The Spiral Arms,
Superplumes and a Unified Model of Mass Extinctions

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Abstract

A model is presented which relates the geological and paleontological events of the past 300 million years to the Sun's passage through the spiral arms of the Galaxy. It synthesises results from different disciplines into a coherent unifying model.

A simple mechanism is formulated which causally relates changes in geophysical phenomena - reversals in the Earth's magnetic field, superchrons where this cycle is suspended for long periods, polar ice variations and superplume volcanism, which gives rise to flood basalts - with astrophysical drivers from impacts and solar system penetration of interstellar gas clouds. This interrelated sequence in turn gives rise to the dramatic extinction events at the Cretaceous/Tertiary and Permian/Triassic boundaries and produces signatures associated with both cataclysmic and gradual extinctions. The question of geological versus astrophysical mechanisms for extinction are argued to be resolved into a coupled mechanism which is consistent with geological and palaeontological data so far known.

1. Introduction

The geological and astronomical history of the Earth is full of events and episodes which may have contributed to the evolution of fauna. These include the well-known Milankovich cycles, massive volcanisms, and catastrophic events which have contributed to mass extinctions such as at the Cretaceous/Tertiary (K/T) boundary, and reversals of the geomagnetic field. Since the discovery by Alvarez et al (1980) of an Iridium rich layer at the K/T boundary, the possibility that a bolide impact could play a major role in the Earth's history has become widely accepted. The identification of a crater at Chicxulub (Morgan et al 1997 and references therein) gave further support for the importance of impacts in the evolution of terrestrial fauna. For a discussion of the possible effects of a bolide impact, see Toon et al (1997).

Set against this have been arguments that more gradual processes must have also played a role at geological boundaries such as K/T and P/T (Permian-Triassic). Furthermore, these two boundaries are associated with massive flood basalts. The near coincidences of the mass extinctions and these flood basalts (Deccan and Siberian) led some authors to propose that the mass extinctions were due to environmental changes brought about by the volcanisms, giving rise to a gradual extinction event.

There is another geological feature which, although not directly implicated in faunal

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extinctions, may be coupled to processes that do affect environment. The geomagnetic field reverses polarity on timescales of a few hundred thousand years, but there exist long (several tens of million year) intervals of time, known as superchrons, where no polarity changes took place. A feature which has not attracted much attention is the fact that superchron periods ended at, or slightly before, both the K/T and P/T mass extinction boundaries and may be a symptom of the processes involved.

We shall present here a model coupling these geophysical and palaeontological observations, which at first glance appear unrelated. We believe that an important clue is provided by the recent work of Leitch & Vasisht (1998) who showed that on a reasonable model of the Galaxy, the sun was in a spiral arm at the times of K/T and P/T boundary events.

That the passage of the sun through spirals arms of the galaxy could bring about changes in the terrestrial environment was discussed by McCrea (1975, 1981), Napier & Clube (1979) and Begelman & Rees (1976). McCrea and Napier & Clube paid attention to the possibility that the terrestrial phenomena which recur at intervals of 10^8 yr may be related to the sun's motion in the galaxy, because it is the time interval between the sun's passage through successive spiral arms. McCrea (1975) discussed the possible start of ice epochs by accretion of interstellar gas onto the sun via the Simpson process (Hoyle & Lyttleton 1939, McCrea 1981) while Napier & Clube (1979) proposed that injection of possible planetesimals into the solar system could start an epoch by bolide impacts on Earth, with particular emphasis on the role played by the fragments of the planetesimals. See also Clube & Napier (1990). Clube & Napier (1996) were also the first to suggest an important link between magnetic field reversals and astrophysical perturbations. The finding of Leitch & Vasisht (1998) is important in that the link between these suggestions and the well known geological boundaries has been made more concrete.

We shall argue that biodiversity is influenced by the Sun's motion around the Galaxy, in accordance with McCrea and Clube & Napier. It differs from the model of Rampino et al (1997), who argued that it is the sun's motion perpendicular to the galactic mid-plane which is the driving mechanism.

In section 2 we shall outline the model showing the interrelations between the mechanisms at work, and in sections 3, 4 and 5 we shall relate it in more detail to geophysical processes and to geological and palaeontological records, and in section 6 elaborate on the role of spiral arm encounters. In sections 7, 8 and 9 we shall discuss the nature and chronology of boundary events.

2. The Model

The orbital motion of the Solar System around the Galaxy drives a perturbation in geophysical processes with a timescale of order 100 million years due to passages through the galactic spiral arms. Consider the state of the Earth at some time after the Solar System has left the region of a galactic spiral arm. Polar ice caps are present and fluctuate with the Milankovitch cycle, these fluctuations change the moment of inertia of the mantle resulting in small differential rotation between core and mantle. These fluctuations have been invoked by Olausson & Svenonious (1975) and by Clube & Napier (1996) as the trigger for terrestrial magnetic field reversals (with timescales of a few hundred thousand years) through small perturbations to circulation patterns. Our model is that the resulting coupling between the core and the mantle gives rise to a disturbance of the D" layer which is unstable (Yuen & Peltier1989) and the result of the disturbance is likely to lead to the formation of a mantle plume as shown by the numerical simulation of Thompson & Tackley (1998). When the mantle plume carries enough energy it can break through to the surface and gives rise to a superplume. These rare superplumes result in extensive flood basalt deposits and transport of heat to the surface and they only occur during geological periods during which field reversals are frequent. This differs dramatically from volcanic activity driven by plate tectonics which redistributes heat from the upper mantle and plates.

Heat transport and production of greenhouse gasses accompanying superplumes results in a steady increase in mean surface temperature, which in turn yields smaller polar ice caps and the possibility that they are lost entirely during minima in the polar ice fluctuations. Eventually the polar ice disappears, the Milankovitch mechanism is then unable to restore the ice sheets and the cycle of ice ages, differential rotation, core mantle boundary perturbations and field reversals is lost. The Earth enters a geologically warm period showing no field reversals and no superplume activity. During this state heat builds up in the D" layer above the core and is only slowly transported away by global mantle circulation patterns.

The warm period is brought to a close only when the Solar System next penetrates a galactic spiral arm. Several processes play a role - increased bolide impacts from perturbations to the Solar System comet population and direct penetration of these molecular clouds leading to impacts of planetismals within proto-stellar clouds and steady accretion of gas and dust. Dramatic cooling leads to reformation of polar caps and the restarting of the cycle of perturbations which trigger reversals in the terrestrial magnetic field and onset of superplumes. Cooling may arise from a single dramatic encounter with a giant molecular cloud in the spiral arm or successive encounters during the traversal, each contributing to cooling. The geological boundary, however, is identified by the onset of the polar ice cycle. The superplume and associated flood basalts following a long quiescent period is seen to be more extensive than later superplumes and is associated with the main extinction event. This boundary is also associated with heightened incidence of impactors, and some extinction features may result locally from specific massive impacts. We expect, therefore, signatures of both rapid and slow extinction episodes to be present in deposits at the same geological boundary.

3. Ice Ages and the change in the length of the day

An ice age is characterized by above average amounts of ice near the polar regions extending down into mid-latitudes. Olausson & Svenonius (1973) calculated various dynamical effects that are brought about by the change in the moment of inertia of the Earth resulting from the movement of water from the equatorial to polar regions. This effect is different from the tidal friction, which operates in one way and uniformly. They argued that the changing moment of inertia and the resulting change in the rotational period of the Earth is the mechanism which drives the magnetic field reversals. They calculated that the change in the length of the day (LOD), dT, (in seconds) is

$$dT \sim 0.5x/100$$

where x is the lowering of the sea level in metres. This is a conservative estimate since they assumed that the entire Earth behaves as a solid body. If the fluid core behaves independently of the mantle motion, then dT will be greater. At the maximum of glaciation, they give a value of x close to 150 m, so that dT $\sim$ 0.8s.

They further give the change in the rotational velocity, dv, at the bottom of the mantle (for zero latitude) as

$$dv \sim 0.00147\ (0.5x/100)\ \mathrm{m\ s^{-1}}$$

and the change in the angular velocity, $d\omega$, as

$d\omega = -(2\pi/T^2)\ dT.$

so that a typical velocity difference (for x=150 m) is 0.001 m s^{-1}. This velocity may appear small, but is comparable to or greater than flow velocities in the core as inferred from balancing the dynamo action and diffusive terms in the equation of dynamo theory (Lowrie 2000 p.262).

We may compare the change in rotational velocity with the one due to tidal friction. The change in LOD by the secular effect of tidal friction is 2.4 ms/century(See Holme 1998, Lowrie 2000 p.41). If the change in LOD by ice formation is brought about in a thousand years, its magnitude will be of the order of 100 ms/century, much greater than due to the change in LOD by the tidal friction.

In the presence of differential rotation, even in the absence of a magnetic field, a circulation is induced which carries angular momentum between the core and the mantle (Bondi & Lyttleton 1948). The mechanisms for dissipating this differential motion will be discussed later. This disturbance of the D" layer leads to mantle plume formation due to its inherent instability.

4. Generation of a Superplume

During the Phanerozoic, two particular instances of superplumes are relevant. One of these corresponds to the volcanism which led to the formation of the Deccan traps 65 Myr BP associated with the K/T boundary, and the other to the Siberian Flood basalts at 250 Myr BP, which coincides with the P/T boundary.

According to Basu et al (1995), the $^3He/^4He$ ratio in the rock collected from Maimecha-Katui in Siberia is up to 12.7 times higher than the atmospheric value, which strongly suggests their origin as a plume coming from lower mantle. It is now commonly accepted that superplumes are generated from the thermal boundary layer, D", between the core and mantle. Yuen & Peltier (1980) investigated the stability of the thermal boundary layer in which the viscosity depends strongly on the temperature and showed that there are modes which are unstable to slight perturbations. The fastest growing mode has a growth time of 10^6 yr and spatial scale of 10^2 km.

Williams (1994) argued that when the Earth's rotation had a period of 22.2 hours, the free nutation of the fluid core would have resonated with the Earth's retrograde annual forced nutation by the solar torque, and this could have amplified the core rotation, thus leading to temperature rise in the thermal boundary layer, D". Williams argued that this could provide a mechanism for generating superplumes from within the D" layer. There is a similar calculation by Greff-Lefftz & Legros (1999) that the rotational eigenfrequency of the fluid core and the solar tidal waves were in resonance around $3.0\text{x}10^9$, $1.8\text{x}10^9$, and $3\text{x}10^8$yr BP. These authors argued that because of the strong frictional coupling between the core and the mantle at these times, energy of enhanced motions was dissipated into heat at the D" layer, which led to the formation of superplumes. This model predicts a time of resonance somewhat different from the actual age of the Siberian flood basalts, but the concept that dissipation of circulation at the boundary may provide a trigger for onset of a superplume will be of relevance.

Courtillot & Besse (1987) argued that energy transmitted to the mantle from the core is gradually stored in the thermal boundary layer, and after a sufficient time, the layer would have become thick and unstable as shown by Yuen & Peltier (1980). It was further shown by numerical simulation of Thompson & Tackley (1998) that a gigantic plume is formed at the core mantle boundary by merger of small scale instabilities. These works would imply that when sufficient heat is stored in the D" layer, a plume can be initiated by a perturbation to the core-mantle boundary (D") layer.

One can conceive of several mechanisms which perturb the core mantle boundary as the result of changes in the LOD (Holme 1998). Holme considers that the electromagnetic coupling between the core and the mantle is most consistent among other possibilities such as viscous, gravitational, and topographic (owing to non-spherical bounday) couplings. The electromagnetic coupling seems to have been first suggested by Runcorn (1982) and discussed by a number of authors. Thus, Holme (1998) showed that the decadal changes in the LOD can be explained by the magnetic coupling between the core mantle boundary, possibly in the D" layer and Buffett et al (2002) argued that variations in nutation and precession are explicable if a thin layer at the boundary has a conductance of 10^8S. Furthermore, Nagao et al (2002, 2003) showed that the so-called geomagnetic jerks of 1969, 1978 and 1991 are not due to external disturbances but are likely to be abrupt changes of the magnetic field in the core-mantle boundary which subsequently diffused through the mantle.

Thus, the coupling between the core and the mantle is most likely to be electromagnetic. We argue that successive changes in the LOD brought about by climatic changes as the sun traverses a spiral arm provide the disturbance in the D" layer, whereby a gigantic plume is formed as shown by the numerical simulation of Thompson & Tackley (1998). It may be mentioned here that a plume head with radius 55 km (corresponding to Deccan traps) is estimated to take only 12 million yrs to reach the surface (Turcotte & Schubert 2002, p259).

To close this section, we wish to point out that the coupling merely serves as the trigger and the energy of plume formation is provided by energy transported from the core. The energy dissipated at the boundary must eventually come from the difference of the rotational velocities of the core and the mantle but this is small compared with energy budget of the Earth, as will be shown.

If $d\omega$ denotes the difference between the angular velocities of the mantle and the core, the difference between the rotational energies of the final state to the one with unequal angular velocities is found to be

$$dE = -(1/2)\ (J_1+J_2)\ \omega^2\ (d\omega/\omega)^2\ J_1\ J_2/(J_1+J_2)^2$$

where J_1 and J_2 are the moments of inertia of the core and mantle, respectively and where ω is the angular velocity of the Earth. The product of the first three factors represent the rotational energy of the Earth ($=2.1365\times10^{29}$J). For the Earth, $J_1J_2/(J_1+J_2)^2=0.71$ (Olausson & Svenonius 1973) so that $dE=0.204\ \text{x}10^{20}$ J for $dT=1$ second. This is about 1.5% of the geothermal energy released per year.

5. Occurrence of Superchrons

A superchron is an interval of the Earth's history where the geomagnetic field does not change polarity for tens of millions of years. Two superchrons are well established; the long reversed superchron, LRS, which ended near the P/T boundary and the long normal superchron, LNS, during the Cretaceous period.

From the distribution of the length of intervals between reversals, Consolini et al (2000) argue that the magnetic field reversal can be regarded as a transition between metastable states. Since the Earth's dynamo is only marginally stable it can be argued that either a destabilizing mechanism is needed to account for field reversals, or a stabilizing mechanism is needed to explain superchrons.

Loper & McCartney (1986) have shown that the temperatures at the top and bottom of the

D" layer remain almost the same and that heat builds up due to a thickening of the D" layer. Generation of a superplume could release this stored thermal energy, resulting in a thinner D" layer, steeper temperature gradient therein and stronger convection in the core. They associate the intervals of strong convection in the core with increased frequency of the geomagnetic field reversals. On the other hand, Larson & Olson (1991) argue that more vigorous convection in the core stabilizes the dynamo against reversals, and associate this with intervals when the D" thermal boundary layer is thin. There is, however, no evidence that the strength of the convective motions will affect the stability of the dynamo.

Field reversals are possible so long as the core convective motions are being perturbed by dissipation of differential rotation. These may also coincide with periods of thin D" layer brought about by superplumes since heat transfer by superplumes from the D" layer to the surface results in a steady heating of the upper mantle and a thinning of the D" layer. Once the plume reaches the surface to become flood basalts, a large amount of carbon dioxide is released, further warming the surface. Superplumes themselves may be generated so long as there are fluctuating polar ice sheets, though the size of superplumes diminish in magnitude as the D" layer is depleted. Eventually the polar ice will disappear entirely and disturbance at the core-mantle boundary ceases to operate and geomagnetic field reversals are interrupted initiating a superchron. The onset of a superchron is not directly related to any external process, but rather arises eventually as the limit of the process of transport of heat from the D" layer to the surface.

A superchron can end either when the polar ice returns (possibly due to some external perturbation), or when the D" layer becomes sufficiently thick that steady full mantle convection becomes impossible. We shall show below, however, that there are reasons to associate both the ending of a superchron and initiation of a superplume with external perturbations and the return of polar ice.

6. Encounters with spiral arms

Comparing the Leitch & Vasisht (1998) model for the motion of the Solar System around the galaxy and the geomagnetic field data it can be seen (Figure 1) that both the LNS and LRS superchrons terminated while the Solar System was moving into a spiral arm. McCrea (1981) argued that, once the Earth plunges into an ice-epoch, the Milankovich cycle begins to operate and the Earth experiences a series of ice ages, as it does at present. Since we have argued that these ice age fluctuations drive geomagnetic field reversals and trigger superplume production it is reasonable to look for a mechanism whereby the Earth is brought into an ice epoch by the galactic spiral arm environment.

The star forming regions in the spiral arms are associated with many interstellar molecular clouds. The Solar System will be affected by dynamical perturbations on the Oort Cloud of comets as well as direct encounters with the clouds themselves and planetismals within them.

The effects on the Sun and Earth when the solar system encounters an IS cloud appear to have been first investigated by Hoyle & Lyttleton (1939) and it has been argued elsewhere (Yabushita & Allen 1989, 1997) that accretion of gas and dust can directly lead to global cooling and initiation of an ice epoch. Similarly, the injection of dust released from disintegrating comets into the terrestrial stratosphere will also result in cooling, even without large scale bolide impacts (Clube & Napier 1990), and regardless of the ultimate origin of the comets, capture from IS molecular clouds or from the Oort cloud.

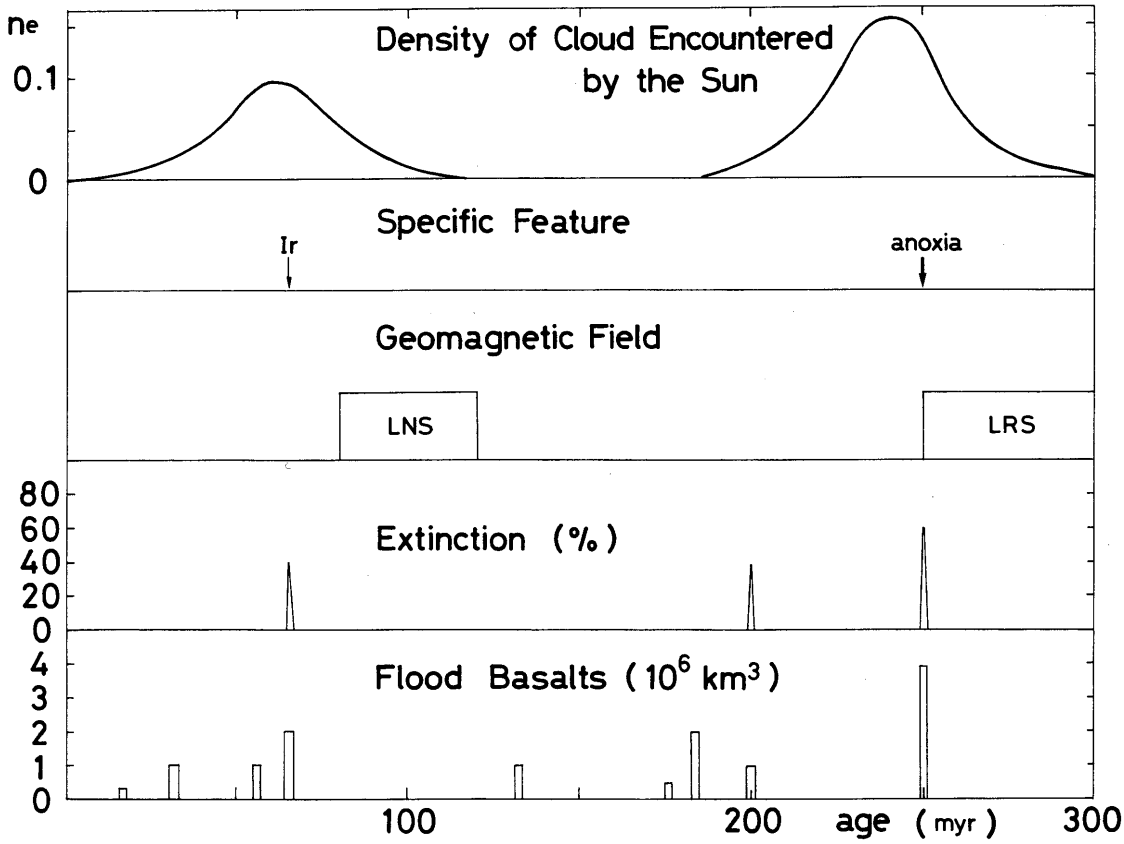

Fig.1.

Fig.1. Geological and astronomical events during the past 300 million yr. The cloud density encountered by the sun is based on Fig. 2 of Leitch & Vasisht (1998). ne is the the number of electrons per cubic centimetre encountered by the sun, as it moves in the Galaxy . Extinction rate per stage (multiple-interval marine genera) is taken from Sepkoski (1995); less significant extinctions are not presented. Flood basalt data are taken from Self & Rampino (2002), except for the basalt for P/T boundary (250Myr BP), for which the data of Reichow et al (2002) are used.

7. The P/T and K/T Geological Boundaries

The Iridium anomaly at the K/T boundary (65 Myr BP) is well established. Alvarez et al (1980) studied the Iridium in the clay layer corresponding to the K/T boundary and collected at Gubbio, Italy. Kyte & Wasson (1984) have measured the amount of Ir in cores of the Pacific Ocean and showed that there is a marked peak in the Ir concentration at the depth corresponding to the K/T boundary.

The impact crater at Chicxulub (Morgan et al 1997) is associated with the K/T boundary, although the nature of the impactor is a matter of controversy. Some authors (Napier & Clube 1996) favour a comet as the imapactor, while many geologists argue that the impactor was an asteroid (Alvarez et al 1980, Kyte 1998). Jeffers et al (2001) discussed the iridium deposit in relation to the crater size and argued that it was a large comet with a short periodic orbit. Zahnle & Grinspoon (1990) have argued that amino acids deposited at this boundary, though not found in the Gubbio clays, are the result of accretion of dust from a comet breaking up in the Solar System, and that the Chicxulub impactor was only a portion of this comet. Geochemical evidence is not yet sufficient to decide on the nature of the impactor (Shukolyukov & Lugmair 1998), and may be further confused by the signature of accreted interstellar dust and gas from molecular clouds at this boundary.

Apart from these geological signatures, the K/T boundary is coincident with the formation of the Deccan Trap in India. Duncan & Pyle (1998) measured the $^{40}A/^{39}Ar$ ratio of the basalts taken from the thickest sequence of the Deccan Trap, and have obtained the formation time of 66.6 to 68.5 Myr BP, somewhat earlier than the age of Chicxulub crater, which is 64.980 $\pm$0.05 Myr. It was Courtillot & Besse (1987) who first ascribed the volcanism, which led to the Deccan Trap flood basalt, to an instability in the core-mantle boundary.

There was a long period of time prior to the K/T boundary where there was no geomagnetic field reversals. This was the Cretaceous Long Normal Superchron (LNS) and the K/T boundary event took place after the geomagnetic reversals resumed (see Fig. 5 of Clube & Napier (1996), Fig. 4(a) of Yabushita (1998), Fig.4 of Courtillot & Besse (1987)).

There are striking similarities between the K/T boundary and the earlier Permian-Triassic boundary, P/T, which took place 250 Myr BP. The P/T boundary was, however, the most dramatic of all extinction boundaries. Nearly 85% of marine species and 70% of terrestrial vertebrate genera became extinct. For a review of mass extinctions, see Sepkoski (1995).

Using geological material collected from southern China, Bowring et al (1998) dated the P/T boundary at 251.4 $\pm$0.3Myr BP, and this corresponds to the end of the Long Reversed Superchron (LRS) (Courtillot & Besse 1987). This superchron ended almost simultaneously with the P/T boundary and the massive Siberian flood basalts (Reichow et al 2002, Duncan & Pyle 1988). According to Reichow et al (2002), the volume of lava erupted in Siberia at the time of P/T boundary could have been as much as 3.9×10^6 km^3. Both the P/T and K/T boundaries follow the ending of a superchron and are followed by long periods when the geomagnetic field reversed polarity frequently.

The P/T boundary differs from the K/T feature in that it is characterized by wide-spread anoxia. Wignall et al (1996) studied rocks collected from Spitsbergen, Italy and Slovenia and found that the late-Permian ocean is characterized by long lasting anoxia in shallow seas. In addition to this result, Isozaki (1997) studied cherts in southwest Japan and British Columbia, Canada, and found that the deep sea anoxia prevailed over the P/T boundary and had lasted for some 20 Myr. Again, the climax of anoxia characterized by gray cherts, siliceous claystone and carbonaceous claystone lasted for more than 10 Myr. There also does not appear to be any significant Ir anomaly at the P/T boundary (Clark et al, 1986), suggesting that impacts were a less important aspect of this boundary.

8. A Plausible Chronology

Adopting the galactic model of Leitch & Vasisht (1998), the Sun was in Sagittarius-Carina and Scutum-Crux arms at the times of K/T and P/T boundary events. The LNS and LRS superchrons ended while the Sun was entering these spiral arms and massive superplumes resulting in extensive flood basalts occurred almost coincident to the boundary events. These boundary events closely followed the end of the superchrons. The time series of events discussed are summarized in Fig.1.

We conjecture that the P/T boundary event resulted when the Sun encountered IS clouds while it was in the Scutum-Crux arm, some 250 Myr BP. The global cooling resulted in the formation of polar ice and the Earth began to experience ice epochs again. A superchron (LRS) came to an end due to the circulation driven by angular momentum transport destabilizing the Earth's dynamo. A superplume would have been generated by dissipation of this circulation at the core mantle boundary acting as trigger for release of heat accumulated in a thick D" layer. The superplume reached the surface, where it became the Siberian flood basalts, largest so far known with a volume of 3.9×10^6 km^3 (Reichow et al 2002). The flood basalts released a large amounts of CO_2 and atmospheric dust, leading to anoxia in the oceans (Wignall et al 1996).

After the Solar System left the spiral arm ice age fluctuations, field reversals and occasional superplumes persisted, transporting heat from the D" layer to the surface. Another extinction event is associated with one of these superplumes at around 200 My BP. Eventually the Earth entered a warm phase in the Cretaceous, possibly as a result of cumulative heat transport or the greenhouse effect following an episode of flood basalt deposition. Polar ice was lost, a new superchron began where no field reversals occurred and no further superplumes were generated (or none reached the surface).

This persisted until the sun again started to enter the region of high cloud density in the Sagittarius-Carina arm and encounters with IS clouds began to become significant at around 80 Myr BP. Geomagnetic field reversals were triggered once again ending the superchron (LNS). A superplume was generated subsequent to this and gave rise to the flood basalts of the Deccan Traps. Extensive bolide impacts are associated with this boundary. This may be a simple statistical fluctuation in the nature of the molecular clouds encountered (larger density of planetismals relative to gas and dust) or the Sun may have entered a core region of a molecular cloud perturbing the Oort cloud of comets, and causing a comet shower in the inner solar system. The Chicxulub impact crater was formed at this time, while also large amount of IS gas and dust would have accreted onto the Earth (Yabushita & Allen 1989, 1997). Both impacts and accreted dust would result in depositing the iridium rich layer associated with the K/T boundary.

The Earth is currently in the Quaternary period (an ice epoch) which started some 1 million yrs BP, possibly by encountering the Orion arm of the Galaxy (Napier & Clube 1979). The Earth is subject to changing moment of inertia and hence differential rotation between core and mantle; geomagnetic field reversals occur and superplumes are possible.

Looking further back in the geological record, another major extinction (upper Botomian) which took place 500 Myr BP (Sepkoski 1996) may coincide with the Sun's passage through the Norma arm, using the galactic model of Leitch & Vasisht (1998). Johnson et al (1995) suggested a superchron in the Ordovician which started 502 Myr and ended at 470 Myr BP. With the uncertainties associated with age determinations and the galactic model one might assign the ending of that superchron and the mass extinction to the sun's passage through the Norma spiral arm.

9. Patterns of extinction

The time-scale for the Cretaceous-Tertiary extinction episode has been the subject of considerable debate. Kaiho & Lamolda (1999) analyzed records of planktonic foraminiferal species collected from Caravaca, Spain and concluded that the extinction over the K/T boundary was abrupt, and sudden changes occurred within the pelagic ecosystem. On the other hand, Officer & Drake (1985) had earlier argued that the K/T extinction lasted for 10 Kyr and regarded the volcanism that made up the Deccan Traps as the major cause that led to faunal extinction. From multidisciplinary studies of the K/T boundary section of at Saharan platform in Tunisia, Keller et al (1998) argued that the long-term stresses due to climatic, sea-level, nutrient, oxygen and salinity fluctuations which started 200-300 kyr before the K/T boundary led to mass extinctions and that the bolide impact played a minor role in the extinction. Padro et al (1999) investigated planktic formanifera and clay mineralogy of Kazakhstan and found that long-term climatic changes may have been the principal factor that led to gradual disappearance of species in the Paratethys region and that the majority of the indigenous Cretaceous species survived into the tertiary period. See also Keller (1997). Officer et al (1987) had earlier pointed out that although calcareous plankton extinction took place rapidly (possibly over 10,000 yr. or as short as 200 yr), other marine extinctions took much longer. Investigation of marine fossils by Marshall & Ward (1996) found that amongst outer-shelf microfossils of the European Tethys, a major extinction took place near or at the K/T boundary but a gradual extinction had already taken place well before the boundary. It appears then that although many species died out at the K/T boundary, some disappeared before the K/T boundary and others survived into the Tertiary.

There is little evidence that extinctions at the P/T boundary were sudden. Fullerenes are detected in the spectra of IS gas clouds (Foing et al 1994) and Becker et al (2001) took the fullerenes collected from Sasayama, Southwest Japan as evidence of an impact. Chijiwa et al (1999) who collected fullerenes from the P/T boundary layer in another part of Japan regard them as product of wild fire in an oxygen poor atmosphere. Isozaki (2001) reviewed the geological evidence used by Becker et al (2001) as indicating an impact, and questioned the origin of the fullerenes claimed to have been detected in their work, suggesting that they may have been produced during the measurement process.

The Iridium detection from the P/T boundary layer has so far been marginal (Yi et al 1985). Thus, unlike the K/T boundary, the evidence for a large bolide impact at the P/T boundary is still uncertain. There is in fact a crater, Araguainha Dome, with an estimated age of 249 $\pm$19 Myr BP and diameter 40 km. From the size, the impactor was probably a comet, but not itself large enough to have brought about the P/T boundary event.

Renne et al (1995) calculated the initiation time of the Siberian volcanism at 250.1$\pm$0.3 Myr, and argued that the flood basalt initiation and the P/T boundary are synchronous. The Siberian flood basalt deposition is often cited as a probable cause of this extinction boundary. Bowring et al (1998) suggested initial cooling due to volcanic ashes and subsequent warming by the greenhouse effect exerted tension upon the fauna. Wignall & Twitchett (1996) regarded the anoxia in the shallow as well as deep oceans as the cause of extinction. They argued that warming of the Earth brought about by the volcanism had decreased the temperature difference between the polar region and the equator, thus weakening the oceanic circulation and causing extensive anoxia. For an extensive review of the patterns of extinction, see Hallam & Wignall (1997).

It would appear that both fast catastrophic processes and gradual processes are involved in these extinction boundaries, and this suggests that there were multiple mechanisms at work, rather than a single decisive cause.

10. Discussion

We have argued that the Sun's passage through spiral arms in the Galaxy brought about the geological events recognized as the K/T and P/T boundaries and outline a new coherent picture drawn from the existing observations, theories and modeling.

Fluctuation of polar ice due to the Ice Age cycle generates small differential velocities between the core and mantle. Dissipation of these differential motions through magnetic coupling of the core with the D" layer provides the perturbation needed for the formation of a superplume. Reversals in the geomagnetic field may result directly from the perturbed circulation pattern from the magnetic coupling, or through the thinning of the D" layer and more vigorous core convection brought about by eruption of a superplume.

Heat transport to the surface eventually removes polar ice entirely, and the geomagnetic field reversals and superplume production stop. During the subsequent superchrons heat will build up in the D" thermal boundary layer.

Polar ice only returns when the Solar System enters a spiral arm where encounters with interstellar clouds cause impacts and accretion resulting in a global winter. Formation of polar ice permits the field reversal and superplume mechanism to be switched on once again and the excess heat stored in the D" layer ensures that the superplume generated immediately after a superchron is abnormally large. This picture unifies much of the existing work into a simple chronology.

Although there are strong similarities between the K/T and P/T boundaries, there are also significant differences. These differences may arise if, during the K/T boundary (65 Myr BP), the sun entered a core region of a molecular cloud, whereas for the P/T boundary, the sun encountered molecular clouds, but did not enter a core region. The large amount of Iridium involved in the K/T boundary layer is then due to accretion (Yabushita & Allen 1989, 1997) and impacts (Clube & Napier 1996, Jeffers et al 2001) from comets perturbed from the Oort cloud or Edgeworth-Kuiper belt and from planetismals within the proto-stellar molecular clouds.

Both catastrophic extinction and prolonged periods of decline have been claimed for the K/T boundary. The association of impacts, gas and dust accretion and massive volcanism with the boundary in this model would naturally give both fast and slow signatures. Impacts would result in rapid extinction signatures at some locations and for some habitats, while accretion and volcanic effects would give a slow signature globally. The P/T boundary has less evidence of impacts, and the slower processes are likely to have been dominant. Nevertheless, some impacts and accretion of interstellar material would have occurred, and one might still expect to find impact craters, Ir anomalies, amino acid deposits and fullerines.

We argue that the sun's passage through a spiral arm can provide a unified account of the P/T and K/T boundary events.

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