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Abstract

The orbit of the Lost City meteorite is investigated to determine the influence of secular and encounter perturbations on the orbital evolution. Secular perturbations are negligible in the interval of 300-400 years and encounter perturbations highly unlikely, so therefore it is valid to interpret the short-lived cosmic radiogenic isotopes as having formed in the current orbit. During a 40,000 year numerical integration, the maximum inclination was 16°, minimum 9.7°, the minimum eccentricity was .414, maximum .447. Over a 500,000 year interval, it was found that the very long period secular terms were effective in preventing earth encounters for a substantial fraction of the time, suggesting the hypothesis that the meteor was a surviving remnant of the early Solar System ought not be completely dismissed.

Orbital elements of a small body in space are subject to large changes. Since radiogenic measurements on the Lost City meteorite are dependent on the orbit in the recent or distant past, an investigation was made of the likely changes in the orbital elements. Also, a dynamical study may yield insight into the origin of the meteor, although dynamics cannot yield as clear-cut a solution as might be hoped, especially with only one sample.

The history of the Lost City Meteorite during the past few hundred years is calculated using a numerical integration program developed by Schubart and Stumpff (1966) for computing N-body orbits. The heliocentric orbital elements derived by McCrosky (1970) from the Prairie Network data were used for input to initiate the backwards computation: $a = 1.6$ au, $e = .417$, $i = 11^{\circ}.98$, $\omega = 161.00$, $\Omega = 283.04$ and t_o = J.D. 2440590 (Jan. 3, 1970). The computation was carried backwards for almost 300 years. The changes in the orbital elements were found to be small during this interval, on the order of a degree in the orientation elements. The variations are associated with the "free oscillation," which results from the gradual perturbations by the planets, mainly Jupiter, in the absence of a large perturbation by a close encounter with a planet (in this case, Earth). At J.D. 2332000, the orbital elements were $a = 1.66$, $e = .417$, $i = 11.96$, $\omega = 158.06$, $\Omega = 284.78$. For this small portion of the free oscillation (period about 17,000 years), the variations will be linear with respect to the uncertainties in the orientational orbital elements, that is, the computed Δi will be the same for $i_o \pm 1^{\circ}$ (an upper limit on the observational uncertainty).

In contrast, the uncertainty in a (estimated error in 1./a = 0.05) could have a distinctly nonlinear effect. This error implies that the orbital period is too indeterminate to make a definite statement as to whether or not the meteor may have passed close to the earth within the recent past. However, the statistical expectation of a close passage to the earth within the last few hundred years is small for almost any orbit that might have been perturbed into the observed orbit. While statistics cannot be applied to an individual sample, it would have been a remote occurrence for a near passage to be followed by a collision in such a short time interval.

The long-term evolution of the orbit is controlled by one, or both, of two competing effects. When the meteor passes close to the earth, there will be sudden changes in the orbital elements due to the earth's gravitational field. The "recent" orbit would pass within the earth's sphere of influence once every 10^5 years, and a close enough pass to alter the orbital elements significantly might occur once every 10^6 years. The second effect (termed "secular" effects) is the steady, gradual perturbations by distant planets, especially Jupiter and Saturn.

The accumulated orbital changes in hypothetical meteor orbits due to encounters has been well studied by Öpik (1965) with an analytic method, and by Arnold (1964, 1965) and Wetherill (1968) using Öpik's development in a Monte Carlo sense. The general conclusions of these studies will be summarized here as they apply to the observed Lost City orbit. The theory is reviewed in order to contrast with the secular effects discussed later and also because it is useful to review the problem of determining the origin of meteors from dynamical considerations in the context of the Lost City orbit.

If chance encounters with the earth have been operating, there is a staggering variety of orbits from which the present orbit may have derived, or may have occupied at one time. Öpik has shown that given a velocity vector relative to the earth (but at a slight distance away from the earth so that the effect of the earth's own gravitational field is not considered), the net effect of the passage near the earth is to change the direction of the velocity vector leaving the magnitude unaltered. This will alter every orbital element of the body, including the semimajor axis, although the total energy is invariant. Using Öpik's formulas, we calculate for the velocity of encounter U

$$U^2 = 3 - 1/A - 2A(1-e^2) \cos i$$

For the Lost City meteorite, U = .33 (dimensionless coordinates, where the velocity of the earth is the unit, $V_E = 1$). The direction of the approach of the meteor is obtained from

$$A = (1 - U^2 - 2U \cos \alpha)^{-1}$$

where α is the angle of the velocity vector to the earth's apex. For Lost City $\alpha = 64^{\circ}$. It would not have been possible for the earth to capture the meteor into its recent orbit directly from "infinity." From energy considerations, the largest semimajor axis of an earlier orbit that the earth could have perturbed into the present orbit is 4.34 au, with an aphelion of 7.69 au. This orbit would have had a perihelion at 1 au. (Capture from infinity could have occurred in a two-step process, with Jupiter having captured the body into an earth-and-Jupiter crossing orbit and then the earth encounter reducing the semimajor axis so that the orbit was no longer Jupiter-crossing.) The minimum orbit that the meteorite might have had would be a = .66 au, perihelion = .289 (aphelion at the earth's orbit).

In addition, Arnold found a change in encounter velocity due to the earth's eccentricity. Arnold termed this acceleration a "Fermi effect"; however, it should be compared with terms in the Jacobi integral for the restricted elliptic three-body problem proportional to e cos f. Variations in the earth's eccentricity may therefore affect the acceleration.

The foregoing discussion assumes that the lifetimes are determined by near encounters and usually are not seriously affected by the gradual perturbations of the planets, particularly Jupiter, which act on the orbit continuously. It is difficult to evaluate the significance of these non-encounter perturbations because it is not possible to compute all hypothetical meteor orbits for billions of years with a rigorous numerical integration program. The orbital data obtained by the Prairie Network system cannot be of sufficient accuracy to permit study of possible commensurabilities in mean motions since the observations are taken at only one instant in time.

However, there are bodies in the Solar System which have relatively well determined orbits and which have been studied with some rigor. Many of these have demonstrated a special feature or features which have the effect of prolonging the lifetime far beyond what would be expected on the basis of encounter analysis.

The most common cause of prolongation of the orbital lifetime beyond what would be expected from encounter probabilities is the commensurability of the period of the small body and the planet whose orbit the body crosses. Minor planets whose orbits cross Jupiter have resonances of 2:1, 3:2 and 4:3. Those observed have aphelions displaced 180° from Jupiter, a natural selection effect. Marsden (1970) has remarked that, of the Jupiter-crossing minor planets, all seem able to avoid Jupiter except Hidalgo, possibly a nearly-extinct comet. Clearly, there must have been originally many more non-commensurable orbits which were quickly eliminated by collisions and ejections by close passage to Jupiter, as predicted by encounter theory. Sometimes more subtle effects than a simple commensurability of mean motions occur. Neptune and Pluto are nearly commensurable, in a 3:2 ratio, and Cohen and Hubbard (1965) showed, in a numerical integration extending for 100,000 years, that the motions of the aphelions enhance the effect so that the angular distance of the aphelions librates around 180° ensuring that Neptune and Pluto cannot collide.

If the orbit of the small body is somewhat inclined, long period variations may develop which will act to change the orbital lifetime predicted by encounter theory. Kozai (1962) found that the argument of perihelion of the minor planet (1373) Cincinnati librates about 90° ensuring that the intersection of the orbits always occurs at a distance greater than 1.5 au from Jupiter, even though the minor planet orbit is Jupiter crossing. Wetherill (1968) found that (1948 EA) cannot collide with earth although it is an earth-crossing asteroid due to the coupling of the variation of eccentricity with the argument of perihelion. This type of variation, hereafter termed free oscillations, is discussed in detail and demonstrated numerically on the Lost City orbit.

The free oscillations are primarily variations in the inclination and eccentricity, having an argument of 2ω. Lidov (1962) has obtained two simple formulas which are surprisingly successful in predicting the overall variations. He has

$$C_1 = (1 - e^2) \cos^2 i$$

$$C_2 = e \, (2/5 - \sin^2 i \sin^2 \omega)$$

where C_1 and C_2 are constants of integration in the perturbed system. From these, the amplitudes of the cycle are found: $e_{min} = .417$ and $i_{max} = 12^\circ.3$ when $\omega = 0^\circ$ and π, and $e_{max} = .421$, $i_{min} = 9^\circ.87$ occur when $\omega = \pi/2$ and $3\pi/2$. Since the semimajor axis remains constant for this type of perturbation, the maximum and minimum distances of perihelion can be computed: for e_{min}, $q = .972$ and for e_{max}, $q = .945$ au. (Incidentally, the Lidov constants are useful for identifying conditions such as Kozai found for Cincinnati, where the argument of perihelion librates about $\omega = 90^\circ$, and may prevent an asteroid from encountering a planet that its orbit crosses.)

When in fact the orbit was integrated numerically, the variations in the eccentricity and inclination agreed in an overall sense with the predictions obtained from the Lidov formulas, but there was also some indication of a trend with a far longer period developing. The computation extended for 40,000 years, an investigation that became possible if only four bodies were considered: Jupiter, Saturn, the Sun and Lost City. This expediency permits analysis of the long period trends with reasonable accuracy while the effect of the earth on the orbit would mainly occur only during encounters, which can't be predicted for one meteor anyway. (Mars has been shown by Öpik to have little significance in encounters and it is unlikely to have exerted a serious perturbation on the orbit). Saturn was included in the computation not only for its own effect, but also because its indirect effec t through its perturbations of Jupiter would cause the development of important terms which are not present when Jupiter is in a strictly elliptic orbit about the sun.

The results of the numerical integration on the variation of the eccentricity and inclination are shown in Fig. 2. The oscillation is occuring with a phase of 2ω as discussed above. However, the maxima and minima of the variation are not constant as assumed in the Lidov computations. If the orbit had not collided (that is, if the curve were extrapolated forward to the left), it appears that the values of e_{min} = .417 and $i_{max} = 12^{\circ}.3$ predicted by the Lidov formula would have occurred.

The extrema shown in Fig. 1 occur at values of $\omega = 0^{\circ}, 90^{\circ}, 180^{\circ}, 270^{\circ}$. The consequence is this: when the perihelion has its minimum value, $\omega = 90^{\circ}$, the radial distance at the node is far beyond the earth orbit. But when $\omega = 0^{\circ}$, the eccentricity is a minimum, the perihelion is at a maximum, and the inclination is a maximum (therefore reducing somewhat the chance of encounter). If the curve above is interpreted as oscillations around a straight line - i.e., if there are no secular terms of longer period with an amplitude comparable to that of the free oscillation observed above - then the lifetime estimated by encounter theory is correct. However, it seemed possible that the above curve represented small ripples superposed on the peak of a sine wave of much longer period. Smith (1970) had found this effect to occur on minor planet orbits. These "very long" secular variations are complex terms, depending upon variations in Jupiter and Saturn's orbits through mutual perturbations. A computation by Smith on the Lost City orbit extending backwards in time for 500,000 years did indeed show the free oscillations to be short term ripples on a variation in the eccentricity of longer period (Fig. 3). The period of this secular oscillation is of the order of 100,000 years, showing a tendency to increase with increasing negative time. Interestingly, the amplitude of the very long period oscillation does not increase if the mid-points of the free oscillations are considered. The amplitudes of the free oscillations increase strikingly as negative time increases. This effect can be explained by examining the increase in the inclination (Fig. 4). The inclination has increased from 12° to 25° at $t = -500{,}000$ years. The growth in the inclination is at a constant average rate and may have been yet higher in the more distant past; there is no clear indication that the inclination has reached maximum amplitude at the termination of the computation. As the inclination increases, the amplitude of the free oscillation increases - an effect predicted by the Lidov formulas.

The increase in the amplitude of the free oscillation is of importance in considering the origin of the meteor. When the eccentricity is below .40, the orbit is no longer earth-intersecting. Further, in order to have an orbit that cannot collide with or pass near to the earth, it is only necessary that the minimum of the free oscillation be below .40, since this is the condition when the radial distance at the nodes matches the earth's orbit. Therefore, from approximately -200,000 years to at least -500,000 years, a collision or a near-earth encounter would not have been possible. Thus the very long period perturbations cause orbits to be more stable than could have been estimated by considering only the effects of the perturbations by near-earth encounters. This effect would not be expected by considering an orbit chosen at random. It is a particularly significant effect for the Lost City orbit because the orbit is not Jupiter-crossing and because the initial inclination (12°) is substantial.

It should be emphasized that this computation is only a possible history of the orbit. It is also possible that this orbit may have been the result of a near encounter with the earth within the last 200,000 years which perturbed the meteor into the present orbit from a completely different orbit. However, this would have had to have occurred within this time period because the orbit beyond -200,000 years is not compatible with an injection by a near earth encounter. In the period before the computation, no information is available; however, the orbit would not have been earth-intersecting for a substantial fraction of the earlier time.

The evidence from the cosmogenic radionuclides (Cressy, 1970; Rancitelli, 1970) is not inconsistent with the hypothesis that the semimajor axis has remained approximately the current value for a million years. If a near-earth encounter had occurred, the resulting perturbation would have changed the semimajor axis as well as other parameters, so the radionuclide data tend to support the orbit as computed above.

Conclusions

The investigation of a possible history of the Lost City meteorite for 500,000 years cannot provide a definite answer to the question of origin of meteorites. But the orbit did indicate more stability than expected because the effects of the long-range perturbations tended to reduce the statistical likelihood of a near-earth encounter.

The Lost City meteorite is the first to have been picked up from the ground after the trajectories of many fireballs had been measured on the photographic plates of the Prairie Network System (McCrosky, 1968). Although more fireballs are observed than expected, the rate of ground retrievals is smaller than anticipated. The bulk of the incoming fireballs is extremely friable, some meteors disappearing much higher in the atmosphere than would be consistent with a dense body. Several authors (Ganapathy et al., 1970) have suggested that these meteors are carbonaceous chondrites, possibly derived from extinct comet nuclei. Öpik has suggested and Marsden found observational evidence for cometary orbits to be reduced by non-gravitational forces. Therefore the bulk of the fireballs may be comets which have recently returned to the Solar System.

The Lost City meteor may have had a similar history and be different only in density. However, the present study suggests that the possibility that some meteorites, like Lost City, may be remnants of the early Solar System which have remained in orbits with prolonged lifetimes and ought not to be discarded without further investigation. In this connection, it will be especially useful to see if future meteorites retrieved from the Prairie Network System are in orbits which the long period perturbations will tend to keep away from the earth.

Acknowledgement

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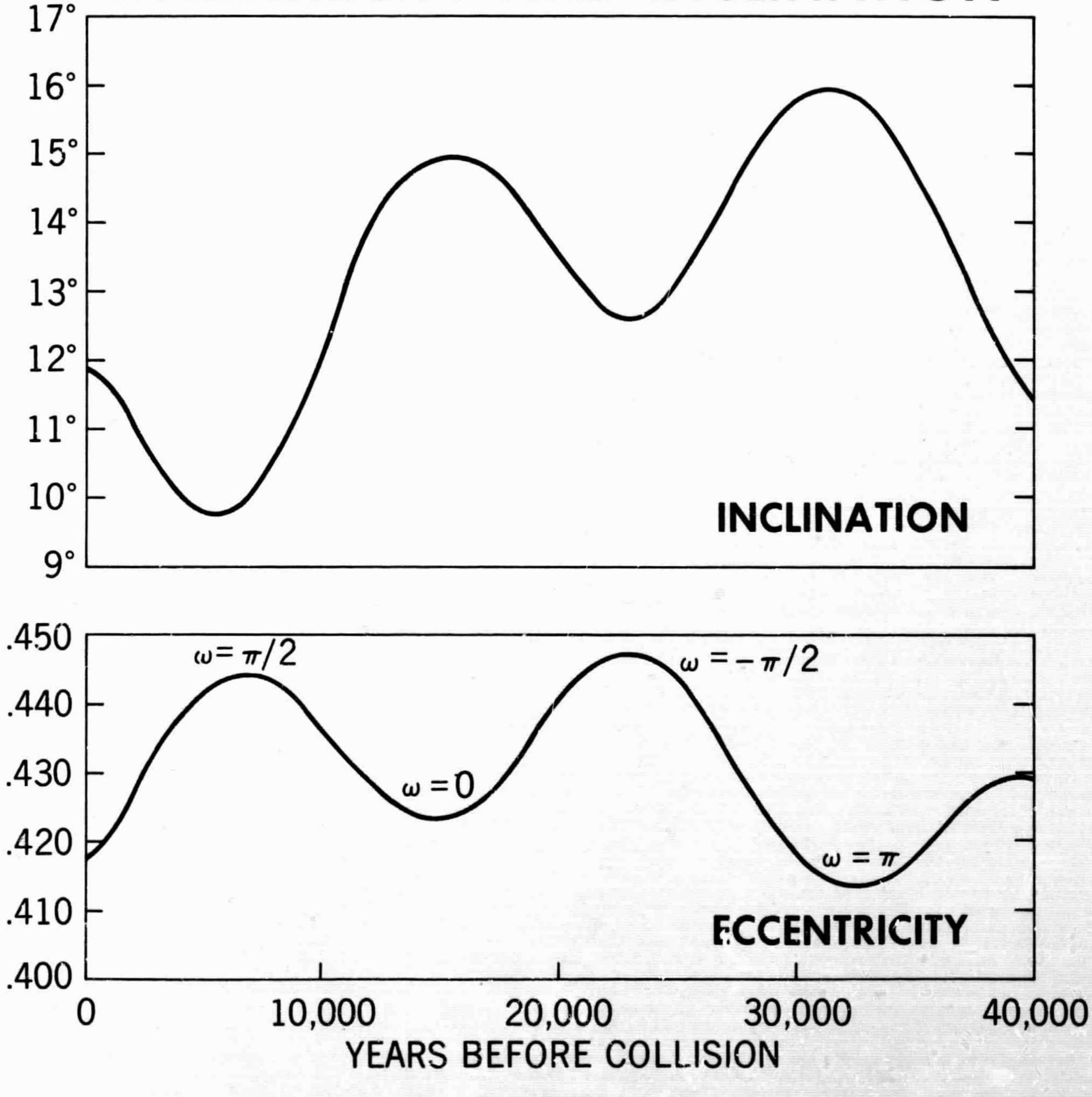
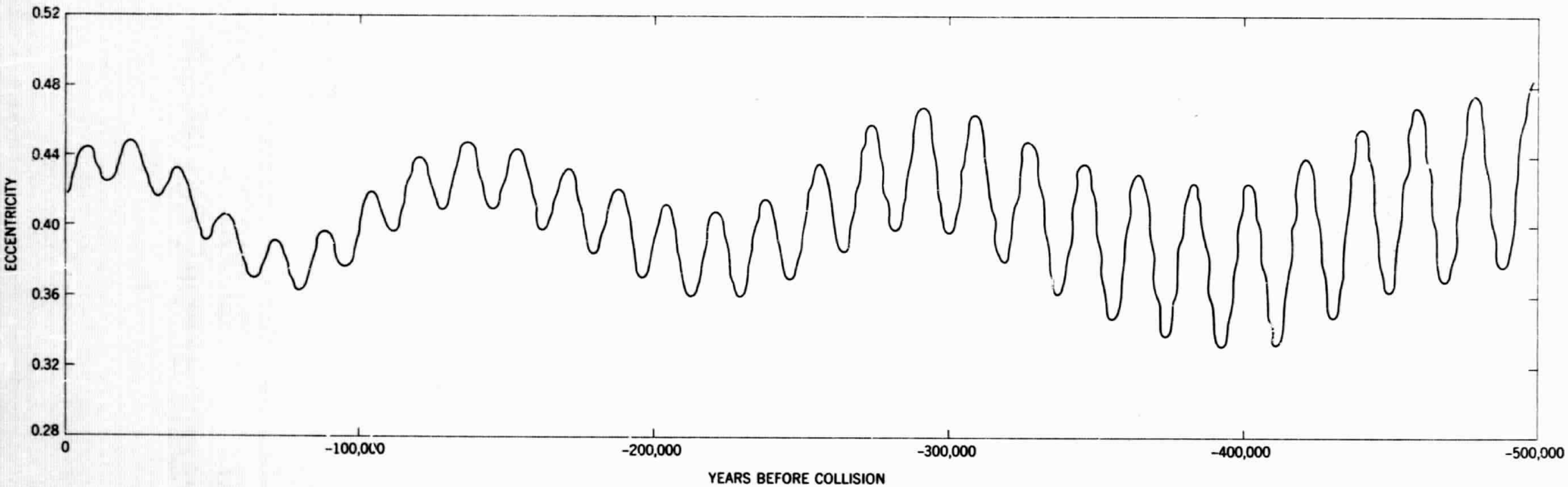
FREE OSCILLATION EFFECT ON ECCENTRICITY AND INCLINATION

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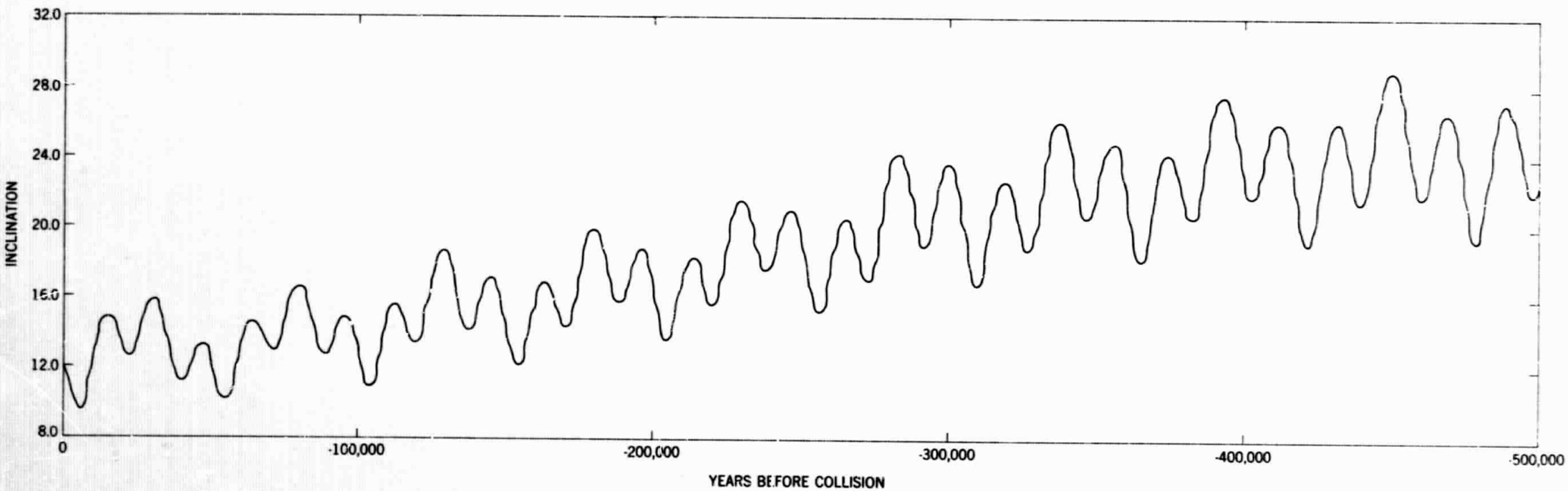
YEARS BEFORE COLLISION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INCLINATION
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YEARS BEFORE COLLISION

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