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Mass extinction due to oscillation of sun about the mid-Galactic plane

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Abstract. Apparent periodicity was observed in the mass extinction event for the past few hundred million years. Previous investigations suggested the observed period to be somewhat lower than the calculated period of oscillation of sun about the Galactic plane. Our knowledge of the structure and surface density of milky way has changed radically over the past decade. The present investigation aims to calculate the time period of sun's oscillation about the Galactic plane using the latest model of the vertical structure the disc in the solar neighbourhood and to see if it matches with the extinction periodicity, which it does indeed, but with a quarter, not one-half, of the period of oscillation.

Key words : mass extinction—solar neighbourhood—oscillation of sun

1. Introduction

It is a known fact that dinosaurs had disappeared quite abruptly at the boundary of the Cretacious period and Tertiary era (or more precisely, Palaeocene period in geological terms), often referred to as the C-T or K/T boundary, about 65 Myr ago. But not only the noted giant reptiles, the dinosaurs, disappeared, but also nearly 50% of all the existing life forms became extinct simultaneously with the dinosaurs. This event has been most well studied over the past 150 years (Couvier 1825; Chamberlin 1909; Moore 1955; McLaren 1970; Russell 1975) but without much of a breakthrough until Alvarez *et al.* (1979, 1980) discovered an abnormally high iridium content in the oceanic sedimentary deposits at the K/T boundary layers of rock samples collected from different continental regions the iridium content being higher in these layers by about a factor of 30 or more compared to its normal abundance in the usual crustal material. Evidence for similar iridium anomaly was discovered in the non-marine stratigraphic sections at the K/T boundary by Orth *et al.* (1981). Similarly, an abnormally high osmium isotope anomaly was also discovered at the K/T boundary by Smit & Hertogen (1980). Abundance anomalies of platinum, osmium and gold were found at the K/T boundary, which tallied with those of chondritic meteorites (Ganapathy 1980). Existence of shocked

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quartz grains originating due to strong seismic waves were found by Bohor *et al.* (1984) in the North America and by Basu *et al.*(1988) in the Deccan traps. In order to explain all these observed facts, the most widely accepted hypothesis is that of an impact of a large comet or asteroid with the earth at the end of the Cretacious period (Alvarez *et al.* 1980; Emiliani *et al.* 1981; Hut *et al.* 1987); the depletion in the usual crustal material being due to possible segregation of these heavy elements towards the core region of the earth when the earth was hot and nearly molten, while the asteroids and cometary material deposited in the K/T boundary layers being still able to retain the pristine composition of the pre-solar nebula. The hypothesis of a nearby supernova bringing about such a catastrophy was ruled out by Alvarez *et al.* (1980) on the ground that plutonium-244, a product of a supernova as sure as iridium and having a radioactive mean life of 115 Myr, would have led to Ir/Pu ratio of about 10^3 in those 65 Myr old layers of enriched Ir, which is not observed in the K/T boundary.

It was Raup & Sepkoski (1984) who discovered a 26 Myr periodicity of the extinctions of familial tetrapods in the earth's history of biological evolution (see figure 1) over the past 250 Myr or so. However, the fact that there were several biotic extinctions was known to the geologists, and a few astronomers, such as Clube & Napier (1982) talked about the hypothesis of sun's oscillation about the mid-Galactic plane as a possible cause for such periodic extinctions arising due to enhanced cometary showers. But the then knowledge of the Galactic structure of the solar neighbourhood suggested the half-period of sun's oscillation to be 31-34 Myr (Rampino & Stothers 1984). Also before Raup & Sepkoski, long term geological periodicities like geomagnetic reversals were found and linked with the Galactic oscillation of the sun by Negi & Tiwari (1983). This result motivated Alvarez & Muller

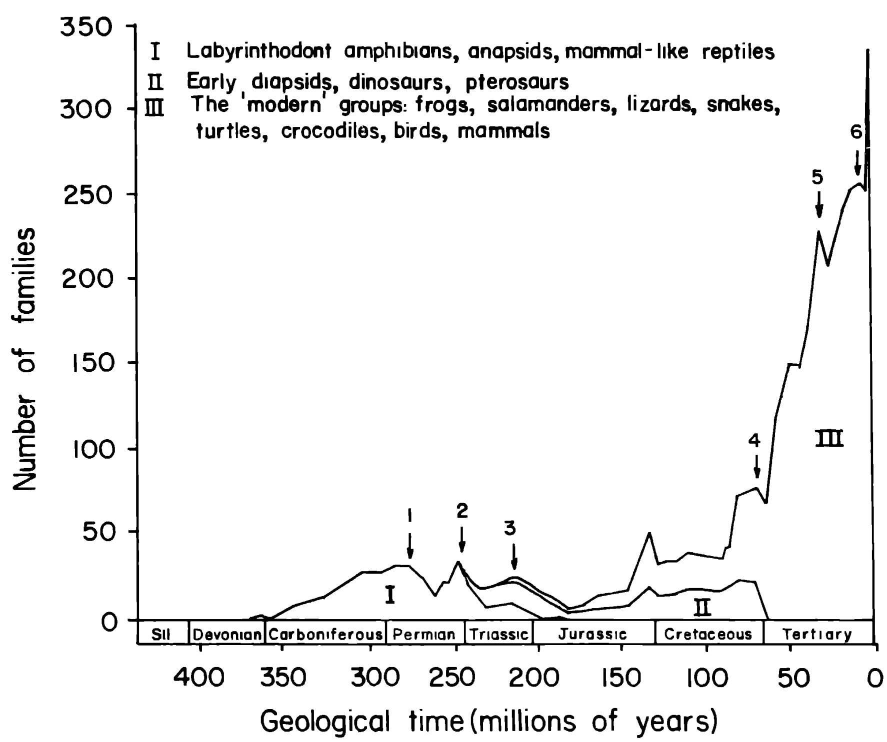

Figure 1. Periodic mass extinctions of terrestrial tetrapod families in number versus the geological age in Myr B. P. (after Benton 1985).

(1984) to make a search for periodicities, if any, in the historical records of terrestrial impact craters, and obtained a periodicity of 28 Myr. So the solar period of oscillation about the mid-Galactic plane did neither match with the observed periods of mass extinction and of impact craters, nor could the above hypothesis explain the last event of extinction that took place only 11 Myr ago. Stothers (1985) reanalysed the data on the age of all the known impact craters over the past 600 Myr, and showed that a 32 Myr periodicity cannot be ruled out, which was obviously aimed at supporting the Galactic-plane crossing hypothesis. But then extinction periodicity could not be explained by the same hypothesis. So alternative theories, such as the hypothetical existence of a dark companion of a sun, dubbed as 'Nemesis', with a periodicity of 26 Myr around the sun was sought for with the hope that it would be able to periodically perturb the Oort cloud during each of its perihelion passage (Muller 1985; Raup 1986; Hut *et al.* 1987). But later calculations showed that the orbit of such a distant companion (the required major axis being 0.85 pc, compared to the distance of 1.3 pc to the nearest star) would not last for billions of years due to more occasional pertubations caused by other stars, interstellar clouds, and in particular, the giant molecular clouds (Bailey *et al.* 1987).

The statistical significance of the claimed periodicities of the extinctions was then challenged and the issue became controversial with the advent of the so-called terrestrial models, such as episodic volcanic eruptions (Officer & Drake 1985, 1986), massive burning of vegetation causing a deposition of a layer of soot as evidenced by the analysis of Woolbach *et al.* (1985), massive regression of oceans and spreads of anoxic water (Hallam 1987), or enhanced global acid rains (Palmer 1991). Nevertheless, an extraterrestrial cause, whatever it could be, has always been favoured by most of the active workers in the field, and it would not be surprising that both the Nobel Laureate physicist Luis Alvarez and his geologist son Walter Alvarez would be among those who would defend such a hypothesis most passionately. At present, there exists no single model which can satisfactorily explain all the diverse data of inter-disciplinary nature.

The present investigation is carried out to see whether the 26 million year periodicity of extinction events over the past 250 Myr, if it truly exists, can still be linked with some regular astronomical events. In particular, we choose to investigate the hypothesis of the oscillation of the sun about the mid-Galactic plane. According to this hypothesis, while the sun passes through the dense, Galactic plane in the course of its oscillation, Oort's cloud zone is perturbed and is likely to send more comets and meteoroids to the interior part of the solar system, so that at those epochs the earth might be subjected to more frequent impact of comets than at any other times. Ample evidence suggest that at least some of the extinction events were most likely caused by the impact of extraterrestrial bodies. Here we plan to investigate whether the period of the sun's oscillation matches with that of the extinction events, given the most up-to-date knowledge of the Galactic structure in the solar neighbourhood.

2. Period of sun's oscillation about the mid-plane of the Galactic disc

Controversies exist in the value of surface density of matter in the Galaxy and the actual mass distribution in the solar neighbourhood (Bahcall 1986; Gould 1990; Kuijken & Gilmore 1991). For consistency we stuck to a single model given by Basu & Rana (1992a, b) which explains several important aspects of chemical evolution of the solar neighbourhood very well. We approximated the actual model for the vertical distribution of main sequence stars with an exponential law (corresponding to an isothermal disc approximation) having 480 pc as its vertical scale height, so that mid-Galactic volume density and surface density of mass due to main sequence stars match with those of Basu & Rana (1992b). Remnants and evolved stars are assumed to behave in the same way as the main sequence stars. Atomic and molecular hydrogen also follow their respective exponential distributions with the vertical scale heights of 130 and 65 pc respectively, as quoted in Rana (1991) and Rana & Basu (1992). Helium and other gases are assumed to be mixed in equal mass proportion of about 27% with both the forms of hydrogen.

The density $\rho(z)$ as a function of the height z from the mid-plane, therefore, consists of three exponential terms due to stars, H_1 and H_2 (including other gases, of course), and is given by

$$\rho(z) = 0.0469 \exp\left(\frac{-z}{480\text{ pc}}\right) + 0.0163 \exp\left(\frac{-z}{130\text{ pc}}\right) + 0.0182 \exp\left(\frac{-z}{65\text{ pc}}\right), \quad \ldots (1)$$

where the unit of density is $M_\odot \text{pc}^{-3}$ (figures 2). The differentialequation of motion in z for a sun like star becomes

$$\ddot{z} = -4\pi G \int_0^z \rho dz = -4\pi G I_1(z), \text{ say}, \quad \ldots (2)$$

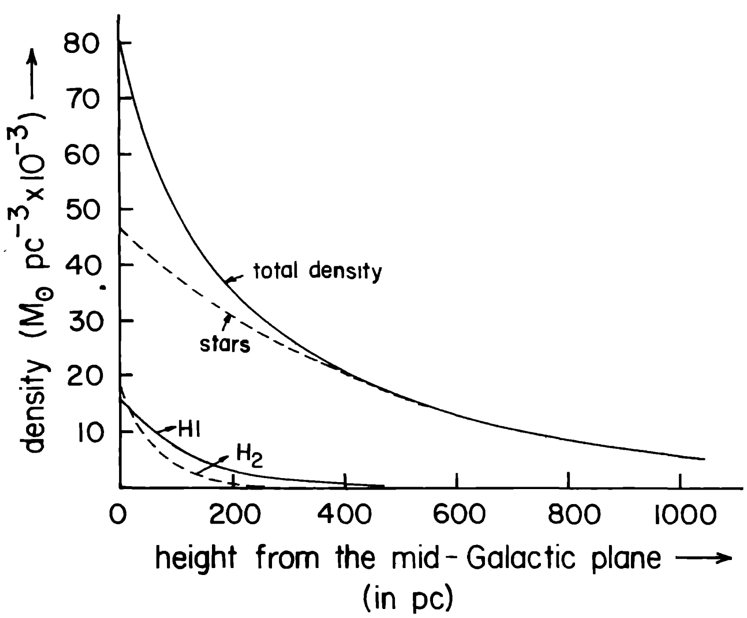

Figure 2. The vertical density profile of the Galaxy in the solar neighbourhood. Density contribution of gases and stars are shown separately along with total volume mass density as a function of vertical height from the mid-Galactic plane.

which is readily integrated to give

$$\frac{dz}{dt} = \sqrt{V_0^2 - 8\pi G I_2(z)}\ , \qquad \ldots (3)$$

with

$$I_2(z) \equiv \int_0^z I_1(z')dz'$$

and V_0 being the mid-plane velocity. Therefore, the time taken to reach the peak height z_{max} is given by

$$T = \int_0^{z_{max}} \frac{dz}{\sqrt{V_0^2 - 8\pi G I_2(z)}}\ . \qquad \ldots (4)$$

For a particular z_{max}, V_0 was calculated from equation (3) by equating the left-hand side to zero. Using this value of V_0 in equation (4) numerical integration yielded T, which is a quarter of the actual time period of oscillation about the mid-plane.

3. Results and discussion

The results obtained are as follows:

(i) Time period of vertical oscillation of a star is a function of mid-Galactic velocity of the star. The time period (actually its quarter) increases almost linearly with mid-Galactic velocity (figure 3), but it should be noted that it is actually the result of numerical integration that is relevant, and therefore, we have used the phrase 'almost linearly'. The relevant physical quantities are given in table 1.

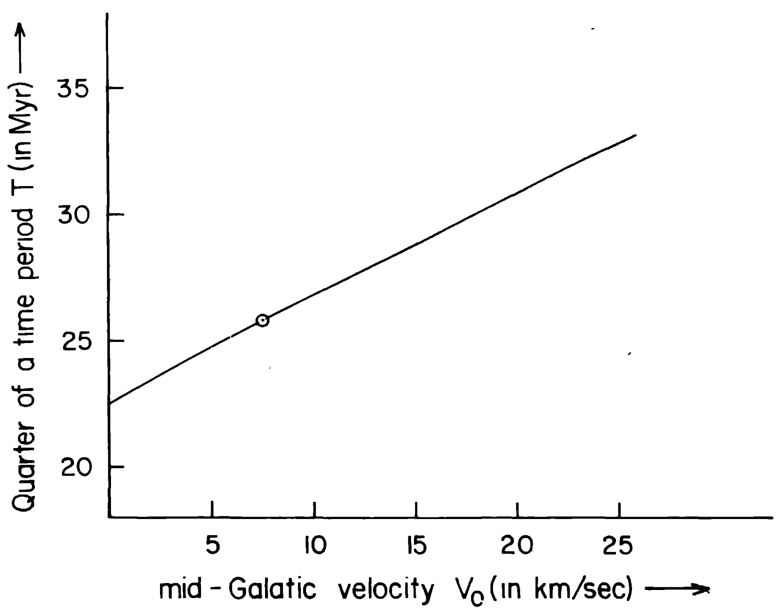

Figure 3. The time of oscillation of any star about the mid-Galactic plane as a function of its velocity at the same position. The position marked by the symbol ⊙ on the curve represents the sun, known velocity and position with respect to the local rest frame.

Table 1. The vertical structure of the disc in the solar neighbourhood

Height z above the mid-plane (pc)	Minimum required mid-plane velocity V_0 (km s^{-1})	Quarter T of a period of oscillation (Myr)	Volume mass density $\rho(z)$ ($M_\odot$ pc^{-3})	Surface mass density I_1 (z) ($M_\odot$ pc^{-2})
0	0.00	22.58	0.0814	0.00
10	0.66	22.87	0.0766	0.79
20	1.30	23.15	0.0723	1.53
30	1.94	23.43	0.0685	2.24
40	2.56	23.70	0.0649	2.90
50	3.17	23.97	0.0618	3.54
60	3.77	24.23	0.0589	4.24
70	4.36	24.48	0.0563	4.72
80	4.94	24.73	0.0538	5.27
90	5.51	24.98	0.0516	5.79
100	6.08	25.22	0.0495	6.30
125	7.46	25.79	0.0450	7.48
150	8.80	26.35	0.0413	8.56
200	11.36	27.38	0.0353	10.46
300	16.12	29.27	0.0269	13.54
400	20.50	30.97	0.0212	15.93
500	24.57	32.57	0.0169	17.82
750	33.68	36.27	0.0099	21.09
1000	41.64	39.72	0.0059	23.01
1500	55.12	46.18	0.0021	24.83
2000	66.36	52.20	0.0007	25.47
3000	84.77	63.05	0.0001	25.77

(ii) The present day position and velocity of sun are $z = +15$ pc and $+7.4$ km s^{-1}, respectively. From this data, the velocity at the mid-Galactic plane is calculated to be 7.465 km s^{-1}. The motion of the sun extends up to 125 pc. Quarter of a period is found to be 25.8 Myr.

(iii) 10% variation in both of the mid-Galactic density and scale heights are considered for all the components and a variation of T from 24.8 to 27.1 Myr is obtained in the extreme cases.

In absence of any other perturbation, the sun ought to pass through the Galactic plane or to come to rest with respect to local intersteller medium every 25.8 Myr. An enhanced visit of the comets from the Oort cloud and possibly from the local interstellar space should be observed when sun passes through the dense mid-galactic plane due to perturbation of Oort cloud by dense gas clouds. When sun comes to rest away with respect to local interstellar medium it is again possible for the sun to experience an extra shower of interstellar comets. The latter should happen simply because the gravitational capture cross-section of the sun is directly proportional to $(1 + v^2_{esc}/v^2_{comet})$, where v_{esc} is the escape velocity from the solar surface and v_{comet} is the relative velocity of the interstellar comet before entering the solar gravitational influence. However, it should be noted that only the z-component of solar motion would vanish, and therefore, the value of v_{comet} cannot become zero, only its z-component would. Thus the capture cross-section would change by about 30% due to the velocity factor and another 40% due to the reduced mass density of the interstellar medium at the turning point.

It is a known fact that only a very few of the known comets have hyperbolic orbits of eccentricity very close to unity. This is possible if either the Oort cloud is the source of all known comets, or the interstellar comets are occasionally trapped by the sun at very low relative velocity only. As shower of comets of the latter category can take place while the sun comes to rest with respect to the local interstellar medium, in addition to the ones that would take place during the passage of the sun through the mid-plane of the disc with a shower of interstellar comets of hyperbolic orbits having reasonably larger eccentricities. Such episodic cometary showers would also explain any import of extra-solar material, for example, the marine deposits bearing the known isotope anomalies (Alvarez *et al.* 1980), or inducing acid rains on a global scale (Palmer 1991).

Therefore an enhanced cometary action is expected every quarter, rather than every one-half, of a period of vertical oscillation of sun, which, according to the present calculation, is found to be 25.8 Myr. This period matches quite nicely with the 26 Myr periodicity of biological mass extinctions found by Raup & Sepkoski (1984) and a 28 Myr periodicity of the large impact craters on earth (Halam 1989). The reason for the earlier investigators obtaining substantially different periodicity of solar oscillation about the mid-plane of the Galaxy is that they used the surface mass density of the local part of the disc as something between 75 and 150 $M_\odot pc^{-2}$ (Bahcall 1986) compared to the most recent values, 54 ± $8 M_\odot pc^{-2}$ (Gould 1990) or 48 ± $8 M_\odot pc^{-2}$ (Kuijken & Gilmore 1991), and a much lower value for the overall vertical scale height of the disc stars (namely 325 pc by Bahcall 1986).

Even though the thin disc is assumed to be quite homogeneous, for practical reasons the homogeneity can be assured on a time scale of no less than 50 Myr. Again, on the upper side, the passage of the spiral density wave through the region, the so-called solar neighbourhood, would affect the secular variation of the local densities on a time scale of about 0.5 to 1 Gr (Sellwood & Kahn 1991), the density contrast between the arm and inter-arm regions being about a factor of 3 to 8 (Adler 1992). The sun is currently at the inner edge of the Perseus-Orion arm of the disc, and therefore, it is possibly relegating to an inter-arm region.

More importantly, the sun is at present located inside a hot interstellar superbubble of size about 80 pc, almost totally devoid of gas, which might have caused some evaporation of the interstellar comets, if any, in this region. It is therefore possible that because of these two reasons (namely, sun's present location in a hot interstellar superbubble, and its recession to the inter-arm region), we now notice a remarkable paucity of hyperbolic comets observed only during the past few hundred years. We have recently investigated the latter two possibilities, and in a different paper (Sen & Rana 1993), we have been able to resolve the problem of non-detection of interstellar comets over the past 150 years.

4. Conclusion

The present investigation is carried out for calculating the possible oscillatory motion of the sun and the solar system about the mid-plane of the Galactic disc, using the most recent data on the vertical structure of the disc in the solar neighbourhood and the current position and velocity of the solar system about the local interstellar frame of rest. These revised data are found to correctly reproduce the observed periodicity of episodic extinctions of the biological species. However, the more important aspect of this work is that the quarter of a period of vertical oscillation matches with the extinction periodicity and not the half a period.

The oscillation period of a star about the mid-Galactic plane is a strong function of the vertical component of its velocity V_0 at the mid-Galactic plane. Because of the stochastic interactions of the sun with other stars, interstellar clouds or nearby supernova explosions on a time scale of no more than 200 Myr, the sun is subject to substantial changes in its velocity over the past 500 Myr. Even if the sun is spared from such catastrophic encounters par chance, the passage of the spiral density waves past the solar neighbourhood cannot be escaped on a time scale of 500 to 1000 Myr. Since the density contrast between the arm and inter-arm is about a factor of 3 to 8, the time period in the thin disc itself would change by a factor of 2 to 3. Here we assumed that the vertical component of the velocity of sun remains unaffected due to existence of the third integral of motion, which is known to have been well respected by the disc population of stars. In that case, the variation of time period of oscillation would be due only to the variation of density caused by propagation of spiral density wave.

However, we do not claim that all mass extinction events are caused by the cometary impact due to sun's vertical oscillation. From the size of the hot superbubble and from sun's position in it, it is estimated that about 10 Myr ago there was a huge supernova explosion nearby. This time matches with 11 Myr, time passed since the last significant biotic mass extinction event.

In this work, we, like the many others in the past, did not however, address to the question of the details of an actual physical mechanism that would link the motion of the sun in the interstellar medium with the extinction of biological species on earth.

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