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Interception of a bolide ?

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Abraracourcix ne craint qu'une chose : c'est que le ciel lui tombe sur la tête, mais comme il le dit lui-même, "c'est pas demain la veille !"

René Goscinny [GU61]

In Mayan language, Chicxulub means "devil's horns".

Charles Frankel [Fra96]

Abstract

We present a review of the literature on the subject of a possible collision between the Earth and a meteorite or comet. We emphasize the global effects when sufficient energy is involved. We propose several types of human actions adapted to the physico-chemical nature of the collider bolide.

Résumé

Nous proposons une revue bibliographique sur la question d'une possible collision entre la Terre et un météorite ou une comète. Nous insistons sur les effets globaux lorsqu'une énergie suffisante est mise en jeu et nous proposons plusieurs types d'actions humaines adaptées à la nature physico-chimique du bolide collisionneur.

Keywords: asteroids, comets, collision, physics, astro-ph.EP

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1) Introduction

Our question is prompted by three events. First, the majority of the scientific community now agrees that the extinction of the dinosaurs and many other living species 65 million years ago was caused by an asteroid or comet, ten kilometers in diameter, which collided with the Earth [Koe96]. Secondly, at the beginning of this century, a 50-meter object hit the Earth in Tunguska, Siberia, with dramatic effects on the local vegetation [CTZ93]. A third such event occurred on Jupiter three years ago, when the two-kilometer Shoemaker-Levy comet crashed into the Jovian atmosphere [Duf94].

Three questions naturally arise: (i) What probability is there for such a catastrophe to occur on Earth in the future? (ii) What is the level of a disaster that is “acceptable” for mankind? (iii) What can be done to prevent such an event?

We stress that a global methodology is required to consider such a problem and refer the reader to previous work done at Aerospatiale [Dar93] to prevent damage to a space plane by micrometeoroids. First, a good knowledge of the threat is required. Second, the effects of collision of an asteroid or comet with the Earth on biological and economic equilibrium must be considered. Third, the ideal type of space protection suitable for preventing such a catastrophe must be calculated.

2) Space threat

It was recently established that the collision of a meteorite with the Earth could have major global effects for living species on our planet. We need only to consider the sudden disappearance of dinosaurs 65 million years ago. In 1980, L. and W. Alvarez, F. Asaro and H. Michel [Alv80] suggested that a correlation between this event and the unusual concentration of iridium in the Cretaceous-Tertiary K/T geological stratum could correspond to the impact of an asteroid on Earth. The asteroid was estimated to have a diameter of 10 kilometers (the same order of thickness as the troposphere). Assuming a density of 3 metric tons per cubic meter and a relative velocity of 30 kilometers per second on impact, the kinetic energy transmitted to the atmosphere by such a meteorite is around 10^{24} joules.

Such an asteroid would produce a crater whose diameter, by initial estimate, would be around 20 times that of the object. And a crater with a diameter of 150-250 kilometers was effectively (re)-discovered in 1991 by A. Hildebrand [HBC91] at Chicxulub in Yucatan, Mexico, with difficulty due to a layer of post-impact sediment around, 1 km thick. The correlation between this major biological extinction and the Chicxulub crater now seems well established. See, for example, the review article of C. Chapman and D. Morisson [CM94], the synthesis made by C. Frankel [Fra96] and the scientific proposal of C. Koeberl *et al.* [Koe96].

Moreover, geological observations suggest that four other similar catastrophic events occurred during the last 500 million years [CM94].

The 1908 event in Tunguska, Siberia, is more mysterious. An area of 2000 square kilometers of forest was destroyed by a meteorite that exploded in the atmosphere without causing any

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human victims. The atmosphere was very perturbed, “night lights” were observed in Europe and Asia [Whi30] and, according to C. Sagan [Sag80], the resulting shock wave traveled twice around the Earth.

Scientific studies of this event did not begin until 20 years later with the mission of the geologist L. Kulik [Kul27]. The energy transmitted to the atmosphere was estimated at $5 \cdot 10^{16}$ joules. But the origin of this meteorite does not seem to have been fully established. According to Sagan [Sag80], the Earth’s orbit intersected the orbit of Enke’s comet on June 30, 1908, and the meteorite could be a piece of this comet. It should be noted that a kinetic energy of $5 \cdot 10^{16}$ joules is compatible with a 100-meter object with a density of 0.1 metric ton/m³ (typical for comets [Wyc87]) and a relative velocity of 30 km per second. The models proposed by C. Chyba, P. Thomas and K. Zahne [CTZ93] exclude dense asteroids and light comets but show that the Tunguska meteorite could be a stony asteroid. The energy data are consistent with a 50-meter object with a specific gravity of 4 relative to liquid water and an incoming velocity of 15 km/s. It is interesting to note that this relatively “small” impacting energy is equivalent to that obtained with 10 megatons of TNT, *i.e.* 1000 times more than that of the atomic bombs which destroyed Hiroshima and Nagasaki in August 1945.

Here we wish to focus on very recent “non-events” concerning interactions between Earth and small asteroids. The asteroid Toutatis (1989AC) discovered by a French team of astronomers (A. Maury *et al.* [Mau89]) is a dual object composed of two stones, 4 and 2 kilometers in diameter, that approaches the Earth every four years. The minimum distance between Earth and Toutatis was equal to 3.6 million kilometers on December 8, 1992 and will be only 1.5 million kilometers on September 29, 2004 (see *e.g.* [Aug92]).

Recently, a small 9-meter object (1991 BA) intersected the Earth’s orbit at only 170,000 kilometers (half the distance between Earth and Moon!) [SRM91]. Object 1989FC with a diameter of 300 meters, which crossed the Earth’s orbit at only 700,000 kilometers on March 23, 1989, was more of a hazard (see *e.g.* [Fra96]).

Currently, no systematic effort is being made to catalog such small asteroids with diameters of, for instance, 100 meters to 10 kilometers, orbiting the Sun and in a position to intersect the Earth’s orbit, causing a major catastrophe. Certain families of asteroids are known (*e.g.* Apollo, Amor, Atens) and some 250 objects have been identified [Fra96]. But there are an estimated 3000 asteroids in the 1-10 km class [SWS90].

Detection of small asteroids is not a trivial problem. For instance, to be compatible with the diffraction of an electromagnetic wave with a wavelength $\lambda = 0.5 \cdot 10^{-6}$ meters, the telescope required to detect a meteoroid with a diameter α of 1 km located at a distance L of 1 astronomical unit (150 $\cdot 10^6$ kilometers) would have to have a diameter D calculated by the following equation:

$$\tan \theta = \frac{\alpha}{L} \leq 1.22 \frac{\lambda}{D}$$

which means that the diameter would have to be more than 100 meters! This unrealistic instrument could be replaced by a sequence of interferometers using CCD cameras, but this technology is still in development, *e.g.* at Kitt Peak Observatory (see [Spa94]).

It should also be noted that long-range prediction of the orbits of such small objects is not obvious because of their complex interactions with the Sun and Earth. The trajectory of an object such as Toutatis exhibits a strong resonance correlation with the Earth and this regular transfer of energy could be potentially hazardous in the future. We feel that a special effort should be made to obtain accurate ephemeris data on these very small objects.

A general effort should also be made to develop a system for studying the Earth's environment to be able to determine the real risk of collision of an asteroid with Earth in the future.

Comets are a second family of meteorites that can collide with the Earth. The risk appears small for periodic comets (*e.g.* Halley's comet) but the most interesting comets are irregular. The problem is to determine the probability of collision of such an irregular comet with the Earth over a typical period of 10^6 years.

We can imagine a stochastic model based on the hypotheses of Oort's cloud (see [Oor63]) located 50,000 astronomical units = $7.5 \cdot 10^{12}$ kilometers from the Sun. A comet with mass M (what is the mathematical probability of this random variable?) has an initial position (what is the probability of this random variable?) with a velocity V (same question) and enters the solar system (what is the probability for the date of injection?). When the positions of the planets are known at time zero (what is the law of this random vector?), it is sufficient (but is it possible?) to compute the irregular comet's trajectory to determine the probability of collision with the Earth and the possible impact parameters (for instance, a relative velocity of such a comet is conventionally estimated at 50-60 km per second).

To our knowledge, this modeling problem has not yet been solved. A major difficulty probably resides in determining the appropriate approximate model that can take into account the mean values of the main planets in the solar system and the filtering effect of Jupiter and Saturn on telluric planets. Such a theoretical development combined with knowledge of comets with an irregular or long period for calibration of the parameters appears important for determining this risk based on irregular comets.

The risk of a collision between the Earth and a meteorite in the future is related to two separate threats: near-Earth asteroids and long-period comets. The first threat is not known, because no systematic program of observations has been developed to detail all the 100 m-10 km objects approaching the Earth. The second threat is structurally uncertain. In both cases, our knowledge could be improved by modeling to accurately predict the future possible collision of objects with complicated trajectories such as the asteroid Toutatis or determine the probability of collision with an irregular comet.

3) Global effects of a single collision

We begin again with the remark that our knowledge of previous global catastrophes remains limited. The Cretaceous/Tertiary transition 65 million years ago has been correlated with a meteorite's impact. But the exact cause of the disappearance of 70 percent of living species on Earth is still an open question. Recent studies (R. Schultz and S. d'Hondt [SH96], N. Bhandari, V. Courtilot and R. Rocchia [BCR97]) show that coupling between asteroid impacts and volcanic eruptions is considerable. In particular, the amount of collision energy transferred to the atmosphere and biosphere is a very crucial parameter.

The energy levels of such collisions must be studied. A Chicxulub-like impact is associated with the transfer of 10^{24} joules from the meteorite to the Earth, whereas the 1980 eruption of Mount Saint Helen's volcano caused an input of (only!) 10^{16} joules, very comparable to the (small?) Tunguska event of 1908. It should also be noted that the total energy released annually by the Earth (heat flow, volcanoes, earthquakes, etc.) is estimated at 10^{21} joules [Koe96].

If 10^{24} joules were transferred to the Earth's system, the amount of energy to be dissipated would amount to 10^{14} joules *i.e.* the energy of 10^6 100-watt light bulbs per person during one year considering a world population of 10^{10} people.

An event comparable to the Chicxulub impact occurred in July 1994, when the Shoemaker-Levy comet entered Jupiter's atmosphere. This comet was discovered in 1993 [SSL93] and probably broke up into 20 pieces one year before discovery, when this long-period comet first entered Jupiter's gravitational field. The impact of several objects was predicted theoretically [Sho94] and the effects caused a spot 1900 kilometers in diameter comparable to a giant red spot with light emission due to excitation of very hot gases. The total energy transferred by the nine impacts between July 16 and 22, 1994 is estimated at $4 \cdot 10^{21}$ joules and the total diameter of the initial object was around 2 km.

This interaction between the incoming meteorite and the Jovian atmosphere is now being modeled (see *e.g.* [Tak95]). Its effects on Jupiter's meteorology are still large several years after the collision. It should be noted that another collision of this type between a meteor and Jupiter was probably observed by J.D. Cassini in December 1690 (see *e.g.* [Hir97]).

Is it possible to mathematically describe the effects of rapid interactions such as the above? We assume that a mathematical model of the atmosphere and biosphere can be obtained by a dynamical system using differential equations, *i.e.* the search for a vector $X(t)$ with a finite number of real components (or parameters) as a function of time, satisfying a nonlinear equation of the type:

$$\frac{d}{dt}(X(t)) = f(X(t)) + g(t)$$

where $f(\bullet)$ describes all the physical-chemical-biological models coupling the internal variables of system X and $g(\bullet)$ describes the external force, typically a function containing

at least two periods, the 24-hour “day forcing” and the 365-day “year forcing”. An event such as Chicxulub corresponds to adding an enormous Dirac delta function to term $g(\bullet)$ in the right-hand side of the above model. After integration over a short period, the initial conditions are suddenly changed at $t = 0$ when the catastrophic event occurs. It seems very reasonable mathematically that different equilibria can be found by the system as the time approaches infinity after such a large perturbation (see *e.g.* [HS74] for the mathematical foundations of this type of dynamical phenomenology). In sum, the impact effects are hazardous if they create ruptures in the global equilibria of the Earth’s ecological system.

The community of Earth sciences has developed a Global Change program (see *e.g.* [GC96]) whose objective is the development of a good understanding of global modifications on biosphere, atmospheric chemistry, terrestrial ecosystems, etc. that are induced by human activities on the planet. This research program is extraordinarily complex and ambitious but mathematically speaking, it corresponds to regular modifications of function $g(\bullet)$. On the contrary, the project of new program of Response of the Earth System to Impact Cratering [Koe96] is much more adapted to these abrupt modifications. We think that this programme is scientifically essential and could be incorporated in a much more complex one. In fact, actual studies concerning risks induced by impact on the Earth by asteroids are at our knowledge based on a life-death binary option [CM94]. Our intuition is that reality of a global catastrophe is much more complex to describe. The important fact is to consider the relations between human beings and a global catastrophe can occur whereas few persons are killed by the initial cause like the impact of an asteroid but if the induced effects destroy the essential links that makes economical activity (agriculture, industry, treatment of information).

Here we wish to focus on the necessity of studying the global effects of collision of a meteorite with the Earth using coupled methods that take into account, not only physically, spectacular phenomena such as those observed with the Shoemaker-Levy comet’s impact on Jupiter, but also the biological and economic consequences. In particular, to be “acceptable”, a collision must not damage either the essential links between human beings (energy fluxes, hydrology) or the more complex ones related to communication, such as education, economy and state organization. The availability of detailed coupled knowledge could be used to determine the cost of an intervention system.

4) Ideas for Human Action

First, it should be remembered that the collision energy of a meteorite with the Earth is basically kinetic, with relative velocities of 10 to 70 kilometers per second. Below, we consider two typical meteorites, modeling a stony asteroid and a long-period comet.

The first object is a cube with length $L = 100$ meters, density $\rho = 3$ metric tons/m³ and relative velocity $V_1 = 20$ km/second. These parameters induce a mass $M_1 = \rho L^3 = 3 \cdot 10^6$ metric tons and a kinetic energy on impact $W_1 = \frac{1}{2} M_1 V_1^2 = 6 \cdot 10^{17}$ joules.

The second object is Halley’s comet, for which the data were synthesized by S. Wyckoff [Wyc87]: a sphere with a half-surface area of 100 km² (*i.e.* a diameter of 8 km) and a

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density $\rho = 0.1$ metric tons/m³ consistent with the icy conglomerate model for comet nucleus proposed by F. Whipple in 1950 (see [Whi63]). The mass of Halley's comet can then be approximated at $M_2 = 3 \cdot 10^{10}$ metric tons, and the typical relative velocity for long-period comets is around $V_2 = 50$ km/second [CM94]. The kinetic energy $W_2 = \frac{1}{2} M_2 V_2^2$ is then equal to $4 \cdot 10^{22}$ joules, *i.e.* 10 times that of Shoemaker-Levy's comet and only 1/25th that of Chicxulub.

The first idea that comes to mind is to destroy the asteroid before impact by an explosion. But although such an action would transfer some of the energy by changing the structure of the incoming asteroid, it is not at all clear whether this would change the total impulse. For instance, for a 10-metric-ton projectile with a velocity of 40 km/s, the momentum is $i = 4 \cdot 10^8$ kg.m/s, which is negligible compared to the momentum of the small cube $I_1 = M_1 V_1 = 6 \cdot 10^{13}$ kg.m/s or the momentum $I_2 = M_2 V_2 = 1.5 \cdot 10^{18}$ kg.meters/second of Halley's comet. The center of gravity then continues its initial trajectory and a huge collision is replaced by a series of smaller ones (see *e.g.* J. Ahrens and A. Harris [AH92]). The energy transferred to the atmosphere would be considerably decreased by dispersion, but the remaining collisions are still very hazardous. According to [AH92], fragmentation is a satisfactory option only if the maximum fragment size is less than 10 meters so that the fragments burn up in the atmosphere. In sum, we feel that fragmentation can only be considered as a "degraded mode" of action, when deflection is not possible.

We now show that deflection of the stony cube is possible using conventional propulsion technologies. First, if it occurs sufficiently before the predicted time of collision, *e.g.* one year, a deflection $\Delta v = 1$ cm/s will produce a much larger displacement due to gravitational amplification (*e.g.* by a factor of 20) than the $\Delta x = 310$ kilometers produced by the simple hypothesis of a straight trajectory. Being optimistic about gravitational amplification, we keep this hypothesis of 1 cm/s as initial velocity deflection.

It should be noted here that the kinetic energy associated with this displacement is $E_1 = \frac{1}{2} M_1 \Delta v^2 = 1.5 \cdot 10^5$ joules. Let us consider the above small asteroid as a space rocket with a propellant mass m and a specific impulse I_{sp} associated with a gas ejection velocity $g_0 I_{sp} = 3$ km/s. The conventional relation (see *e.g.* [DF94]):

$$\Delta v = g_0 I_{sp} \log \left[\frac{M_1 + m}{M_1} \right]$$

simplifies since $m \ll M_1$ yielding $m = M_1 \frac{\Delta v}{g_0 I_{sp}}$, *i.e.* for a cubic asteroid and the above data, $m = 10$ metric tons of propellant. It is then necessary to apply such a push to the asteroid after a complex space rendez-vous somewhere in solar system relatively close to the Earth's orbit. This is of course not an easy mission, but it is a priori compatible with today's technology. However, detailed design of such a system remains to be done.

We now consider the problem of giving a similar tap to Halley's comet. First, it should be noted that the kinetic energy associated with this deflection of 1 cm/s is $E_1 = \frac{1}{2} M_2 \Delta v^2 = 1.5 \cdot 10^9$ joules [a thousand megajoules!]. This is an enormous amount of energy from the

standpoint of today's capabilities. It should be noted that although this energy is huge, it is nothing compared with $W_2 = 4 \cdot 10^{22}$ joules that would be transferred to the Earth's system by a direct collision. The problem is to create an impulse $J_2 = M_2 \Delta v = 3 \cdot 10^{11}$ kg.meters by second somewhere around Jupiter, because there is a good probability that such a space threat would interact first with Jupiter, which is a good place in the solar system for playing with gravity.

Aside from the fact that the associated propellant mass ($m = 10^5$ tons) is unrealistic, the solution suggested above for a small asteroid is obviously unfeasible because a comet-like object with low density ($\rho = 0.1$) is somewhat like cotton wool and is a very fragile object.

A brutal method was suggested in [AH92]. It consists of using explosive nuclear radiations causing the sublimation of matter and therefore transverse impulses. Our experience at Aerospatiale shows that the explosion of a few megaton burst at a distance of few kilometers causes a velocity increment given by the equation

$$\Delta v = \frac{3 \pi}{8} \frac{I_0}{\rho R}$$

where $\rho = 0.1 \text{ ton/m}^3$ is the typical density of a comet, R is its radius of 4 kms and I_0 is the impulse induced by the physical processes described above. The typical value of I_0 is around 3000 pascals.second, giving $\Delta v = 9 \cdot 10^{-3}$ m/s, *i.e.* what is desired. It should be noted that the distance of some kilometers considered here is quite unrealistic and other effects such as material shock waves inside the comet may destroy the internal structure. Moreover, a large amount of energy is lost in space in the other directions by γ -ray emissions and we have not considered here the ethical problem of using nuclear charges in the space environment.

We conclude this section with a straightforward idea concerning impulse conservation. Let us assume that it is possible to sublimate a quantity of ice from the comet's nucleus. This water vapor would then expand in a vacuum with a rarefaction wave. The ejection velocity from the comet's nucleus is exactly equal to the speed of sound in the gas (see *e.g.* the classic book by R. Courant and K. Friedrichs [CF48]). Under these rarefied conditions of low external pressure and temperature, it is difficult to estimate the speed of sound; we suggest a speed $c = 100$ meters per second. Then, the momentum conservation equation $M_2 \Delta v = m c$ establishes that the sublimation of $m = 3 \cdot 10^6$ tons of Halley's comet will deflect it by $\Delta v = 1$ cm/s. The advantage of this approach is that no propellant is required. The drawback is that the ejection velocity is relatively low and the energy cost of such a propulsion system is very high.

From conventional thermodynamic data (*e.g.* [PR93]), the latent energy of fusion is equal to 330 kjoules/kg and the evaporation energy is around 2300 kjoules/kg. As a first approach, we can estimate that the energy required for water sublimation is equal to around $3 \cdot 10^6$ joules/kilogram. This means that the energy required to create the appropriate impulse is $S_2 = 10^{16}$ joules, to be compared with $E_2 = 10^9$ joules and $W_2 = 4 \cdot 10^{22}$ joules. If such

an energy is communicated by a laser source, we could also take into account the radiation pressure associated with the optical reflection of the ice off the comet, creating an additional impulse.

In this section, we have shown that human action is possible on a small asteroid using today's technology one year before impact, with the help of gravity, which would typically amplify the effect by a factor of 20. The deposit of a mass of 10 metric tons of propellant is sufficient to deflect a 100 m stony asteroid. With the same assumptions concerning kinetics, an energy of some megatons on a Halley-type comet would probably create a sufficient impulse by sublimation. This system design could be an alternative to the explosion of a large nuclear charge at a short distance from the meteor and should be studied in greater detail.

5) Conclusion

We have studied the problem of possible bolide interception from three aspects: space threat, global effects and human action. The space threat is due to predictable asteroids which are not sufficiently well known and to irregular comets whose possible long term impact prediction remains generically uncertain. The effects on Earth must be considered globally using, for instance, methodologies developed by the Global Change science community, taking into account the fact that the energy transfer induced in the system by the impact of a large object is of the same order of magnitude as the total energy dissipated each year by geophysical phenomena. Finally, possible human action remains modest in terms of velocity transfers (1 cm/s) when using early detection, interception a long time before the predicted date of the catastrophe and deflection with the help of the gravitational field. Action using a conventional propulsion system is possible for deflecting small asteroids, whereas a very large source of energy would be necessary to change the trajectory of a Halley-type comet by sublimation of a large quantity of solid ice of the comet's nucleus.

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References

- [AH92] Ahrens, A. Harris, "Deflection and Fragmentation of Near-Earth Asteroids", *Nature*, volume 360, page 429–433, December 3, 1992.
- [Alv80] L. Alvarez, W. Alvarez, F. Asaro, H. Michel, "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction", *Science*, volume 208, pages 1095-1108, 1980.
- [Aug92] J.F. Augereau, "Le retour de Toutatis", *Le Monde*, Paris, December 9, 1992.
- [BCR97] N. Bhandari, V. Courtillot, R. Rocchia, *European Congress of Geosciences*, March 1997.

- [CM94] C. Chapman, D. Morison, “Impacts on the Earth by Asteroids and Comets : Assessing the hazard”, *Nature*, volume 367, pages 33-40, January 6, 1994.
- [CF48] R. Courant, K. Friedrichs. *Supersonic Flow and Shock Waves*, Interscience, New York, 1948.
- [CTZ93] C. Chyba, P. Thomas, K. Zahnle, “The 1908 Tunguska Explosion: Atmospheric Disruption of a Stony Asteroid”, *Nature*, volume 361, pages 40-44, January 7, 1993.
- [Dar93] P. Darquey, “Hermes space plane. Design assessment report for meteorites and orbital debris environment”, *Aerospatiale Espace & Defense* n° 120183, January 1993.
- [DF94] F. Duret, J.P. Frouard. “Conception générale des systèmes spatiaux ; conception des fusées porteuses”, *Ecole Nationale Supérieure de l’Aéronautique et de l’Espace*, Toulouse, 1994.
- [Duf94] J.P. Dufour, “La fin d’une étoile”, *Le Monde*, Paris, July 16, 1994.
- [Fra96] C. Frankel, *La mort des dinosaures : l’hypothèse cosmique. Chronique d’une découverte scientifique*, Masson, Paris, April 1996.
- [GC96] W. Steffen, A. Shvidenko (Eds). International Geosphere-Biosphere Programme : A Study of Global Change of the International Council of Scientific Unions, *Report n° 37*, Stockholm, 1996.
- [GU61] R. Goscinny, A. Uderzo. *Asterix le Gaulois*, Dargaud, Paris, 1961.
- [HBC91] A. Hildebrand, W. Boynton, A. Camargo, G. Penfield, M. Pilkinson, D. Kring, “Chicxulub crater : a possible cretaceous-tertiary boundary impact crater on the Yucatan peninsula, Mexico”, *Geology*, volume 19, pages 867-871, 1991.
- [Hir97] P. Le Hir, “Le choc probable d’une comète et de Jupiter “observé” 300 ans après”, *Le Monde*, Paris, January 16, 1997.
- [HS74] M. Hirsch, S. Smale, *Differential Equations, Dynamical Systems, and Linear Algebra*, Academic Press, New York , 1974.
- [Koe96] C. Koeberl *et al.*. “Response of the Earth System to Impact Processes”, *Proposal for an European Science Foundation scientific programme*, November 1996.
- [Kul27] L. Kulik, “To the question about a place of the Tunguska meteorite fall”, *Doklady Akademii Nauk SSSR*, volume 23, pages 399-402, 1927.
- [Mau89] J.L. Heudier, R. Chemin, A. Maury, C. Pollas, “1989AC”, *International Astronomical Union Circular* n° 4701, page 1, January 5, 1989.
- [Oor63] J. Oort, “Empirical data on the origin of comets”, in *The Moon, meteorites, and comets*, volume 4, *the solar system*, edited by B.M. Middlehurst and G.P. Kuiper, U. of Chicago press, Chicago & London, pages 665-673, 1963.
- [PR93] J. Pérez, A. Romulus, *Thermodynamique ; fondements et applications*, Masson, Paris, 1993.
- [Sag80] C. Sagan, *Cosmos*, Random House, Inc, New York, 1980.
- [SH96] P. Schultz, S. D’Hondt, “Cretaceous-Tertiary (Chicxulub) impact angle and its consequences”, *Geology*, volume 24, pages 963-967, November 1996.

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- [Sho94] E. Shoemaker, C. Shoemaker, “The crash of Shoemaker-Levy 9 into Jupiter and its implications for comet bombardment on Earth”, in *New Developments Regarding the KT Event and Other Catastrophes in Earth History*, Houston University, pages 113-114, 1994.
- [Spa94] Spacecast 2000, “Preparing for Planetary Defense. Detection and Interception of Asteroids on Collision Course with Earth”, November 1994.
- [SRM91] J. Scotti, D. Rabinowitz, B. Marsden, “Near miss of the Earth by a small asteroid”, *Nature*, volume 354, p. 287-289, 1991.
- [SSL93] E. Shoemaker, C. Shoemaker, D. Levy, J. Scotti, P. Bendjoya, J. Mueller, “Comet Shoemaker-Levy (1993e)”, *International Astronomical Union Circular* n° 5725, page 1, March 26, 1993.
- [SWS90] E. Shoemaker, R. Wolf, C. Shoemaker, “Asteroids and comet flux in the neighborhood of the Earth”, *Geological Society of America*, Special paper n° 247, pages 155-170, 1990.
- [Tak95] T. Takata, “Three-dimensional analysis of impact processes on planets”, PhD. Thesis, *California Institute of Technology*, NIPS-96-33178, Pasadena, 1995.
- [Whi30] F. Whipple, “The great Siberian meteor and the waves, seismic and aerial, which it produced” *Quarterly Journal of the Royal Meteorological Society*, volume 56, pages 287-304, 1930.
- [Whi63] F. Whipple, “On the origin of the cometary nucleus”, in *The Moon, meteorites, and comets*, volume 4, *the solar system*, ed. by B.M. Middlehurst and G.P. Kuiper, University of Chicago Press, Chicago & London, p. 639-664, 1963.
- [Wyc87] S. Wyckoff, “Ground-based observations of Halley’s comet”, *AIAA paper* n° 87-630, January 1987.