, 1997, 2000; Svensmark, 1998; Marsh and Svensmark, 2000; Todd and Kniveton, 2001; Solanki, 2002). To which extent do the magnetic fields of the galaxy, Sun, and Earth contribute to the modulation of the CRF? Is the cloud formation significantly influenced by changes in the CRF? Is climate cooling an effect of increased CRF? In order to evaluate the impact of cosmic rays on climate we need to investigate the system Earth during various stages of the different magnetic fields which operate in the system. Both the interplanetary magnetic field and the geomagnetic field modulate the CRF in the vicinity of our planet. The most reliable information can be obtained from the geomagnetic field of which the polarity reversal history preserved in the rocks is well-known and dated for the last 320 Ma (Eide and Torsvik, 1996; Jacobs, 2001). Geomagnetic reversals represent extrema when the geomagnetic field strength reached a minimum, i.e. the geomagnetic contribution in modulating cosmic ray-forced atmospheric processes was low. Examples for a link between geomagnetic variations and climate change are discussed in the first part of the present paper.

Besides the potential relation of geomagnetic reversals and climate change, external forcing also seems to play a significant role in controlling climate modes on longer time scales. Calculations of the dynamics of our 4-arm spiral galaxy (Vallée, 2002) indicate that the solar system has an orbital position which takes it around the galactic center in about 250 Ma with a rotational speed which is about 10 km/s/kpc faster than the 4 spiral arms (Shaviv, 2002, 2003 and references therein) which are commonly believed to be density waves (Binney and Tremaine, 1988). Recent research on the link of galactic dynamics and Earth history suggests that long-term climate variability may have been forced considerably by intrinsic variations in galactic cosmic radiation. A model of Shaviv (2002, 2003) and Shaviv and Veizer (2003) offers an attractive way of triggering ice age epochs (Frakes et al., 1992) by variations in the CRF. This flux is higher within the galaxy's spiral arms which are cyclically passed by the solar system during its galactic revolution. Passages of spiral arms were modelled very differently and are currently thought to have happened once every 143 Ma years according to Shaviv (2002, 2003) or with a $\sim$180 Ma year periodicity according to Leitch and Vasisht (1998). The spiral arms are characterised by a higher density of stars, abundant interstellar clouds and strong magnetic fields. These magnetic fields confine cosmic radiation to the spiral arm regions. The CRF is increased within spiral arms mainly because of abundant star formation and supernovae in these regions of the galaxy. Further evidence is needed to check the hypothesis of periodic spiral arm passages, and to evaluate the effects of such galactic forcing on the system Earth. The long-term alternation of the geomagnetic field between its reversing and non-reversing (superchron) state might represent such evidence and is discussed in the second part of the present paper.

2. Data

This study represents a synthesis based on a review of data from the literature. In the first part of the paper the few studies available so far on a geomagnetic reversal-climate relation in the Quaternary are summarised and interpreted. Tertiary sedimentary cycles from the lower Danian section Bjala, Bulgaria (Preisinger et al., 2002) are discussed. The compilation of data on the geomagnetic history, galactic motion of the solar system and geological characteristics of the Ordovician through Recent (Fig. 1) comprises phenomena which have previously only partly been compared regarding their temporal distribution and causal links. Palaeomagnetic data (panel A) are based on the compilation and calculations of Eide and Torsvik (1996). The occurrences of large igneous provinces were summarised by Wignall (2001). Data on the meteorite cosmic ray exposure (panel B) and the galactic spiral arm crossings (panel C) are based on the works of Voshage and Feldmann (1979) and Shaviv (2002, 2003). A second model for the spiral arm passages of the solar system (Leitch and Vasisht, 1998) was used to evaluate the time uncertainties induced by modelling differences. The sequences (panel D) of transgression/regression on the North American craton (Sloss, 1963) and the Russian platform (Sloss, 1972) are chosen to indicate significant global changes in sedimentary deposition which have been previously shown by Larson (1991) to correlate with superchrons. Further sedimentary data comprise the accumulation of oil, coal and gas (panel I; after Larson, 1991) and the deposition of black shales (panel J; Frakes et al., 1992). The data in panels G and H on the climate modes are based on the comprehensive overview of Frakes et al. (1992) modified according to more recent updates (http://www.scotese.com; Frakes, 1999). The compilation of panels E and F must be regarded as preliminary due to scarcity of data on the length of day perturbations (Machetel and Thomassot, 2002), and true polar wander (Van der Voo, 1994; Prévot et al., 2000; Evans, 2003).

Of course, when relating these phenomena to each other one must be aware of the low resolution of time in the range of millions of years with tolerance ranges and lag times of the same order of magnitude.

3. Discussion

3.1. Cyclic geomagnetic, climatic, and sedimentary variability?

To verify the role of the geomagnetic field in climate forcing it is essential to find unequivocal geological hints. If low geodynamo intensities during a reversal were

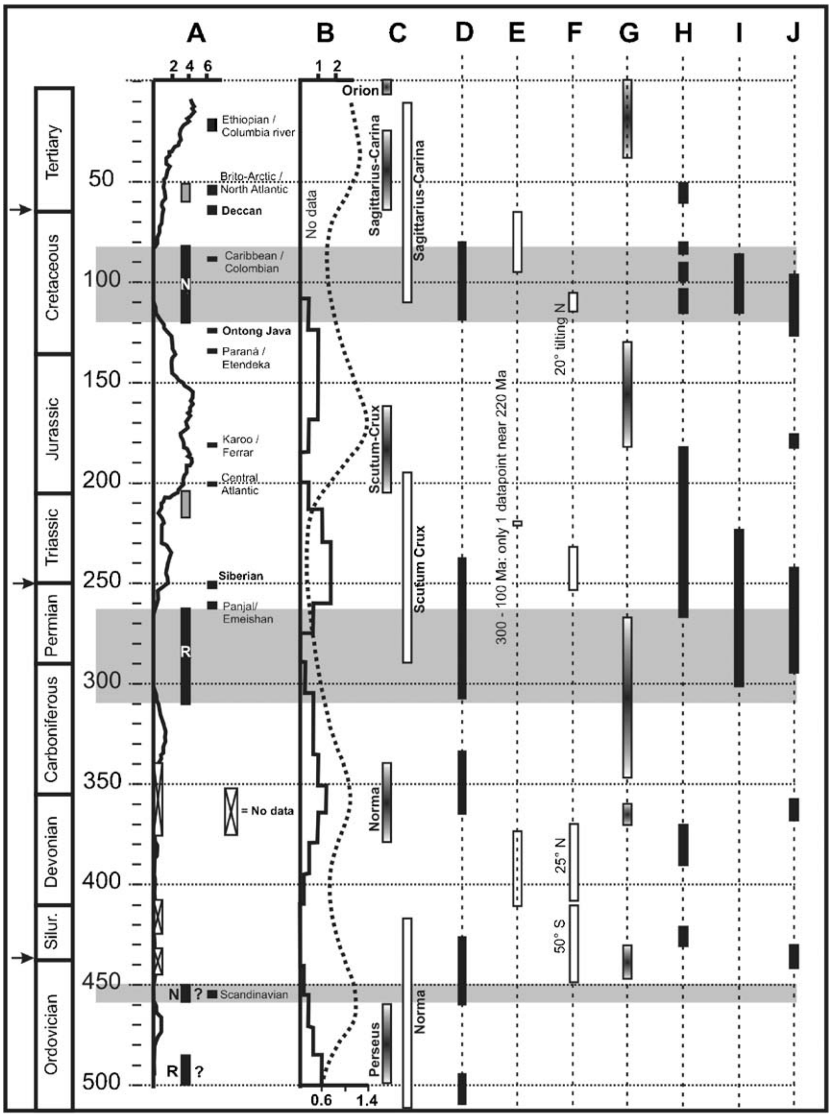

Fig. 1. Compilation of data on the geomagnetic history, galactic motion of the solar system and geological characteristics of the Ordovician through Recent. Arrows on the time scale mark mass extinction events. A: Geomagnetic reversal rate (per Ma), superchrons (black bars in A; and shaded grey from A to J), R = reversed polarity, N = normal polarity; and phases of very long-duration chrons (grey bars) after Eide and Torsvik (1996); Large igneous provinces with names after Wignall (2001). B: CR diffusion model data from Shaviv (2003). Histogram (1-2-1 averaged; $\langle N \rangle$/bin): exposure age clustering of iron meteorites with error smaller than 100 Ma based on Voshage and Feldmann (1979). Dotted curve: cosmic ray flux calculated by statistical analysis of exposure ages (CRF/CRF_{today} values given at bottom of the diagram). Note the phase relationship of curves A and B. C: Galactic spiral arm crossings; left: after Shaviv (2002), right after Leitch and Vasisht (1998). Note the differences in crossing times which lead to very different interpretations of the relations between galactic motion and Earth history. D: Sequences of transgression/regression on the North American craton (Sloss, 1963) and the Russian platform (Sloss, 1972)-illustrated are phases of deposition, i.e. probably transgressions during warm climate (note contradiction to panel G particularly in the late Carboniferous). E: Length of the day shortenings after Machetel and Thomassot (2002). Note the occurrence of such periods prior to the crossing of a spiral arm. F: True polar wander according to Van der Voo (1994), Prévot et al. (2000), Evans (2003). Numbers indicated the latitudinal shift of the Earth's axis of rotation. G: Cold climate modes after Frakes et al. (1992). Note that these general climate states apparently lag after spiral arm crossings (B). H: Times of particularly warm palaeoclimate (Frakes et al., 1992; Frakes, 1999). I: Coal, oil and gas deposition from Larson (1991) showing a strong relation to the superchrons. Biological production was probably favoured by the related low CRF (B) and/or the superplume activity. J: Black shales after Frakes et al. (1992). Note occurrence of black shales independent from the palaeoclimate mode (G, H).

related to climate change this should have been recorded in the sediment. Recently, St-Onge et al. (2003) showed a millennial-scale geomagnetic forcing of ^{10}Be and ^{14}C production rates which have been solely attributed to solar activity in the past. A tentative positive correlation seems to exist between this geomagnetic field intensity record and solar magnetic activity: Low solar activity was related to high cosmogenic isotope production and dryer conditions of the monsoon (Neff et al., 2001); this record corresponds with cooler ice-bearing surface waters in high northern North Atlantic latitudes (Bond et al., 2001). It appears from these examples that both geomagnetic and solar variability force climate cooling on a phase-linked periodicity of 1000–1500 years. Does the geomagnetic field even react to the solar magnetic cycle through some yet unknown coupling?

Examples for a relation between geomagnetic reversals and cooling were found by Liu et al. (1985) studying the deposits of loess at the Chinese plateau shortly following the Gauss-Matuyama geomagnetic reversal. Nabel et al. (2000) recorded the start of cooler and dryer climate conditions in the Pampean area of Argentina following the Matuyama–Brunhes chrons boundary. Worm (1997) found that short-term events of weak geomagnetic field strength and the Matuyama–Brunhes chrons boundary are clustered along each of the decreasing parts of the late Quaternary temperature curve (delta ^{18}O stable isotope record). He concluded that probably changes in the ice volume influenced the geodynamo. Given the cosmic ray–cloud relation which was found to be existing by a number of studies (e.g. Svensmark and Friis-Christensen, 1997; Svensmark, 1998; Tinsley et al., 1989), although still controversially discussed (Pallé and Butler, 2002; Laut, 2003), the record of Worm (1997) could also reflect an influence of the geomagnetic field on Earth's climate. This relation suggests increased cloud nucleation and cosmogenic isotope production during times of a higher CRF predominantly due to lower shielding by the interplanetary magnetic field (solar wind). However, also geomagnetic intensity lows are linked to increased CRF (van Geel et al., 1999; Wagner et al., 2000a, b). The relation found by Worm (1997) points at geomagnetic variability being linked to the quasi 100 ka cycle of ice ages through the late Quaternary. This period is in phase with the orbital eccentricity cycle commonly thought to be the ice age trigger. Alternatively, Sharma (2002) suggested recently that there is also a ~ 100 ka cycle of solar magnetic activity at the same phase. While there is no reasonable physical explanation, so far, to link magnetic and orbital cycles, the phase relationship is interesting and again suggestive of a link between the geomagnetic and solar magnetic field at this time scale. However, the recent increase in solar activity over the past 120 years (Hoyt and Schatten, 1997 and references therein) parallel to a decreasing geomagnetic dipole (Olson, 2002) opposes the above relation. Clearly, further research is needed to explain these interrelations.

A very interesting data-set showing a clear relation between palaeomagnetic field reversals and carbonate content of Palaeogene limestones was published by Preisinger et al. (2002) without, however, discussing implications for the geomagnetic field–climate link. In this study, a 1.5 Ma duration section of chalk-marl Milankovitch precession cycles contains 4 geomagnetic reversals each of which is related to an extreme minimum in carbonate content. This indicates that the carbon cycle was significantly disturbed parallel to the geomagnetic reversals. The data clearly show a bundling of precessional cycles into sets of about 5 which is the typical expression of the interference of the 100 ka eccentricity cycle of the Earth orbit and the 21 ka precessional cycle (e.g. Schwarzacher, 1994; House, 1995; Wendler et al., 2002). Interestingly, bundle boundaries fall together with the geomagnetic reversals in all 4 cases. This suggests that the spacing of reversals, if geomagnetic activity follows a quasi-cyclicity, is phase-linked to the ~ 100 ka eccentricity cycle. This observation could shed more light on the discussion whether or not a quasi-periodic 100 ka signal (in phase with the orbital eccentricity cycle) exists in geomagnetic palaeointensity and inclination variations of the past 2.25 Ma (Negi et al., 1993; Yokoyama and Yamazaki, 2000; Yamazaki and Oda, 2002) which is controversially discussed regarding its periodicity (e.g. Sato et al., 1998; Guyodo and Valet, 1999). Studying the Early Cretaceous geomagnetic behaviour, Iorio et al. (1998) identified a 100 ka cycle in the intensity of oceanic magnetic anomalies.

If geomagnetic variability is connected with climate change more than previously thought, then we may ask: what happened during times when the magnetic field stopped reversing its polarity for tens of millions of years, the so-called superchrons? Evidence is growing that during superchrons the geomagnetic field was strong (Larson and Olson, 1991; Glatzmaier et al., 1999; Tarduno et al., 2001; Kruiver et al., 2002) although this is still a matter of debate (Prévot et al., 1990; Pick and Tauxe, 1993). If stronger it was more effective at modulating external climate forcing (affecting tropospheric ionisation). According to the above-mentioned examples, ceasing of reversals would have: lowered the average CRF, prevented cooling events, changed long-term atmospheric circulation, and could have contributed to global warming. However, before conclusions can be drawn about these effects, the amplitude of secular geomagnetic intensity variations which continued through e.g. the Kiaman superchron (Kruiver et al., 2002) must be known.

3.2. *The long-term behaviour of the geomagnetic field*

Palaeomagnetic data are continuous and reliable as far back in time as the Carboniferous (Fig. 1). The well-established long Kiaman reversed superchron (312–264 Ma) and the Cretaceous normal polarity superchron (120–84 Ma) represent significant non-reversal time spans. Superchrons were shown to be concomitant with world-wide geophysical, tectonic and sedimentary events, such as superplume activity, oil, gas and coal deposition, and large-scale periods of sedimentation at the North American craton and Russian platform (Larson, 1991; Larson and Olson, 1991; illustrated in Fig. 1 D, I, J). The phases of platform sedimentation (panel D) are mainly due to sea level highstands and occur in conjunction with the superchrons (panel A). They suggest generally warmer paleoclimates.

Going further back in Earth history the data become scarce and get larger errors. A few studies point at a period of long normal polarity of the geomagnetic field in the upper Ordovician between 465 and 450 Ma (Eide and Torsvik, 1996) and a reversed polarity superchron probably during the lower to middle Ordovician (Johnson et al., 1995; Pavlov and Gallet, 2001). The time span between the Ordovician and Kiaman superchron epochs was about 140 Ma, and the Cretaceous superchron follows the Kiaman superchron after 140 Ma (180 Ma between mid-points of the superchrons). Although three such periods are not enough to derive a cyclicity it is striking that they are almost equally spaced. A periodicity of superchrons was previously postulated by Johnson et al. (1995). Fig. 1 (arrows) also shows the positions of the Ordovician/Silurian (O/S), Permian/Triassic (P/T) and Cretaceous/Tertiary (K/T) mass extinctions. Between the O/S and P/T mass extinctions 188 Ma years passed while the P/T and K/T event are spaced by 185 Ma. The mass extinction events follow the superchrons with a lag time of 15–20 Ma. The relation between superchron epochs and mass extinctions merits further investigation and will be discussed in a separate paper.

3.3. *Relation between superchrons and the galaxy's spiral structure*

The geomagnetic field structure, its intensity variations and even polarity reversals can be modelled (e.g. Glatzmaier and Roberts, 1995; Glatzmaier et al., 1999) without applying external forcing. The geodynamo can be regarded a self-organising system (Jonkers, 2003). In this case an external force is not needed to explain an oscillation of the system. Our current knowledge on the geodynamo–Earth mantle relation suggests that changes of the magnetic field are generated in the Earth's interior and stopping of reversals of the geodynamo is thought to be modulated by mantle plume activity (Larson and Olson, 1991) connected with peak convective activity of the core of the Earth. The superplume model also explains the occurrence of continental and oceanic large igneous provinces (LIP) parallel with superchrons (Larson and Olson, 1991; Larson, 1991). Wignall (2001) summarised the occurrences of large igneous provinces, the timing of which is plotted in Fig. 1A. It is important to note that several large continental and oceanic igneous events characterise the time around the Cretaceous superchron indicating long superplume activity before, throughout, and following this period of time (see also Larson, 1991). However, the above relation slightly weakens as LIP's also occurred during times of frequent geomagnetic reversals.

In addition to the above-mentioned superchron-related processes in the Earth's interior, a link between the reversal behaviour and the structure of the Milky Way galaxy can be noted from Fig. 1, suggesting that external forcing plays a role in modulating the geomagnetic field. The idea of a galactic influence on the geomagnetic field has been previously discussed by Crain et al. (1969) and Negi and Tiwari (1983) and is given an important aspect here. It seems that geomagnetic reversals occur frequently with the passages through a spiral arm while, oppositely, Earth experienced superchrons when the solar system was positioned between spiral arms. It should, however, be noted from Fig. 1 that large uncertainties occur when applying different models for the spiral arm pattern speed. The two models shown are roughly comparable in their timing of the solar system's encounter with the Sagittarius–Carina spiral arm although the passage durations are modelled very differently. The passage through the Scutum-Crux arm already differs considerably and the disagreement is extreme for spiral arm passages older than 300 Ma. The modelling differences arise from a lower spiral arm pattern speed in the Leitch and Vasisht (1998) model causing a passage timing of the Scutum-Crux spiral arm about 60 Ma earlier than in the Shaviv (2002, 2003) model. In their concept of a galactic habitable zone, Gonzalez et al. (2001) even doubt that spiral arm encounters happen at all. This concept is based on calculations in which the solar system is placed close to the co-rotation zone of the galaxy (Mishurov and Zenina, 1999). If true, the solar system stays out of the spiral arms, travelling at an orbital speed about equal to the spiral arm pattern speed. However, according to the summary by Shaviv (2002, 2003) of observational and model results on the Milky Way most data suggest that the radius of the solar system orbit is smaller than the co-rotation radius.

The model differences illustrated in Fig. 1 imply different relations between spiral arm passages and superchrons. While superchrons are placed right between the passages modelled by Shaviv (2002, 2003), they seem to occur when the solar system enters a spiral arm in the model of Leitch and Vasisht (1998). The Shaviv (2002, 2003) model is supported by cosmic ray exposure ages of meteorites (Voshage and Feldmann, 1979) as a proxy which is independent from modelling. Therefore, this model is favoured in the present paper. Attempts have been made to put the galactic motion of the solar system into context with grand geological episodes such as the ice age epochs (Shaviv, 2002, 2003). More such relations would support the theory that the solar system experienced spiral arm passages which in turn can influence the system Earth.

3.4. *Galactic influence on the Earth's magnetic field?*

The geomagnetic reversal rate (Fig. 1A) varies in phase with the CRF (Fig. 1B). The Kiaman and Cretaceous superchrons occurred during times of a low CRF. Changes in the cosmic ray exposure of meteorites can reflect the intrinsic galactic CRF fluctuation caused by the spiral arm passages and/or changes in the strength of the interplanetary magnetic field (shielding by the heliosphere). Thus, if it is not a mere coincidence, the reversal rate of our planet is correlated with externally forced CRF changes. This consequently would mean that the geomagnetic field is not exclusively internally driven. That the geodynamo responds to external forcing has been previously discussed in a different context regarding an influence of lunar-solar tidal forces on the geomagnetic field (Greff-Lefftz and Legros, 1999).

Could the observed magnetic field behaviour result from variations in the Earth's rotation caused by some kind of tidal forces from the galaxy? When a star experiences spiral arm passages it accelerates on the way into the arm and slows down within the arm. Regarding the solar system, changes in travel speed and tidal forces are not well studied concerning their influence on the solar system bodies and lack exact physical explanation. Acceleration of the solar system on its way into a spiral arm is assumed to be minute compared with orbital eccentricity acceleration so an effect seems unlikely. Nevertheless, two phenomena of the geological record possibly related to the galactic motion are worth mentioning (Fig. 1): During passage of the solar system through the inter-arm areas (as calculated by the Shaviv (2002)-model) true polar wander took place shifting the whole geoid relative to its axis of rotation (Fig. 1F). The scarce data which are available so far indicate that these periods were followed by phases of shortening in the length of day (Machetel and Thomassot, 2002), i.e. an acceleration of the Earth's rotational speed during the 30 Ma before entering the Norma and Sagittarius-Carina spiral arms (Fig. 1E). As an analog, observable secular changes in the rotational speed of our planet have been shown to influence the geomagnetic field, and interact with atmospheric currents such as the strength of the jet stream and ocean currents (Gross, 2001; Moerner et al., 2003). Future research is needed to evaluate whether long-term rotational variations by galactic tidal forces are possible, and had the potential to shape the geomagnetic reversal history.

Besides variations in the galactic tide, the magnetic fields of the galaxy also differ between spiral arms and the inter-arm areas. Beck (2002) found that strong, turbulent magnetic fields are concentrated along the spiral arms of a galaxy. Oppositely, the inter-arm parts of galaxies were found to be characterised by homogenous rather than turbulent magnetic fields (Beck, 2002). Thus, when entering a spiral arm such turbulent magnetic fields could affect the solar and planetary magnetic fields. It might be that such interaction of the magnetic fields is a motor which is capable of driving the geodynamo into its reversing mode. Could, on the other hand side, the homogenous galactic magnetic fields force Earth's magnetic field to stop reversing its direction by contributing a uniform seed-field to the variable geodynamo? If so, the superchrons would occur while the solar system is positioned in the space between spiral arms and, conversely, reversal rate should increase during the passage of a spiral arm. Fig. 1C shows that this is in fact the case if applying the spiral arm-model of Shaviv (2002). Even in the scarce Ordovician palaeomagnetic data an increase in reversal rate in conjunction with the Perseus arm crossing can be noted. The hypothesis put forward here is supported by the finding that the galactic magnetic fields of the Milky Way seem to reverse from one inter-arm area to the next (Han et al., 1999) which is in line with the polarity reversal between the Kiaman-Reversed and the Cretaceous Normal Superchron.

Vigorous outer-core convection and mantle plumes are considered to be a prerequisite of a superchron (e.g. Larson and Olson, 1991; Tarduno et al., 2001; Kruiver et al., 2002). In a physical explanation of external magnetic field forcing, yet to be established, the importance of these processes in the Earth's interior will have to be considered. While the relation between the Milky Way magnetic structure and the terrestrial magnetic record is striking the two most critical aspects to be evaluated regarding the causality of this relation are the difference in strength of the two fields, and the fact that normally the heliosphere (about 50 μG near Earth, Scherer et al., 2001) hinders a coupling of the geomagnetic field with the galactic magnetic environment. The local galactic magnetic field is only in the range of 4–15 μG (Beck, 2001) while Earth's magnetic field intensity is about 3×10^5 μG. According to modelling, the geomagnetic dipole strength decreases to about 10% and multipole components remain during reversal which implies that the field would not reach the galactic or heliospheric levels. However, what is the reality? The time-resolution of rock measurements is limited and does not allow for observational data on the field strength at the very point of reversal.

Future research should focus on the following points: (1) Did geomagnetic field intensity lows reach values in the 10 μG-range enabling the galactic magnetic field to act as a seed-field for the re-establishing dipole? (2) Even if geomagnetic intensity at reversals gets low enough for the galactic magnetic fields to have any influence, the heliosphere would need to have an appropriate configuration: Is solar magnetic activity depressed when geomagnetic reversals happen, enabling a coupling between the geodynamo and the galactic magnetic field? (3) Is the Sun the transmitter of the galactic forcing by having a long-period cycle of magnetic activity in phase with spiral-arm passages and superchrons on Earth? Analogous to the Sun–Earth relation at millennial timescales, a high-energy state of the geomagnetic field during superchrons could be speculated to have been related to a long-term solar activity enhancement providing efficient shielding from cosmic rays. Occurring in conjunction with a low intrinsic galactic cosmic ray flux outside the spiral arms this would have lowered the cosmic ray flux at Earth even further.

4. Conclusions

Studies of the Quaternary climate record indicate changes towards cooler and locally dryer conditions in conjunction with geomagnetic intensity lows, geomagnetic reversals, and lows in solar magnetic activity.

Examples of carbonate sequences of the Tertiary period indicate a break-down in carbonate content related to geomagnetic reversals. Future research should verify whether or not CRF-induced changes in cloudiness are preserved in these ancient carbonate sequences. Geomagnetic reversals and low-geomagnetic-intensity events seem to occur in phase with the orbital 100 ka eccentricity cycle and a 100 ka solar magnetic activity cycle.

The rate of geomagnetic reversals is increased near the passages of the solar system through the spiral arms of the galaxy. Oppositely, Earth experienced superchrons when the solar system was positioned between spiral arms of the Milky Way galaxy. Thus, the reversal rate of our planet is correlated with externally forced CRF changes. This could mean that the geomagnetic field is not exclusively internally driven i.e. galactic tides and/or galactic magnetic fields play a role in shaping our reversal history. The polarity change between the Kiaman-Reversed and the Cretaceous Normal Superchron might have an explanation in the possible reversing of the homogenous galactic magnetic fields from one inter-arm area to the next.

The heliosphere must play a role in transmitting the galactic forcing signal to the geomagnetic field. A parallel behaviour of solar and geomagnetic activity which is indicated at millennial timescales encourages believe in long-period connections of both magnetic fields.

This review paper shows that geological history is linked to galactic forcing in which magnetic control of the cosmic ray flux played a significant role. The hypotheses put forward here merit evaluation by detailed investigations. Only by combining the knowledge "readable" in the geological record with the physical understanding of cosmic-ray-forced atmospheric processes and astronomical research, we can make progress in each of these participating fields of science. In this sense I hope that this paper stimulates synergetic co-operations.

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