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# MODULATING TERRESTRIAL IMPACTS FROM OORT CLOUD COMETS BY THE ADIABATICALLY CHANGING GALACTIC TIDES.

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Time modulation of the flux of new Jupiter-dominated Oort cloud comets is the subject of interest here. The major perturbation of these comets during the present epoch is due to the tidal field of the relatively smooth distribution of matter in the galactic disk. A secondary source of the near-parabolic comet flux are stars penetrating the inner Oort cloud and providing impulses that create brief comet showers. Substantial stellar-induced showers occur approximately every 100 m.y. Less frequent (but stronger) impulses due to giant molecular clouds can also perturb comets from the inner cloud. These occur on timescales of ≈500 m.y. In contrast to these infrequent stochastic shower phenomena is the continuously varying tidal-induced flux due to the galaxy. As the Sun orbits the galactic center it undergoes quasiharmonic ($T_z \approx 64$ m.y.) motion about the galactic midplane, which is superimposed on the small eccentricity, near-Keplerian motion in the plane having epicycle period ≈150 m.y. In the process the galactic tidal field on the Sun/cloud system will vary, causing a modulation of the observable Oort cloud flux. We have created a model of the galactic matter distribution as it affects the solar motion over a time interval ranging from 300 m.y. in the past to 100 m.y. into the future. As constraints on the disk's compact dark matter component we require consistency with (1) the observed galactic rotation curve, (2) today's flux distribution of new comets, (3) the studies of K-giant distributions, and (4) the periodicity found in the terrestrial cratering record. The adiabatically varying galactic tidal torque is then determined and used to predict the time dependence of the flux. We find that a model in which approximately half the disk matter is compact is consistent with these constraints. Under such circumstances the peak-to-trough flux variation will be ≈5:1 with a full width of 9 m.y. This variability will manifest in the terrestrial cratering record and is consistent with the observed cratering periodicity, if over half of the impacts on Earth are caused by comets or asteroids that originate in the outer Oort cloud.

**Analysis:** The galaxy is modeled using a modified CBIP potential with a nucleus, a bulge, a halo, and a disk. The analysis is similar to that described in Innanen et al. [1]. A central issue here is the question of local dark disk matter. Bahcall et al. [2] have analyzed the distribution of K giants and have concluded that there is "significant but not overwhelming evidence for disk dark matter." We are guided by their ISM-like model. Two of the three disk components of the disk are fixed as having scale heights of 325 pc and 125 pc, mass fractions of 4:1 respectively, and represent old stellar and atomic gas contributions. The third component is compact and simultaneously includes contributions of young stars, dust, molecular H, and the dark matter. We then vary three disk parameters, the total disk mass, the fraction of disk matter that is compact, and the scale height of the compact component.

The disk mass is tightly constrained by a present solar velocity, which we fix at $\Theta = 225$ km s$^{-1}$. The scale height and mass fraction of the compact component are primarily limited by the K-giant studies and the period requirement. The equations of motion of the Sun about the galactic center are solved both backward and forward in time. As initial conditions we adopt $Z_\odot = 10$ pc and $R_\odot = 8$ kpc along with a Z component of velocity of 7.5 km s$^{-1}$. The scale height and mass fraction of the compact component is then varied (keeping the total mass fixed) and the solar motion is determined. In Fig. 1 we show the parameter range that reproduces the required plane-crossing period. For further illustrations we choose the specific parameter set for the compact disk component to have scale height 50 pc and mass fraction 0.50. It corresponds to total local disk midplane density of 0.29 $M_\odot$ pc$^{-3}$ and yields a mean plane crossing period of 32 m.y. This is within the $1\sigma$ range of values (dark matter mass fraction 0.24–0.74) given in [2] for their ISM model. In Fig. 2 we illustrate the trajectory of the Sun as it orbits the galaxy. The time interval considered is from 100 m.y. in the future to 300 m.y. in the past.

**Results:** It has been demonstrated that the galactic tidal field dominates random stellar encounters in making Oort cloud comets observable [3–5]. Matese and Whitman describe how the time evolution of all orbital elements can be analytically determined if the disk density $\rho_\odot(t)$ can be taken as adiabatically changing. The results are expressible in terms of Jacobi elliptic functions. Of the elements $\omega$, $\Omega$, i, e, and a only the last is taken to be invariant in the

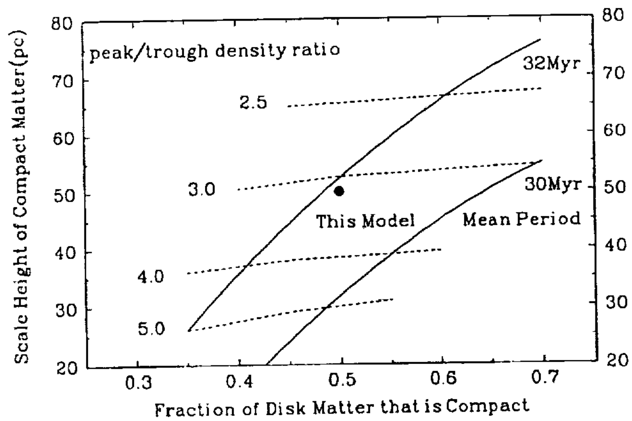


**Fig. 1.** Parameter range of the disk compact matter. Solid curves border parameters for galactic midplane crossing intervals of 30–32 m.y. Dashed curves illustrate the ratio of maximum to minimum disk density per oscillation cycle.

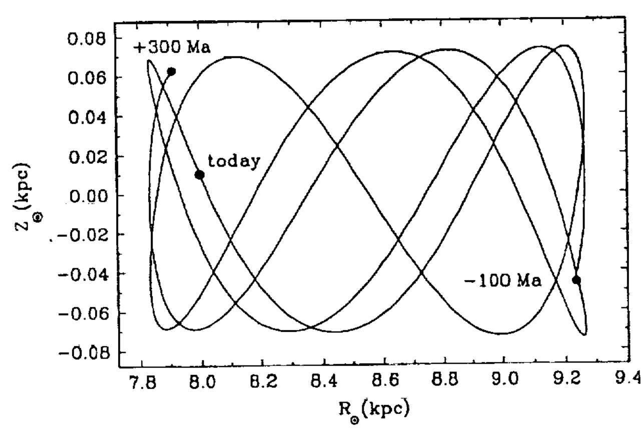


**Fig. 2.** Solar trajectory from 300 m.y. in the past to 100 m.y. in the future.

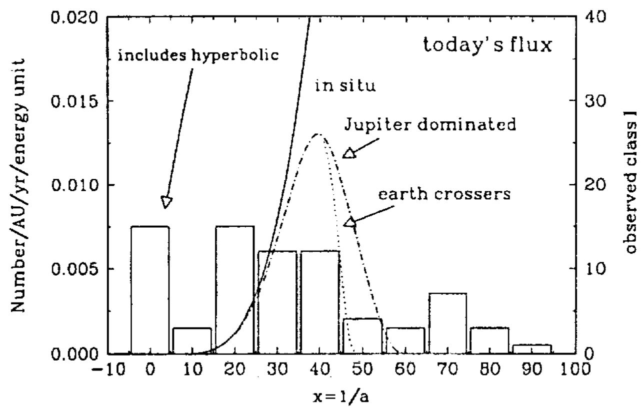


**Fig. 3.** Theoretical Oort cloud flux for today's density. The observed flux of new class I comets is shown also.

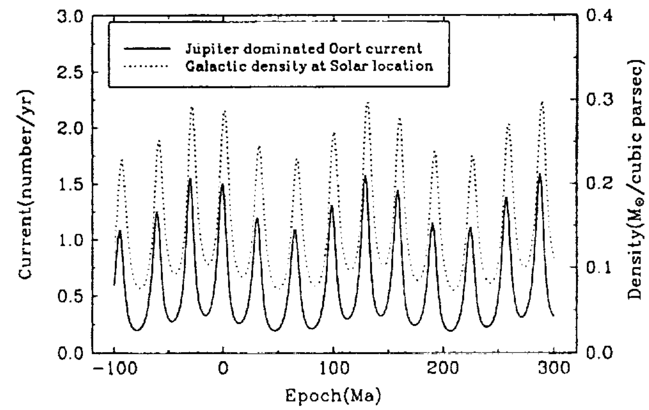


**Fig. 4.** Time dependence of the Jupiter-dominated current of comets from the outer Oort cloud due to the adiabatically changing galactic tides. Note the small retardation between the current and the density.

adiabatic limit. Since a typical Oort comet has a semimajor axis a ≈ 30,000 AU (period ≈5 m.y.) this approximation is adequate here. Our model of the Oort cloud includes the following assumptions.

The distribution of comet angular momenta and perihelia directions is taken to be random. For the *in situ* comet energy flux (shown in Fig. 3) we adopt the predictions of Bailey [6] where $x \equiv 10^6$ AU/a is a dimensionless original energy and the nominal cloud boundary is a = $10^5$ AU. A Monte Carlo analysis proceeds in a manner detailed in [4,5] in which trajectories are evolved one period into the future and new orbit parameter values are determined. The notion of a "tidal efficiency," which measures the ability of the galactic tide to overcome the loss cylinder barrier and change the perihelion distance, was described in [5]. We use the tidal efficiency, at a time retarded by half an orbital period, along with *in situ* flux density to predict the flux of Oort comets whose perihelia leap the loss cylinder barrier (15 AU) to the zone of Jupiter dominance in a single orbit due to tides.

Figure 3 also shows today's predicted Earth-crossing as well as Jupiter-dominated flux. The results are scaled to the observed flux of new comets today. For comparison we further show the observed distribution [7] of class I comets that are broadened by measurement errors and nongravitational forces. The time-dependent Jupiter-dominated current is displayed along with the galactic density at the solar location in Fig. 4. We have subjected the results of Fig. 4 to a conventional regression analysis to determine the width of the current peaks. The standard deviations are 4.0–4.5 m.y.

In Table 1 we list the epochs of peak Oort cloud currently entering the solar system as well as the maximum and minimum rates. One observes that the cycle interval, τ, changes, i.e., the "periodic" oscillations have in fact a variable period. Further, the phase of the nearest cycle peak is 0.6 m.y. in the future with the adopted parameters. This is consistent with the terrestrial cratering record [8,9]. There is ample evidence from the dating of impact structures and impact glass that suggests that the nearest flux maximum may not have occurred as yet. The predictions are in good agreement with the dating of impact glasses, microspherules, and the Ir anomalies that have peaks at 1, 35, and 65 m.y. ago [9].

Shoemaker and Wolfe state that the cratering record appears to be periodic but consider it to be a statistical fluke as they can find no mechanism for the periodicity. In particular they reject the galactic oscillations model of Rampino and Stothers [8] since it requires the impulsive perturbation of inner Oort cloud comets by molecular clouds. As the plane-crossing epochs are too close to the crater peak times of 2, 32, 65, and 99 m.y. ago to be due to rare stochastic cloud impulses, the Rampino-Stothers mechanism was rejected as a clock for this phenomena. These objections are obviated in the present model since modulation of outer Oort cloud comet flux is the physical mechanism for the periodicity.

In comparing these results with the numerical experiments on impact periodicity, we need to estimate the total dispersion expected from a strictly periodic sequence, i.e., we should convolve the standard error in the mean cycle interval (≈1 m.y.) with the standard deviation of the modulation about the cycle peak (≈4 m.y.) and the dating uncertainties of the most accurately dated craters (≈4 m.y.). If terrestrial cratering impact probabilities were modulated as described here with dating uncertainties of this order, we would expect a net dispersion about a strictly periodic signal to be ≈5–6 m.y. Were such a signal to have a reasonable probability of

TABLE 1. Oort cloud maximum [minimum] currents.*

| $-t_{max}$ † | (τ††) | Earth | Jupiter |
|---|---|---|---|
| -95.0 | (33.8) | 0.146 [0.025] | 1.088 [0.199] |
| -61.2 | (31.1) | 0.168 [0.035] | 1.250 [0.275] |
| -30.1 | (29.5) | 0.210 [0.043] | 1.554 [0.328] |
| -0.6 | (31.3) | 0.202 [0.033] | 1.501 [0.260] |
| 30.7 | (34.0) | 0.160 [0.025] | 1.193 [0.193] |
| 64.7 | (33.4) | 0.145 [0.027] | 1.085 [0.210] |
| 98.1 | (30.5) | 0.176 [0.038] | 1.306 [0.294] |
| 128.6 | (29.7) | 0.212 [0.042] | 1.571 [0.323] |
| 158.3 | (31.9) | 0.194 [0.031] | 1.441 [0.241] |
| 190.2 | (34.2) | 0.153 [0.024] | 1.143 [0.189] |
| 224.4 | (32.9) | 0.148 [0.029] | 1.107 [0.224] |
| 257.3 | (30.0) | 0.185 [0.040] | 1.376 [0.311] |
| 287.3 | | 0.214 | 1.581 |

* Scaled to 0.2 Earth-crossers/yr today.
† Epoch of maximum comet current, in Ma.
†† Cycle interval to previous maximum, in m.y.

manifesting itself in the cratering record the steady-state main-belt asteroidal cratering rate would have to be <50% of the total.

It is noted that the actual galactic disk matter compactness and the past solar motion are not well known. Should it be verified that (1) over half the disk matter is compact and of scale height ≈50 pc, and (2) over half of terrestrial cratering is due to active, dormant, or extinct comets having an origin in the outer Oort cloud, then the solar oscillation cycle will manifest itself in the cratering record at the marginally significant level observed. These results do not require the dark matter to be in the form of massive objects capable of impulsing the inner Oort cloud. Detectable modulation will exist even in the absence of infrequent molecular cloud showers. The observed periodicity in terrestrial cratering would then no longer be rejectable as a statistical fluke and we would be approaching a flux maximum from the outer Oort cloud within the next ≈1 m.y. We could then say that today we are at the peak of a continuous cometary drizzle, if not a shower.

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**A SEARCH FOR TEKTITE-RELATED STRUCTURES IN NORTHEASTERN THAILAND: AN EXAMINATION OF SPOT SATELLITE IMAGES.** J. F. McHone Jr.[1], K. Pitakpaivan[2], S. Bunopas[2], P. Angsuwathana[2], T. Supajanya[3], and J. T. Wasson[4], [1]Arizona State University, Tempe AZ, USA, [2]Geological Survey Division, Department of Mineral Resources, Bangkok, Thailand, [3]Chulalongkorn University, Bangkok, Thailand, [4]University of California, Los Angeles CA 90024, USA.

The dip of the magnetic remanence indicates that layered (Muong-Nong-type) Australasian tektites formed as puddles of melt with their layers roughly parallel to the Earth's surface [1,2]. Wasson [3] concluded that, because silicate melt can only retain its heat within the incandescent impact plume, these melts were ejected from nearby small (kilometer-sized) craters. Several deposits of layered Australasian tektites have been found in northeastern Thailand, with the largest in the northeastern corner.

We obtained a set of seven high-resolution, 1:50000-scale, SPOT-1 and SPOT-2 satellite images covering parts of the southeastern corner of northeastern Thailand and examined them for possible impact structures. Four adjacent images and corresponding topographic maps provided location and elevation controls for the most promising region comprising more than 3000 km². Examination of these yielded several sites that may be craters.

Layered tektites are found over a band 1200 km long extending from Hainan Island in the north-northeast to central Cambodia in the south-southwest. Wasson [3] noted that it appears to be impossible for a single large (5–20-km radius) crater to produce puddles of melt over such a large region and suggested that a cometary projectile broke up in deep space with the fragments producing many thousands of small craters across the region where layered textiles have been found. The microtektites and the tektites showing atmospheric ablation features were launched from the largest one or more craters whose formation deposited enough energy to produce a plume that penetrated through the atmosphere.

TABLE 1. Kilometer-sized circular features near Buntharik and Det Udom, Thailand, recognized on satellite images and topographic maps.

| Site | °E | °N | Feature |
|---|---|---|---|
| 1 | 105.42 | 14.73 | Shallow 1.5-km-diameter basin with annular ring at 2.5 km. |
| 2 | 105.46 | 14.73 | 1-km depression includes reservoir. Bleached rim indicates grading. Airstrip. |
| 3 | 105.15 | 14.77 | Bull's-eye structure. Radius of outer ring (with stream) 2.5 km, inner ring 1 km. |
| 4 | 105.24 | 14.80 | Village on central mound. Annular rings at 1-km and 4-km radii. |
| 5 | 105.48 | 14.83 | Annular drainage. May be eviscerated dome. |
| 6a | 105.07 | 14.98 | Small elliptical feature on topographic high. Radius 0.15 km. |
| 6b | 105.14 | 14.85 | Several elliptical to subrounded features. Radii ≤0.3 km. |
| 6c | 105.06 | 14.76 | Elliptical features, some farmed. Possible meander scars. |
| 6d | 105.17 | 14.85 | Elliptical feature. Bleached southern margin. Radius 0.3 km. |
| 6e | 105.32 | 14.63 | Numerous small, vegetated, rounded features having radii ≤0.3 km. |

Much of this 1200-km-long field of the layered tektites is mountainous and has experienced appreciable erosion during the 770 ka since the Australasian tektites were formed [4]. Other regions, particularly in the valley of the Mekong and some other major rivers, have been covered by recent sediments. Particularly promising for crater preservation is the flat-lying Khorat Plateau of northeastern Thailand. The southeastern corner of northeastern Thailand is within the layered-tektite band; in fact, large deposits of layered tektites have recently been discovered near the county-seat town of Buntharik. The existence of these tektites demonstrates that erosion in the region has been minimal during the past 770 ka. The bedrock is mainly sandstone; there seems to be little salt or limestone in the stratigraphic column, and thus there are no solution features that would mimic small craters.

The locations of the most promising sites are summarized in Table 1. All sites are on the four quadrangles 60381–60384 covering the region 105.0°–105.5°E and 14.5°–15.0°N. The Thai coordinates listed in Table 1 are kilometers east of Bangkok and north of the equator. The prime search site is the first, which shows up prominently on aerial photos, the SPOT image, and the 1:50000 topographic sheet. All bear investigating; one, site 5, is only a few kilometers from a region where large layered tektites are being found today.

**Site 1:** Centered about 5 km south-southeast of Amphoe Buntharik, this site was the target of a brief reconnaissance visit in February 1989. The site is a topographic depression about 0.7 km in radius surrounded by a discontinuous, slightly elevated rim to the east. An isolated hill in the west may represent a large ejecta block. A north-south road from Buntharik to Kaeng Sawang traverses the