NEAR-EARTH POPULATIONS OF BODIES COMING FROM THE OORT CLOUD AND THEIR IMPACTS WITH PLANETS

M.J. VALTONEN and J.Q. ZHENG
Tuorla Observatory, University of Turku, Finland

and

J.J. MATESE and P.G. WHITMAN
Department of Physics, The University of Southwestern Louisiana, USA

Abstract. When Oort cloud comets enter the planetary region their orbital evolution is dominated by encounters with the planets. Some of them become short period comets and enter the terrestrial planetary region to form a potential source of cratering. We have computed the orbital evolution of comets by encounters with the seven major planets. We find 0.5–2 impacts/Myr on the Earth, somewhat lower than the observed rate of about 2.8 impacts per Myr causing craters $\geq$ 20 km in diameter. Thus as far as numbers go, it is quite possible that dead comets are a major, even if not the dominant source of cratering on the Earth. We have also tested how well the expected variations in the Oort cloud comet flux show up in the rate of impacts. We find that the periodicity is reflected also in the cratering rate, though with a time delay and with added noise.

1. Introduction

Two major sources of impacts causing large craters are generally recognized: asteroids and comets. There may be an overlap between these two sources if dead comets enter the lists of asteroids. The relative importance of these two sources is still unknown. Shoemaker et al. (1990) estimate that 29 % of craters larger than 30 km in diameter are caused by comets while the remainder is caused by asteroids. On the other hand, Bailey and Stagg (1988) estimate that only about one percent of craters larger than 20 km in diameter are due to comets, the rest arising from asteroid impacts.

Another related issue is the question of periodicities in the cratering and related geological records (see eg. Rampino and Haggerty 1994). If the claimed $\sim$ 30 Myr period is real, then one must consider whether either of the assumed sources of impacts can produce such a periodicity. In case of asteroids no convincing cause for the periodicity has been put forward. On the other hand, a periodic enhancement in the Oort cloud flux of new comets is expected at every plane crossing of the Sun in its orbit up and down through the central plane of the galaxy (Matese and Whitman 1989), and this period may be equal to or close to 30 Myr (Matese et al. 1995). Even in this case we still have two major questions to answer: (1) Is the cratering rate derived from the Oort cloud comets, and from comets captured from the Oort cloud, high enough to make a noticable contribution to the overall cratering rate?, and (2) Does the periodic signature of the Oort

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cloud comet flux transmit to the cratering rate without being smeared out by the long time interval between the Oort cloud perturbation and the final impact on the Earth?

Both of these questions are investigated in the following using the code of Zheng et al. (1995b).

2. The method of calculation

In the Monte Carlo scheme of Zheng et al. (1995b) the orbit of a body is followed from one strong encounter to the next until the body collides with a planet or escapes from the Solar System. The basic assumption which allows for fast calculation is that the orbital elements a (semi-major axis), e (eccentricity), and i (inclination) remain unchanged between the strong encounters while the remaining orbital elements are randomized. Therefore at any given time the three orbital elements are known and they may be used to calculate the probability of a collision with a planet. The procedure for calculating the collision probability is given by Öpik (1951). A compact collection of the relevant equations are found in Shoemaker and Wolfe (1982). The details of the calculation will be given elsewhere (Zheng et al. 1995a).

One of the shortcomings of the method of Zheng et al. (1995b) is the lack of treatment of secular perturbations. Secular perturbations may become important especially in low inclination strongly bound orbits, and they may reduce the dynamical lifetime of a small body in the inner Solar System. In order to allow for this possibility we have assigned the maximum dynamical lifetime of 40,000 revolutions to our orbits, in accordance with Levison and Duncan (1994).

In order to test the collision code, we performed a calculation similar to Everhart (1969) and found practically identical results. However, the model of Everhart (1969) included only Jupiter as the dominant outer planet. Zheng et al. (1995b) have found out previously that the other outer planets play an important role in the capture of the Oort cloud comets and in their subsequent dynamical evolution. Thus we include the seven major planets (from Venus to Neptune) in our calculation, and count the collision rates on them.

3. Collision rates

In our numerical simulations we send 1 million comets from the Oort cloud with a time varying rate predicted by Matese et al. (1995). The relevant rate at 1 AU used in scaling to observations is 0.5 comets/AU/yr at $H_{10} = 10.8$ (see Zheng et al. (1995b) for the calculating of the observed rate). However, in the Galactic tide model of Matese and Whitman (1989) the rate averaged over 30 AU is about 3.5–7 times higher than at 1 AU. During the period of 300 million yrs $(1.75 - 3.5) \cdot 30 \cdot 300$ million comets will thus enter the perihelion zone 0–30 AU which is $(1.5 \cdot 10^4 - 3 \cdot 10^4)$ times more comets than we have used in our experiments. Thus the annual rates are obtained by multiplying our results by $(1.5 \cdot 10^4 - 3 \cdot 10^4)/300$ Myr = (50–100)/Myr (at $H_{10} = 10.8$).

We find 0.02 impacts on the Earth in our simulations. Only 1% of the impacts come from active comets, the rest are dead comets. Most of them have orbits which would place them in the Jupiter family, but also dead comets from Halley type and long period orbits will impact the Earth. The active lifetime of a comet is taken to be 400 revolutions with $q < 2.6$ AU. Impacts on Venus and Mars are of the same order of magnitude as on the Earth (0.01 and 0.006, respectively) while Jupiter impacts number 18.6.

In order to compare with the observed numbers of impacts on the Earth, there are several rather uncertain steps to take. First, we need the cratering rate which has been estimated at 2.8 impacts per Myr causing craters $\geq$ 20 km in diameter (Grieve 1984). Then we have to estimate the size of the cometary body which makes a crater of 20 km. We assume this body to be 1 km in diameter (Bailey, Clube and Napier 1990). Finally, we have to know the absolute magnitude of a new comet of 1 km size; Bailey and Stagg (1988) estimate it to be $H_{10} = 9.6$. This number depends on the assumed comet fading and could be even $H_{10} = 10.7$ if the fading is negligible (Hughes 1988). Since comets of magnitude $H_{10} = 9.6$ are thought to be less common than comets of magnitude $H_{10} = 10.8$ by about a factor of 2 (Hughes 1988), the multiplication factor to be applied to the data is 25–50/Myr, as far as we are discussing impacts causing 20 km craters or larger. Thus our calculations give us 0.5–1.0 impacts/Myr (1–2 impacts/Myr with no fading) on the Earth by dead comets which is a fairly large fraction of all observed impacts, and considering the uncertainties, could be even the dominant source of impacts.

Correspondingly the expected rate of impacts on Jupiter is one per 1000 yr of Shoemaker-Levy class bodies. We also notice a very good correspondence between our derived rate of collisions of live comets on the Earth, 0.005–0.02 collisions per Myr, and the rate derived from the observations of Earth-approaching comets by Bailey and Stagg (1988) of 0.012 ± 0.08 collisions per Myr. Thus we confirm the estimates of both Shoemaker et al. (1990) and Bailey and Stagg (1988) as far as we recognize the two works referring to dead comets and live comets, respectively.

The periodic nature of impacts on the Earth is demonstrated in Figure 1. It shows that the Galactic tidal perturbations show up in the impact rate of dead comets. Whether this periodic signal is important in the overall

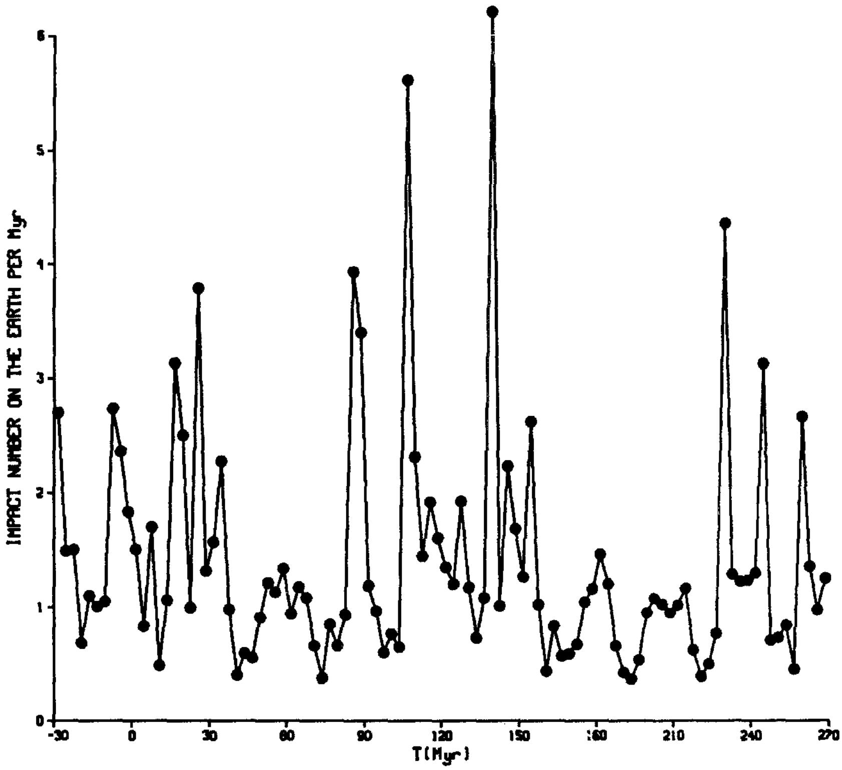

Fig. 1. The time varying rate of impacts on the Earth by (mostly) dead comets. The calculation starts 270 Myr in the past and is carried up to 30 Myr in the future.

impact rate depends on the fraction of all impacts which are caused by dead comets.

We also notice a small phase shift from the time of maximum tides to the time of maximum bombardment on the Earth. We are still approaching the maximum bombardment episode resulting from the latest Galactic plane crossing.

References

Bailey, M.E., Clube, S.V.M. and Napier, W.M.: 1990, *The Origin of Comets*, Pergamon, pp. 376–379.
Bailey, M.E. and Stagg, C.R.: 1988, *Mon. Not. R. Astron. Soc.* **235**,1.
Everhart, E.: 1969, *Astron.J.* **74**, 735.
Grieve, R.A.F.: 1984, *J. Geophys.Res.* **89**, B403.
Hughes, D.W.: 1988, *Icarus* **73**, 149.
Levison, H.F. and Duncan, M.J.: 1994, *Icarus* **108**, 18.
Matese, J.J. and Whitman, P.G.: 1989, *Icarus* **82**, 389.

Matese, J.J., Whitman, P.G., Innanen, K.A. and Valtonen, M.J.: 1995, in *Worlds in Collision – Interactions of Planets and Small Bodies*, eds. H. Rickman and M.J. Valtonen, Kluwer, in press.

Öpik, E.J.: 1951, *Proc. Roy. Irish Acad.* **54**, 165.

Rampino, M.R. and Haggerty, B.M.: 1994, in *Hazards Due to Comet and Asteroids*, ed. T. Gehrels, Univ. of Arizona Press, Tucson, in press.

Shoemaker, E.M. and Wolfe, R.F.: 1982, in *Satellites of Jupiter*, ed. D. Morrison, Univ. Arizona Press, Tucson, pp. 277–339.

Shoemaker, E.M., Wolfe, R.F. and Shoemaker, C.S.: 1990, in *Global Catastrophes in Earth History*, eds. V.I. Sharpton and P.D. Ward, Geological Soc. of America SP–247 (Boulder: Geological Soc. of America), pp. 155–170.

Zheng, J.-Q., Valtonen, M.J., Matese, J.J. and Whitman, P.G.: 1995a, in preparation.

Zheng, J.-Q., Valtonen, M.J., Mikkola, S., Korpi, M. and Rickman, H.: 1995b, in *Worlds in Collision – Interactions of Planets and Small Bodies*, eds. H. Rickman and M.J. Valtonen, Kluwer, in press.