ON THE ATMOSPHERICS DYNAMICS OF THE TUNGUSKA COSMIC BODY

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ABSTRACT

We studied the available scientific literature on the Tunguska event of 30 June 1908 to obtain parameter sets of the Tunguska Cosmic Body atmospheric dynamics. We performed a comparative analysis by means of available theoretical models and with the help of interplanetary dynamics, and we excluded unphysical orbits. Our results indicate a very high probability that the TCB was an asteroid.

Key words: Tunguska; fragmentation; atmospheric dynamics.

1. INTRODUCTION

At the dawn of 30th June 1908, a powerful explosion over the basin of the Podkamennaya Tunguska river flattened 2150 ± 50 km^2 of Siberian *taigà*, releasing in the atmosphere about $10-15$ Mton of energy. After more than ninety years of studies and researches, the origin of the cosmic body that caused the devastation is still dubious, though a cometary or asteroidal origin is more accredited. The majority of Russian scientists follows the cometary hypothesis, while many western scientists prefer an asteroidal model: a comprehensive review of theoretical and experimental works can be found in the proceedings of the international workshop *Tunguska96*, held in Bologna (Italy) on 15th – 17th July 1996 (see the special issue of Planetary and Space Science, vol. 46, n. 2/3, 1996, edited by M. Di Martino, P. Farinella, and G. Longo). See also Krinov (1966), Trayner (1997), Vasilyev (1998), Bronshten (2000b).

Figure 1. Boarding the helicopter MI–26 at Krasnoyarsk during the Tunguska99 Scientific Expedition.

Almost each year there is some expedition to Tunguska, but so far there was no recovery of macroscopic remnants. The data and samples collected in the burned area have not permitted a certain discrimination to be made between an asteroidal or a cometary nature of the TCB. In July 1999, an Italian Scientific Expedition (Figure 1), organized by the University of Bologna with the collaboration of researchers from the Turin Astronomical Observatory and the Institute of Marine Geology of the National Research Council (CNR), went to Siberia in order to collect more data and samples (Longo et al. 1999, Amaroli et al. 2000, Longo et al. 2001)[1].

While part of the collected samples of the lake sediments (Gasperini et al. 2001) and of the aerophotosurvey (Longo et al. 2001) have been analysed, we performed theoretical studies and modelling to support the field research. We studied the available

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[1] See also `http://www-th.bo.infn.it/tunguska/`.

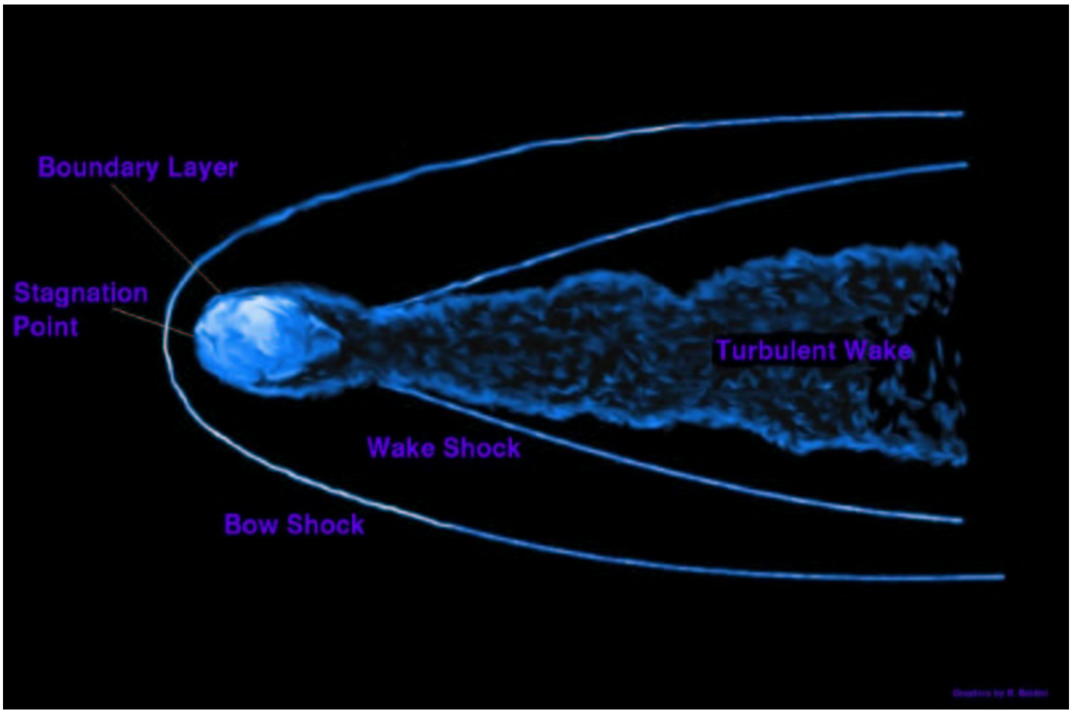

Figure 2. The hypersonic flow around a small asteroid (drawing not in scale). For a description see the text.

literature and the atmospheric dynamics of the TCB in order to extract a set of possible trajectories, from which we calculated the corresponding orbits.

In our work we prefer to assume, as one usually does, that a single explosion caused the Tunguska event, though some authors suggested the possibility of multiple explosions (cf. the discussion in Sect. 2.1 of Farinella et al. 2001). As recently newly underlined (Jull et al. 2001), most of the gas and debris would be injected in the stratosphere and, up to now, there are no proofs that distinct explosions have occurred at low altitude. We are studying this question using the aerophotosurvey's results. In the meanwhile we consider the fact that many witnesses have heard a single explosion and some of them have heard multiple explosions, that can be echoes. Anyway, if there were many bodies, like in the case of the impact of the Shoemaker–Levy 9 comet with Jupiter, all orbits would be very similar and the differences between the individual orbits would be much smaller than the differences due to the uncertainties in the parameters chosen.

Then, we studied the interplanetary dynamics and evaluated the probability that the TCB could come from one certain source in the Solar System. The complete study can be found in the paper by Farinella et al. (2001), while in the present proceedings we focus on the atmospheric dynamics calculations.

2. THE HYPERSONIC FLOW

The physical phenomena developing when a small asteroid (or a large meteoroid) enters the Earth atmosphere are quite different from the physics of bolides or the collision with kilometre–sized asteroids. It is very difficult to put boundaries among different regimes, but we can roughly identify that when we speak about the impact of small asteroids we are in the size range from some metres to some hundreds of metres. When such a cosmic body enters the atmosphere with velocities in the range $12 \div 72$ km/s, it moves at hypersonic speed, i.e. with Mach number higher than 5. In addition, the size of the meteoroid is large when compared to the atmospheric mean free path already in the upper atmosphere, so that it is possible to consider the continuum approximation for the fluid flow. A schema hypersonic flow is shown in Figure 2.

A bow shock that envelops the body, develops in the front of the cosmic body. When the shock is normal to the stream – on the symmetry axis – we have the strongest point. The maximum strength is in the stagnation point, i.e. in the point of maximal thermal and mechanical stress. As the air flows toward the rear of the asteroid (or comet), it is reattracted to the axis, just like in a Prandtl–Meyer expansion. Therefore, there is a rotation of the stream in the sense opposite to that of the motion and this creates an oblique shock wave, which is called wake shock. Since the pressure rise across the bow shock is huge when compared to the pressure decrease across the Prandtl–Meyer expansion, we can adopt the reasonable approximation that there is a vacuum behind the cosmic body.

Closer to the body surface, there is a zone where the main process is the molecular dissociation and even closer to the surface, there is the boundary layer, where viscous effects are dominant. The fluid temperature increases in the boundary layer, because the speed must decrease to zero at the meteoroid surface; moreover there are heating effects due to viscous dissipation. In the flow, there are also regions (as the rear of the body) in which the presence of near–vacuum strongly reduces the heat transfer. This contributes to the increasing body temperature. If the generation of heat increases so quickly that the loss of heat may be inadequate to achieve an equilibrium state, we may have a thermal explosion. In addition, the presence of massive ablation – although tiny when compared to the whole mass of the incoming cosmic body – changes the flow properties. We expect that the layer between the shock and the surface is entirely turbulent, because of the ablation and the large Reynolds number. The turbulence can interact with shock waves, if the Mach number is not constant, while on the contrary the effect of compressibility suppress the turbulence.

Therefore, it is necessary to distinguish between two flow regimes, according to the fact that the Mach number during the atmospheric entry is constant (*steady state*) or not (*unsteady state*). In the latter case, the distortion of shock waves caused by changes in the Mach number causes the amplification of the turbulent kinetic energy. So, we expect sudden outburst of pressure that can overcome the mechanical strength of the body, starting the fragmentation process.

On the other hand, in the first case – the steady state – the effect of compressibility suppress the turbulence, and then the viscous heat transfer becomes negligible. The cosmic body is subjected to a combined thermal and mechanical stress.

For more details about these concepts refer to Farinella et al. (2001) and Foschini (1999, 2001).

3. THE CASE OF TUNGUSKA

The temperature as a function of height during subartic summer is almost constant along the stratosphere down to the troposphere. Therefore, it is reasonable to assume that the Mach number of the hypersonic flow around the TCB remained almost constant during the second half of its atmospheric path. In this case, it is possible to relate the maximum speed of the flow with the temperature at the stagnation point. Changes in the stream properties are mainly due to changes in the stagnation temperature, which is a direct measure of the amount of heat transfer.

Under these conditions, it is possible to relate the *maximum* speed $V_{\max}$ of the TCB at the fragmentation height (Foschini 1999, 2001):

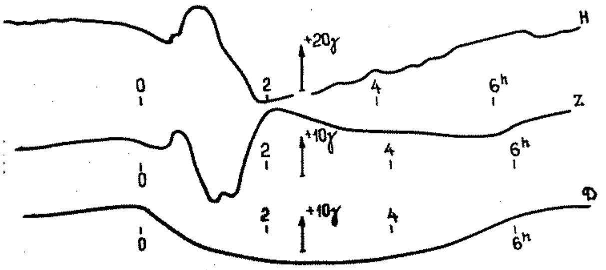

Figure 3. Local disturbances of the geomagnetic field recorded at Irkutsk Observatory $5.9 - 6.6$ *minutes after the explosion. From Ivanov (1964).*

$$V_{\max} = \sqrt{\frac{2\gamma}{\gamma - 1} \frac{S}{(1+\alpha)\rho_{\text{fr}}}} \tag{1}$$

where S is the mechanical strength of the TCB, ρ_{fr} is the undisturbed air density at the height of fragmentation, α is the percentage of ionization ($\alpha = 1$ full ionization), and γ is the specific heat ratio.

The selection of parameters is not straightforward: as stated above, the ablation changes the hypersonic flow, so that α and γ changes along the atmospheric path. For sake of simplicity, it is possible to assume that these parameters remain constant: it is a commonly used assumption. But the problem is now connected to the value of γ, that is the most important parameter in this type of study. Foschini (1999) used a value of $\gamma = 1.7$, according to the experimental investigation of hypervelocity impact by Kadono & Fujiwara (1996); this is also the value commonly used for a monatomic gas or metal vapors. The gas around the TCB is composed by air compressed, dissociated, and even ionized, in addition to the metal vapors derived from the ablation: therefore, $\gamma = 1.7$ could be reasonable.

However Bronsthen (2000a) raised a doubt about this value and he proposed $\gamma = 1.15$, derived from the equation (rearranged from Zel'dovich & Raizer 1966):

$$\gamma = \frac{5\epsilon_{\text{trans}} + 3Q}{3(\epsilon_{\text{trans}} + Q)} \tag{2}$$

where the sum of Q and ϵ_{trans} gives the internal energy of the gas, i.e. the sum of translational energy ϵ_{trans} and Q, the potential energy and the energy of the internal degree of freedom of the particles (vibrational and rotational, for molecules).

There is a third possibility: if the hypersonic flow around the TCB was in the state of plasma (i.e. a ionized gas where the charged particles density is sufficient to dominate the dynamics of particles), this means that electric and magnetic fields are present (e.g. Beech & Foschini 1999) and, therefore, they can limit the degree of freedom of particles. Indeed, the specific heat ratio can be written, according to

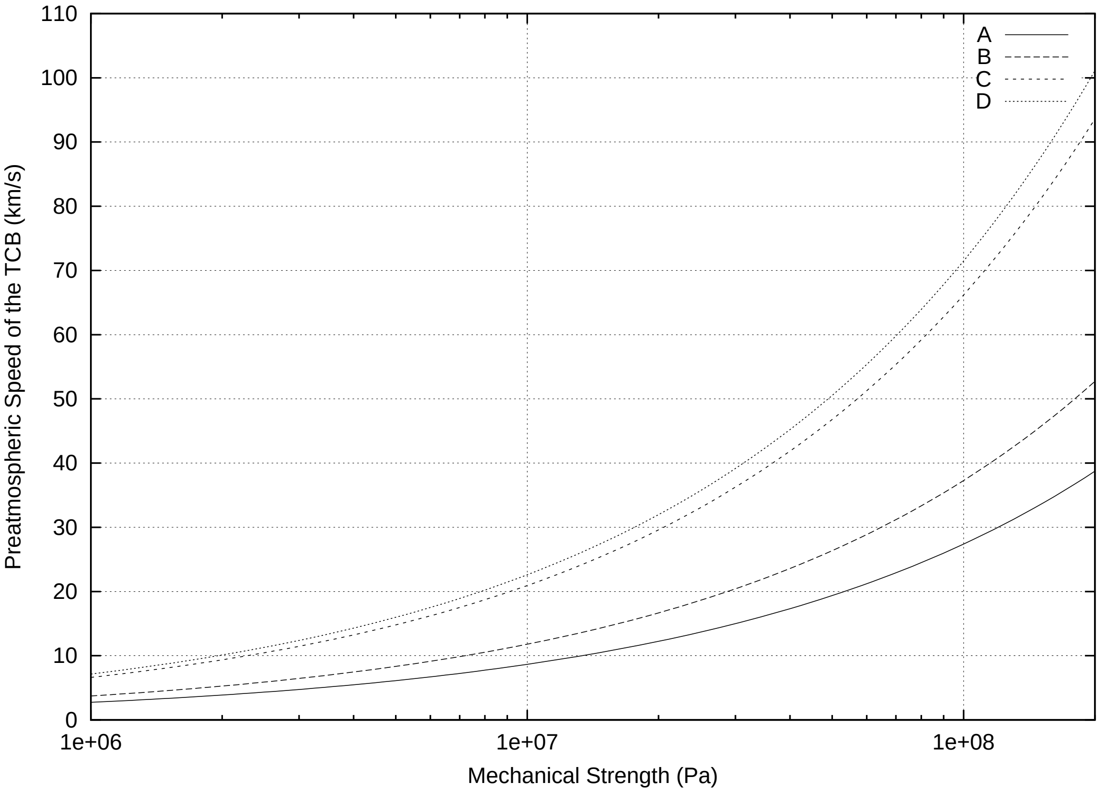

Figure 4. Evaluation of maximum speed of the TCB for four different compositions of the TCB and four different states of the shocked air: (A) $\gamma = 3$, $\alpha = 1$, plasma; (B) $\gamma = 1.7$, $\alpha = 0.75$, fully ionised gas; (C) $\gamma = 1.15$, $\alpha = 0.75$, partially dissociated and ionised air at high temperature; (D) $\gamma = 1.15$, $\alpha = 0.5$, dissociated and ionised air at high temperature.

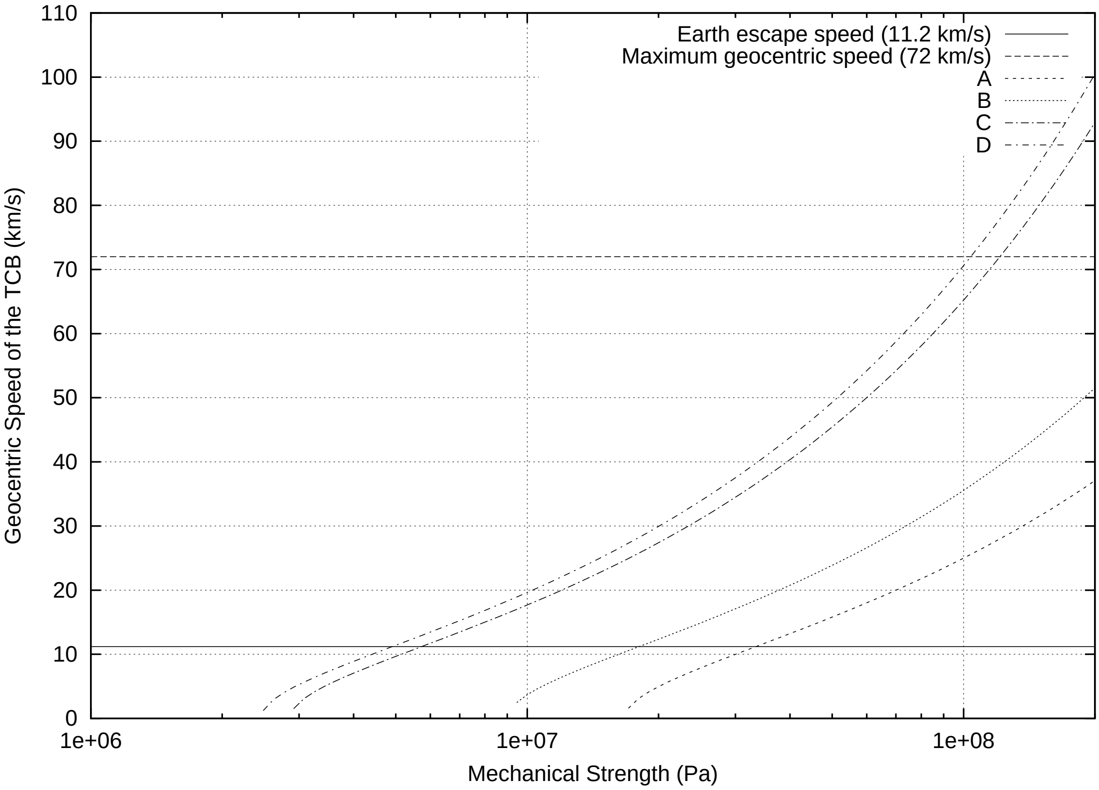

Figure 5. As in Figure 4, but with values of geocentric speed.

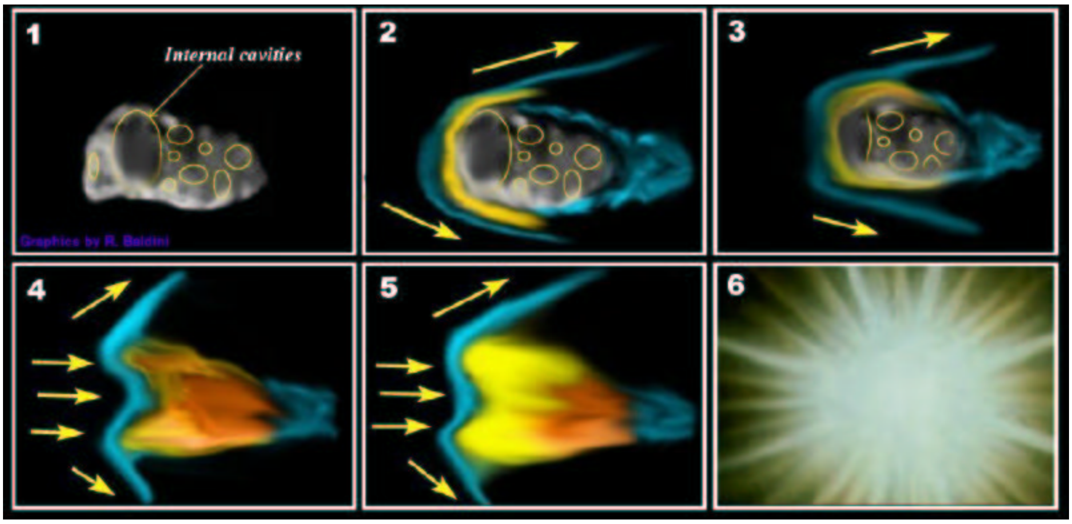

Figure 6. *Schema of the possible process by means internal cavities could increase the deceleration and airburst efficiency. As the cosmic body enters the Earth atmosphere, the ablation removes the surface, discovering the internal cavities, which act as something like a parachute, increasing the deceleration.*

the law of equipartition of energy (Landau & Lifshitz 1980):

$$\gamma = \frac{l+2}{l} \tag{3}$$

where l is the degree of freedom of particles. For example, $l = 3$ for a monatomic gas or metal vapours, because the atom has three degrees of freedom (translation of atoms along x, y, z directions) and $\gamma = 5/3$. For plasma, the presence of electric fields forces the ions or even ionised molecules, if present, to move along the field lines, and therefore $l = 1$. This implies that $\gamma = 3$, close to Kadono & Fujiwara's original experimental value of 2.6 (Kadono & Fujiwara 1996). Indeed, their original experimental results gave a value of $\gamma = 2.6$, that the authors considered too high. They modified the calculations considering that the expansion velocity of the leading edge of the plasma was about twice that of the isothermal sound speed, obtaining a more reasonable – in their opinion – $\gamma = 1.7$.

Concerning the Tunguska event, it is worth noting that a *local* disturbance of the geomagnetic field had been registered $5.9 - 6.6$ minutes after the beginning of seismic waves and continued for about four hours, reaching a peak of 0.056 A/m for the H component (Figure 3; see Ivanov 1964). So there were electromagnetic effects and we can expect that they derived from the plasma cloud developed during the explosion or even from the hypersonic flow before the explosion. In any case, it is reasonable to include the possibility to have $\gamma = 3$ in the hypersonic flow during – at least – the terminal part of the atmospheric trajectory of the TCB.

In Figure 4, the maximum speed according to Eq. (1) is plotted as a function of the mechanical strength and for different values of specific heat ratio and ionisation coefficient. The undisturbed air density at the fragmentation height is taken equal to $\rho_{\mathrm{fr}} \approx 0.2$ kg/m^3 (Allen 1976), that corresponds to a height of 15 km, just a scale height before the airburst. In Figure 5 the same as in Figure 4 is plotted, but for the geocentric speed as a function of the mechanical strength: in this case, the two reference speeds (11.2 and 72 km/s, the minimum and maximum geocentric speeds of a cosmic body at 1 AU) can give further constraints on the values of velocities.

As already noted by Ceplecha (1999, personal communication), the key point in fragmentation is how the ablation changes the hypersonic flow. If the ablation does not appreciably modify the shocked air around the TCB, the carbonaceous body hypothesis could be plausible (cases C and D). However, if the shocked air is mixed with ionised atoms from the TCB so that the gas around the body is fully ionised or even plasma, the only possible solution appears to be an asteroidal body (stony or even iron; cases A and B). The values obtained in Figure 4 show that, in any case, it is very unlikely that a cometary body could reach such a low height, because it would have an unphysical low value of speed. However, given the large uncertainties, it is not possible to exclude at all the cometary hypothesis. In addition, the existence of asteroids with an extremely low density is known, such as Mathilde (≈ 1300 kg/m^3), which suggest some connections with comets. Such a body could have an increased efficiency in deceleration (see Figure 6; cf. Foschini 1998).

During the *Meteoroids* 2001 conference, the results about the Tagish lake meteorite (see contribution by P. Brown and D.O. ReVelle in this issue) showed spectral characteristics close to D–class asteroids and a bulk density of 1670 kg/m^3. This means that the parent body should have lower density, because the cosmic body is compacted by aerodynamic load. On the basis of these studies, D.O. ReVelle (personal communication) suggested that the Tunguska Cosmic Body could have a similar structure. ReVelle's studies also suggest that a porous body have an enhanced luminous and vaporization efficiency, so that it could explain why a chondritic body was completely vaporized. In addition, it can also explain the absence of smoky trails, which generally occur during the falling of chondritic bodies, bypassing the objection invoked by Rasmussen et al. (2001) as argument in favour of the cometary hypothesis, and the fact that no macroscopic remnant has been found until now.

4. FINAL REMARKS

These studies on atmospheric dynamics together with a comprehensive examination of the available literature on the Tunguska event, allowed us to select a set of possible atmospheric trajectories, from which we computed the related orbits (1120). This set was later restricted, by eliminating orbits hyperbolic (30) and with semi–major axis greater than 4.2 AU (204). The remaining 886 orbits were examinated by using the Bottke et al. (2000, 2001) method, based on the dynamic properties of celestial bodies, in order to find the sources. We find that 739 orbits (83%) are of bodies coming from typical asteroidal sources, while only 17% are from cometary sources. This result, combined with what we obtained from the atmospheric dynamics, suggest that the asteroidal nature is the most probable for the Tunguska Cosmic Body. Full details of the part concerning the interplanetary dynamics can be found in the paper by Farinella et al. (2001).

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