Tidal Effects Of Passing Planets And Mass Extinctions

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Recent observations suggest that many planetary-mass objects may be present in the outer solar system between the Kuiper belt and the Oort cloud. Gravitational perturbations may occasionally bring them into the inner solar system. Their passage near Earth could have generated gigantic tidal waves, large volcanic eruptions, sea regressions, large meteoritic impacts and drastic changes in global climate. They could have caused the major biological mass extinctions in the past 600 My as documented in the geological records.

Geological records indicate that the exponential diversification of marine and continental life on Earth in the past 600 My was interrupted by many mass extinctions (1). The records also indicate that the major mass extinctions were correlated in time with large meteoritic impacts, gigantic volcanic eruptions, sea regressions and drastic changes in global climate (2-5). Some of these catastrophes coincided in time. The reason for that is not clear. Meteoritic impacts alone, volcanic eruptions alone or sea regressions alone could not have caused all the major mass extinctions: A large meteoritic impact was invoked (6) in order to explain the iridium anomaly and the mass extinction which killed the dinosaurs and claimed 47\% of existing genera (1) at the Cretaceous-Tertiary (K/T) boundary 64 My ago. But, neither an iridium anomaly, nor a large meteoritic crater have been dated back to the Permian/Triassic (P/T) mass extinction, 251 My ago, which was the largest known extinction in the history of life (7,8), where global species extinction ranged between 80\% to 95\%. The gigantic Deccan basalts flood in India that occurred around the K/T boundary (2,3) and the gigantic Siberian basalts flood that occurred around the P/T boundary have ejected approximately $2 \times 10^6 \ km^3$ of lava (4). They were more than a thousand time
larger than any other known eruption on Earth, making it unlikely that the other major mass extinctions, which are of a similar magnitude, were produced by volcanic eruptions. However, although there is no one-to-one correspondence between mass extinctions, large volcanic eruptions, large meteoritic impacts, and global environmental and climatic changes, there are clear time correlations between them whose origin is not clear. Here we suggest that tidal effects of planetary-mass objects which pass near Earth could have caused all of these and can explain the complex geological records of the major biological mass extinctions. In fact, frictional heating of planetary interiors by gravitational tidal forces can lead to strong volcanic activity, as seen, for instance, on Jupiter’s moon Io, the most volcanically active object known in the solar system (9,10). But, the moon, the sun and the known planets are too far away to induce volcanic eruptions on Earth. However, recent observations (11,12) and theoretical considerations suggest that thousands of planet-mass objects may be present in a distant ring in the solar system between the Kuiper belt (13) and the Oort cloud (14). Gravitational perturbations may occasionally change their parking orbits and bring them into the inner solar system. Various “anomalies” in the solar planetary system can be explained by collisions (15), capture or scattering of such objects by the planets. Passage of such objects near Earth could have generated on it gigantic tidal waves, large volcanic eruptions and drastic changes in global climate and sea level. Moreover, upon crossing the asteroids and Kuiper belts these planetary mass objects could have diverted large meteorites and asteroids into a collision course with Earth (16,17). Thus visits of distant planets may be the common cause for the various catastrophes that were jointly responsible for the major biological mass extinctions.

DISTANT PLANETARY-MASS OBJECTS

The recently discovered gigantic asteroids (11) in the outer solar system between the Kuiper belt and the Oort cloud, various extrasolar observations (12,18-19) and theoretical considerations (20-22) suggest that many planetary-mass objects may be present in distant
solar rings. Probably, they have been formed together with the sun, since star formation commonly involves formation of a thin planar disk of material possessing too high an angular momentum to be drawn into the nascent star and a much thicker outer ring of material extending out to several hundred AU. Evidence for this material has been provided by infrared photometry of young stars and also by direct imaging (18). Moreover, the recently discovered Jupiter-mass planets orbiting very near solar-like stars (19) much closer than where their formation was expected to take place, led to the conclusion (20) that very many planetary-mass objects must be formed at large radii where most of the disk mass resides, and migrate inward as a result of tidal interactions with the planetary disk. Furthermore, analysis of the properties of axisymmetric planetary nebula led to the conclusion that many gas-giant planets are present around most main sequence stars (22). Indeed, recent observations of the nearest planetary nebula, the Helix Nebula, with the Space Telescope (12) discovered \( \sim 3500 \) objects with a comet like shape (termed Cometary Knots) and a typical mass of about \( 10^{-5}M_\odot \) (for comparison, \( M_{\text{Earth}} \approx 3 \times 10^{-6}M_\odot \) and \( M_{\text{Jupiter}} \approx 9.6 \times 10^{-4}M_\odot \)). In a distant ring around the central star. It is not clear whether they contain a solid body or uncollapsed gas. They are observed at distances comparable to our own Oort cloud of comets but they seem to be distributed in a planar ring rather than in a spherical cloud like the Oort cloud. It is possible that these planetary-mass objects and the recently discovered gigantic asteroids (11) in the outer solar system between the Kuiper belt and the Oort cloud are the high mass end of the vastly more numerous low mass comets. The planetary-mass objects are more confined to the ecliptic plane while the very light ones are scattered by gravitational collisions into a spherical Oort cloud. Gravitational interactions can change their parking orbits into orbits which may bring them into the inner solar system.

**PLANETARY COLLISIONS**

Collision of planet-mass objects with the known planets may explain various “anomalies” in the solar planetary system (23): A collision of a Mars-size object with Earth could have
formed our moon (15) and tilt the spin plane of Earth (23.5°) relative to the ecliptic. Such a collision could have formed Pluto’s moon Charon, tilted Pluto’s orbital plane relative to the ecliptic plane by the observed 17.1° and change it into its observed high eccentric orbit, e = 0.253. The inclination of Mercury’s orbit by 7.0° and its high eccentricity, e = 0.206, could also have resulted from a near encounter with a visiting planet. Collision, or near encounters, with visiting planets could have tilted the spin plane of the other planets/moons/satellites relative to their orbital plane (Mars: 25°, Jupiter: 3°, Saturn: 25°, Neptune: 28°, Uranus: 98° and Venus: 178°).

Capture by the giant planets of passing miniplanets/moons/asteroids, or of fragments resulting from a collision or a tidal disruption can explain: (a) why there are moons/satellites, such as Phobos and Deimos of Mars, with completely different density and composition than that of their planets, (b) why there are moons with unexplained retrograde orbits, such as Triton around Neptune, (c) why the orbit planes of some moons, minimoons and asteroids are tilted relative to the equatorial plane of their planets, in particular those with retrograde orbits around the heavy planets Jupiter, Saturn and Neptune, and those with prograde but very eccentric orbits, such as Nereid of Neptune which has the most highly eccentric orbit of any known planet or satellite. Out of the 61 known moons, the six with the retrograde orbits (four around Jupiter, one around Uranus and one around Neptune) and about the same number of prograde moons have a large inclination (∼ 20°) with respect to the equatorial plane of the planet which they orbit. This is consistent with the fact that prograde and retrograde approaches are equally probable, but, tidal interactions between the heavy planets and their retrograde moons bring them closer and lead eventually to their tidal capture or disruption into rings like those around Saturn.

**RECENT ENCOUNTERS**

Most of these could have happened in the early solar system when the collision rate was much higher, as it is evident from dating of moon and planetary craters (10). However,
there are observations which suggest that near encounters of planet-like objects with the Earth-Moon system have occurred also more recently. For instance, fossil corals show that the rate of decrease in the number of diurnal rings during annual cycles, i.e., the rate of decrease in the number of days in a year, has changed suddenly into a slower rate at the end Devonian (10). Since the lengthening of the day is due to slowing of the rotation of Earth by the well understood moon’s tidal forces, it implies that at the end Devonian the moon-Earth distance increased suddenly by a significant fraction. Such an increase could have been induced by a tidal pull in a nearby passage of a visiting planet/moon (a crash into Earth induces a discontinuous change in the length of the day rather than a continuous one). The tidal pull increases the Moon-Earth separation if its projected trajectory in the Moon-Earth orbiting plane does not fall between them. The maximal radial kick to the moon is when the trajectory of the visiting planet is perpendicular to the Earth-Moon line on the far side of the moon. For a passing distance $d$ it is

$$V_r \approx \frac{2GM_p}{v} \left[ \frac{1}{d} - \frac{1}{d + D} \right],$$

(1)

where $D = 380000 \text{ km s}^{-1}$ is the Moon-Earth distance and $v$ is the velocity of the visiting planet relative to the Earth-Moon system (if $V_p(\infty) \approx 0$ then $V_p(1 \text{ AU}) \approx \sqrt{2}V_E$, and $(\sqrt{2} - 1)V_E \leq v \leq (\sqrt{2} + 1)V_E$ with $V_E \approx 30 \text{ km s}^{-1}$). For $d \gg D$, this tidal velocity is quite small. But, if the visiting planet passes near the moon in a direct orbit at a distance $d \leq D$, then $V_r \sim 2GM_p/vd$. Such a tidal velocity can increase significantly the moon’s distance from Earth and divert it into an eccentric and inclined orbit (as observed). The eccentricity will be damped by terrestrial tidal forces. For $d < 0.1(M_p/M_E)D$, a planet can even eject the moon from its Earth-bound orbit. Nearby passage can also slightly change the Earth orbit around the sun and its spin orientation. Even slight changes in the orbit or in the spin orientation of Earth can have dramatic effects on climate, sea level and glaciers.
TIDAL EFFECTS

Visiting planets and moons that pass near Earth can cause also gigantic tidal waves and intense volcanism. For simplicity, we limit our discussion here to a single visit and ignore “multiple visits” before escape to “infinity” or, capture/disruption by the sun. (which will be discussed in detail elsewhere). Although exact calculations of surface tidal effects are beyond the scope of this paper, an approximate estimate of the flexing of Earth by a passing planet can be easily obtained by neglecting the rotation of Earth and the speed of the passing planet (of mass $M_p$) and by assuming a quasi hydrostatic equilibrium. By balancing the terrestrial forces against the tidal force one obtains a surface displacement along the line of sight to the planet which is given approximately by (24)

$$h \approx \frac{3}{4} \frac{M_p}{M_E} \left( \frac{R_E}{d} \right)^3 R_E.$$  \hspace{1cm} (2)

The maximal land tide due to the moon is 27 cm. However, a visiting planet with a typical mass like that of the Cometary Knots (12), which passes near Earth at a distance comparable to the Earth-Moon distance, produces gigantic oceanic and continental tidal waves which are a few hundred times higher than those induced by the moon. Scaling of the tides produced by the moon to those produced by visiting planets is justified for approximate estimates since the duration of the strong tidal acceleration by the moon, which is determined by the Earth rotation, is similar to $t \sim d/v$, the passage time of a visiting planet at a passing distance $d \sim D$ from Earth, with a velocity $(\sqrt{2} - 1)V_E \leq v \leq (\sqrt{2} + 1)V_E$ relative to Earth. Oceanic tidal waves, more than 1 km high, can flood vast areas of continental land and devastate sea life and land life near continental coasts. The spread of ocean waters by the giant tidal wave over vast areas of land and near the polar caps will enhance glaciation and sea regression.

Flexing Earth by $h \sim 100$ m will deposit in it $\sim \alpha GM_E^2 h/R^2 \approx 10^{34}$ erg, where $\alpha \sim 0.1$ is a geometrical factor. It is approximately the heat release within Earth during $10^6$ y by radioactive decays. The flexing of Earth and the release of such a large energy in a very short...
time upon contraction might have triggered the gigantic volcanic eruptions that produced the Siberian basalts flood at the time of the P/T extinction and the Deccan basalts flood at the time of the K/T extinction (3,4). More distant encounters and/or smaller visiting planets could have caused smaller extinctions and sea regressions without massive volcanic eruptions.

**PLANET ACCRETION**

A reliable estimate of the masses and the flux of the visiting planets/planetesimals is not possible yet. However, it is tempting to estimate them from the assumption that the unaccounted energy source of Jupiter and its tilted spin plane relative to its orbital plane are both due to accretion of visiting planets/moons. An accretion rate of $\dot{M} \approx 5.8 \times 10^{-12} M_J y^{-1}$, in addition to its absorption of 55% of the incident sun light, can explain its effective 134$K$ surface temperature. It implies that Jupiter has accreted $\approx 2.65$% of its mass during the $t_\odot \approx 4.57 Gy$ lifetime of the solar system. Jupiter’s effective capture cross section is, $\sigma_J \approx \pi R_J^2 (1 + M_J D_J / M_\odot R_J)$, where we assumed that visiting planets arrive near Jupiter with a free fall velocity in the sun’s gravitational field, $V_p \approx \sqrt{2GM_\odot / D_J}$ with $D_J = 5.2 AU$ being Jupiter’s distance from the sun. The impacts are from random directions in the orbital plane. If the visiting planets have a mean mass $M_p$ then the number of random impacts are $N_J \approx 0.0265 M_J / M_p$. Each random impact deposits on the average $\sim (2/3)^{3/2} M_p V_J R_J$ of angular momentum perpendicular to Jupiter’s spin, $S \approx I_J \Omega_J \approx (2/5) M_J R_J^2 \Omega_J$, where $I_J$ and $\Omega_J$ are its moment of inertia and angular rotational velocity, respectively, and $V_J$ is the planet’s impact velocity. Thus, the random deposition of orbital angular momentum in Jupiter during $t_\odot$, could have tilted its spin by a mean angle

$$\sin \theta_J \approx \sqrt{N_J M_p \left(2/3\right)^{3/2} R_J \left[\frac{2GM_\odot}{R_J^2} + \frac{2GM_\odot}{D_J}ight]}^{1/2} / I_J \Omega_J.$$  \hspace{1cm} (3)

From the observed 3.13$^\circ$ tilt of Jupiter’s spin and the accreted mass, we infer that $M_p \approx 0.5 M_E$ and $N_J \approx 16$. Similar estimates for other planets, although yielding the correct
order of magnitude for the tilts of their spins, are less reliable because the inferred number of accreted planets is too small.

The sun is the main “planet sweeper” of the solar system. Its $7^\circ$ spin tilt could have been produced by the impact of $\sim 3 \times 10^4$ planets of characteristic mass $\sim 0.5 M_E$ (we ignore angular momentum loss by the solar wind). This means that the sun has accreted $\sim 5\%$ of its mass after its formation, at a rate of $\sim 7$ planets per My. In each capture episode, $\sim 6 \times 10^{42}$ erg of gravitation energy is released in the sun’s convective layer. It produces optical and X-ray flashes at a rate $\sim 7 \times 10^{-6} L_\odot^{-1} y^{-1}$ for sun-like stars. It also causes a significant luminosity rise for an extended time which may have induced climatic and sea level changes on Earth, and extinctions of species which could not have adapted to large environmental changes. The predicted rate, is consistent with the observed rate of large changes in $^{18}$O concentration in sea water sediments which record large changes in sea water level (25) and in the total volume of glaciers. Other implications of planet-sun and planet-star collisions will be discussed elsewhere.

**BIOLOGICAL MASS EXTINCTIONS**

Using our inferred planet flux from Jupiter and its collimation by the sun, we obtain that a “visiting rate” of once every $t_v = 100$ My for planets with $M_p \sim 0.5 M_E$ which fall towards the sun implies a passing distance $d \leq (t_\odot/t_v)^{1/2} [R_J M_J D_\odot/N_J M_\odot]^{1/2} \approx 170000$ km from Earth. Then, from eq. 2 we conclude that such visits produce land tides of $h \geq 125$ m and ocean tidal waves which can reach $1 km$ height. The combination of ocean tidal waves, volcanic eruptions, meteoritic impacts and environmental and climatological changes can explain quite naturally the biological and time patterns of mass extinctions. For instance, the giant tidal waves devastate life in the upper oceans layers and on low lands near coastal lines. They cover large land areas with sea water, spread marine life to dry on land after water withdraw, and sweep land life into the sea. They flood sweet water lakes and rivers with salt water and erode the continental shores where most sea bed marine life is concentrated.
Amphibians, birds and inland species, can probably survive the ocean tide. This may explain their survival after the K/T extinction. Survival at high altitude inland sites may explain the survival of some inland dinosaurs beyond the K/T border. Volcanic eruptions block sunlight, deplete the ozone layer, and poison the atmosphere and the sea with acid rain. Drastic sea level, climatic and environmental changes inflict further delayed blows to marine and continental life. But, high land life in fresh water rivers which are fed by springs, that is not so sensitive to temperature and climatic conditions has better chances to survive the tidal waves, the volcano poisoning of sea water, and the drastic sea level, environmental and climatic changes.

**CONCLUSIONS**

In spite of intensive studies it is still not known what caused the biological mass extinctions and whether they were caused by a single or a combination of extinction mechanisms. So far no single mechanism has provided a satisfactory explanation of the complex biological extinction patterns in sea and on land, the rate of mass extinctions and their correlation with the largest volcanic eruptions, sea regression and meteoritic impacts (1-5). These include astrophysical extinction mechanisms such as meteoritic impacts (6) passage of the solar system through molecular/dark matter clouds (26), supernova explosions (27-29) gamma ray bursts (30) and cosmic ray jets (31). However, visiting planets offer a simple solution to the puzzling correlations between mass extinctions, meteoritic impacts, volcanic eruptions, sea regression and climatic changes as documented in geological records. The hypothesis that a substantial amount of mass is present in the outer solar system (and in most other solar-like systems) in the form of planet-mass objects may be tested in the near future by advanced gravitational lensing experiments and by space based IR interferometric observations. Other consequences for the solar system are currently under elaborate numerical and analytical investigations (32).
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