

Near Earth Objects, our (sometimes inconvenient) celestial neighbours

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Once upon a time...

Once upon a time...

It all started in 1770, when Charles Messier discovered the comet that is now known under the name of comet Lexell.

This comet passed exceptionally close to the Earth, and posed problems to those who tried to compute its orbit.

Lexell succeeded in establishing:

- that the comet was on a 5.5 yr period orbit,
- that its orbit before 1767 was of longer period and had been modified by a close encounter with Jupiter,
- that another encounter with that planet in 1779 would send again the comet in an outer orbit.

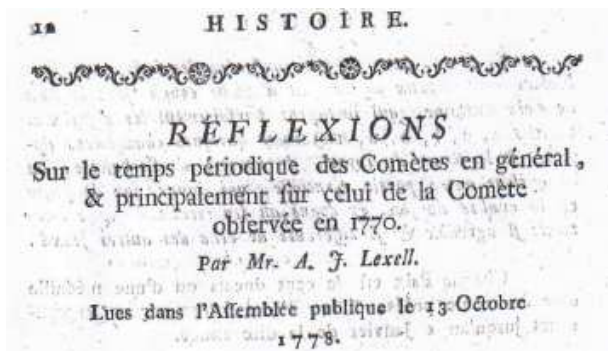
In short, with the work of Lexell the modern era of the dynamics of small solar system bodies was born.

An old problem: ephemerides



The difficult problem of predicting the future position of an Earth-approaching body with a short observed arc was born then, and was a major concern for Lexell.

An old problem: communications



Another difficult problem: to talk to fellow scientists and to the interested public about these matters.

Line of Variations, chaos and all that...

In mid XIXth century LeVerrier understood that the best-fit orbit of comet Lexell computed from the available observations is poorly constrained.

He identified a line in the space of orbital elements (what we would nowadays call the **Line of Variations**, LoV) in which the point corresponding to the true orbit most probably lies. Current impact monitoring software robots exploit the same concept.

LeVerrier computed the post-1770 time evolution of orbits lying on the LoV, and found them to be extremely sensitive to initial conditions, due to the 1779 jovian encounter. LeVerrier's computations are possibly the **first instance of chaotic dynamics** in physics and astronomy.

LeVerrier's LoV

$$a = 3,147\ 86 + 0,01\mu,$$

$$e = 0,785\ 7161 + 0,000\ 7260\mu,$$

$$\varepsilon = 356^{\circ}\ 15'\ 55'',51 - 12'',67\mu,$$

$$\varpi = 356.16.26,03 - 27,16\mu,$$

$$\varphi = 1.34.19,53 + 4,17\mu,$$

$$\theta = 131.53.56,00 + 83,00\mu.$$

The Line of Variations introduced by LeVerrier for comet Lexell:
from top to bottom, semimajor axis, eccentricity, mean longitude
at epoch, longitude of perihelion, inclination and longitude of node.

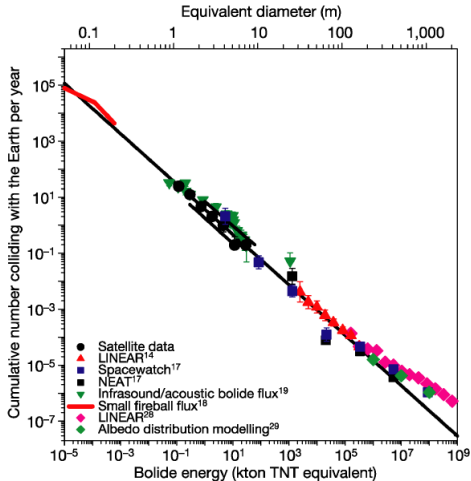
Sensitivity to initial conditions

- 0,3	3,784	0,6632
- 0,2	4,909	0,5251
- 0,1	8,923	0,5349
0,0	+ 60,097	0,9127
+ 0,1	- 58,617	1,0926
+ 0,2	+ 49,751	0,8987
0,3	12,444	0,6532

A small excerpt from LeVerrier's computations: for the values of μ in the left column, the corresponding post-1779 values of semimajor axis and eccentricity of the orbit of comet Lexell.

The problem

The flux of interplanetary bodies (Brown et al. 2002)



Near-Earth Objects (NEOs)

Near-Earth Objects are asteroids and comets on orbits with perihelion distance $q < 1.3$ Astronomical Units.

Among Near-Earth Asteroids (NEAs) are comprised:

- Amors ($q < 1.3$ AU, $a > 1$ AU);
- Apollos ($q < 1.017$ AU, $a > 1$ AU);
- Atens ($Q > 0.983$ AU, $a < 1$ AU);
- NEAs with $Q < 0.983$ AU, $a < 1$ AU.

The solution

Steps to Decrease the Risk

- 1 Detect near-Earth objects.
- 2 Determine their orbits.
- 3 Compute collision possibilities.
- 4 Exclude collision possibilities with further observations.
- 5 Deflect/destroy the object(s) going to collide with our planet.

Discovery of NEAs: current state

With automated surveys currently operating (Catalina, LINEAR, Spacewatch, LONEOS, NEAT) there has been rapid progress; as of November 2008 ≈ 875 NEAs with estimated diameter > 1 km have been discovered.

The total population estimate is tricky, but more than $2/3$ of the 1 km NEAs have been discovered. The remaining ones, however, will take long to discover.

Since “most of the risk” can be shown to come from 1 km objects, if all of them are known not to impact in the next 100 yr, then the risk is decreased by more than $2/3$ with respect to background risk.

Orbit Determination

A single detection does not normally allow to compute an orbit.

Follow-up accumulates observations of the same object until an orbit can be computed.

Identification selects two or more detections from archives and proves that they belong to the same object.

Follow-up is crucial for NEAs and can be a problem for the thousands of detections of an automated survey.

Orbit determination is more difficult for NEAs than for MBs.

For NEAs the orbit can remain poorly determined for a long time.

Can we predict an impact?

Before 1998 the problem of computing all possible impact solutions for objects with a given set of observations had not been solved.

Since orbital evolution is deterministic and is computable with the required accuracy, why do we have a problem? And why do we need to talk about probability?

Actually, there is **not** such a thing as **the orbit** of an asteroid determined from the observations. There is always **a range** of possible orbits, all compatible with the observations. Probability is then just a measure of our ignorance.

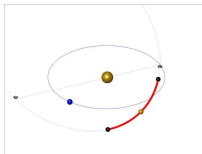
Virtual asteroids and impactors

The orbits compatible with the observations of an asteroid can be described as a swarm of **Virtual Asteroids (VAs)**: only one of them is real, but we don't know which one.

Each VA follows its own orbit; if one of them has an impact with the Earth, we call it a **Virtual Impactor (VI)**, with an associated Impact Probability (IP) depending upon the statistics of the observational errors.

If a NEA has an IP of $1/1\,000$, through the computation of 1 000 VAs we can expect to find one VI. However, if the IP is $1/1\,000\,000$, to find a VI by brute force we need to compute $\approx 1\,000\,000$ VAs: too much, even for current computers.

NEO impact monitoring



Detecting VIs with low IP can be done by arranging VAs along a string.

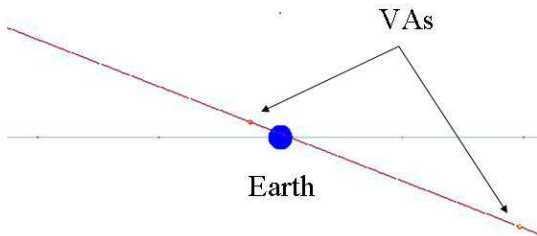
As the VAs proceed on their separate orbits the string stretches, mostly along track, until it wraps around a large portion of the orbit.

If there is a point where the orbits are close to the Earth's orbit, some VAs have close approaches to the Earth.

Detecting VIs

Interpolation on the string is possible. If two consecutive VAs straddle the Earth, an intermediate VA can be built to find the minimum possible approach distance.

The **efficiency gain** with this computational strategy is more than a factor **1 000**.



Impact Monitoring Robots

In March 1999 we could detect a VI with IP 1/1 000 000 000 with only 1 000 VAs (asteroid 1999 AN₁₀).

In **November 1999** the software robot CLOMON began operations in **Pisa**. Each new NEA is monitored for possible impacts in the next century. When VIs are found, they are posted on the Risk Page of NEODyS (<http://newton.dm.unipi.it/neodyS/>).

In 2002 the 2nd generation impact monitoring robots CLOMON2 (replicated in Valladolid, Spain) and Sentry (at JPL, Pasadena, U.S.A., <http://neo.jpl.nasa.gov/risk/>) became operational.

Cross-checking has solved the problem of verification, and indeed has increased reliability.

Dissemination of information

If no VI is found, a NEA is safe.

The fact that a NEA has some associated VIs can change **only as a result of observations**. In these cases, the astronomical community has to provide further observations.

After an initial turbulent period, the publication of VIs on the WWW has become a well established procedure that does not lead anymore to frequent (and counterproductive) media storms.

This procedure makes sure that the essential information (i.e., the need for further observations) reaches all interested parties.

Eliminating Virtual Impactors

VIs are posted on the NEODyS and Sentry risk pages. Since 2000 (with an interruption due to lack of funds in 2005) the Spaceguard Central Node (SCN) coordinates follow-up observations to reduce the orbital uncertainty. Usually, observers react quickly.

Probability changes when the available information changes. New observations can push IPs both up and down. In the end, an IP can only go to 0 or 1.

If an asteroid is lost while it still has a VI, then the IP cannot change until it is recovered by chance. This currently happens especially for small asteroids.

Deflection

What to do in the (unlikely, but possible) case we discover a NEA that impacts our planet? Can we be prepared for that?

Arguably, deflection is a better option than destruction, but we need to know how to design a deflection mission.

We expect to discover a significant impactor with a **warning time of decades**.

Kinetic Energy Deflection

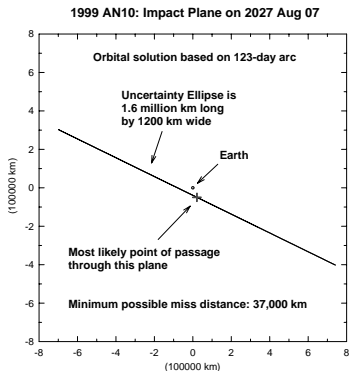
For asteroids of $300 \div 500$ m diameter, enough deflection to avoid collision can be obtained by impacting with a spacecraft. Problem: how to control the exact amount of deflection, and to keep the asteroid in one piece.

The ESA study Don Quijote aims at acquiring the know-how to do this. It envisages two spacecrafts: Sancho orbits around the asteroid, Hidalgo impacts it at > 10 km/s. Seismometers placed on the asteroid determine its internal structure; tracking of Sancho measures the deflection achieved.

Real deflection might need one or more impactors with large masses.

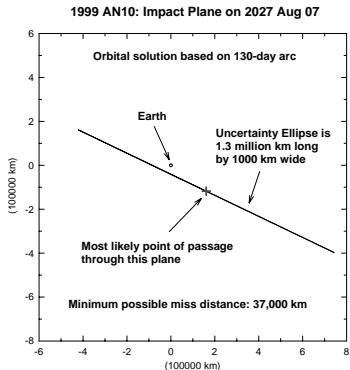
Tricks of the trade

Uncertainty region on the b -plane



The uncertainty region, based on a 123 d observed arc, of 1999 AN₁₀ projected on the b -plane of its Earth encounter on 7 August 2027 (from Chodas 1999).

Uncertainty region on the b -plane

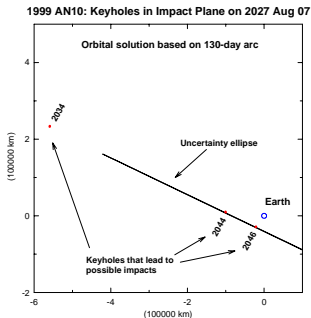


The same region, based on a 130 d observed arc, is smaller, and the nominal solution has moved (from Chodas 1999).

Keyholes

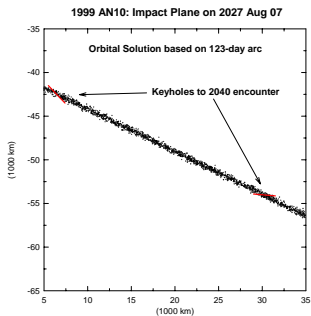
A **keyhole** (Chodas 1999) is a small region of the b -plane of a specific close encounter of an asteroid with the Earth such that, if the asteroid passes through it, it will hit the planet or have a very close encounter with it at a subsequent return.

Keyhole locations



The positions of keyholes in the b -plane of the encounter of 7 August 2027 of 1999 AN₁₀, for impacts in 2034, 2044, and 2046 (from Chodas 1999).

Keyhole locations



The positions of keyholes in the b -plane of the encounter of 7 August 2027 of 1999 AN₁₀, for a very close encounter in 2040 (from Chodas 1999).

Öpik's theory of close encounters

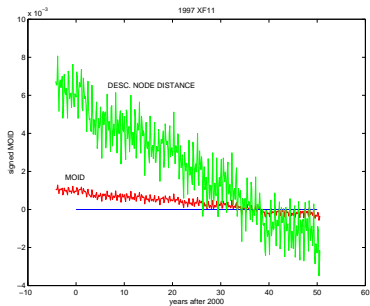
Model: restricted, circular, 3-dimensional 3-body problem; far from the planet, the small body moves on an unperturbed heliocentric keplerian orbit.

The encounter with the planet: modelled as an instantaneous transition from the incoming asymptote of the planetocentric hyperbola to the outgoing one, taking place when the small body crosses the b -plane.

Our contribution: added equations to take into account the finite nodal distance and the time of passage at the relevant node (Valsecchi, Milani, Gronchi and Chesley 2003).

Limitation: this model does not take into account the secular variation of the nodal distance, that has to be given as an additional input.

The MOID and its variation with time



Time variation of the nodal distance and of the Minimum Orbital Intersection Distance (MOID) for 1997 XF₁₁.

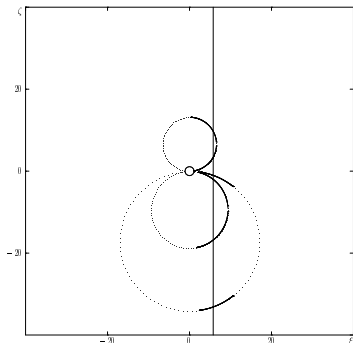
Problem for the modelling: there are large short-period variations superimposed on the secular trend.

Keyhole locations

Keyholes (seen in another way): points on the b -plane such that, if the small body passes through one of them, it is put in an orbit of given period/semimajor axis.

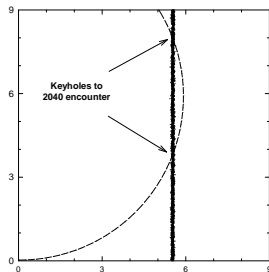
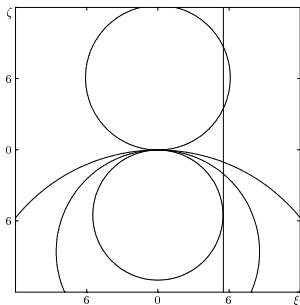
Our result: the locus of the b -plane points leading to a final orbit of given semimajor axis is a circle, whose radius and coordinates of the centre are functions only of the initial orbital parameters and of the given final semimajor axis.

Keyhole locations



The location of keyholes, on the b -plane of the 7 August 2027 encounter with the Earth of 1999 AN₁₀, for encounters within 4 Earth radii at the resonant returns in 2040, 2044, 2046.

How good is the theory?



Top: b -plane circles for resonant return in 2040, 2030, 2044, 2046.
Bottom: Chodas' plot for 2040, suitably rotated; the circle comes from a best fit.

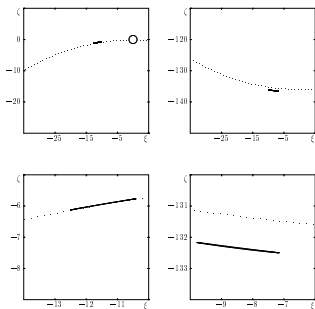
Shape and size of an impact keyhole

Problem: how varies the distance between two points of the b -plane of the current encounter when considering their **images** after propagation to the b -plane of the next encounter?

Result: the **horizontal** distance on the b -plane is essentially unchanged, the **vertical** one is stretched by a large factor, depending on the circumstances of the encounter.

Geometric consequence: the **pre-image** of the Earth on the b -plane of the encounter preceding the collision is a thick arclet closely following the shape of the circle corresponding to the suitable orbital period.

Shape and size of an impact keyhole



Keyholes on the 2028 b -plane of 1997 XF₁₁, for collision at the resonant return in 2040. Left keyhole: vertical compression between 15 000 and 21 000; right keyhole: vertical compression of about 124.

The story of Apophis

20 December 2004: 2004 MN₄

- CLOMON2 finds for 2004 MN₄ an IP of $7.7 \cdot 10^{-4}$ on 13/4/2029...
- ...but absolute magnitudes in June and December don't fit (2.5 ÷ 3 magnitudes discrepancy)!
- June astrometry looks noisy, their quality looks suspicious.
- We (Milani, Chesley, Sansaturio, GBV) decide to ask the June observers (Tholen, Tucker and Bernardi) to check their data.
- JPL (Chodas) makes Monte Carlo runs (probability is so high that it becomes worthwhile, and they represent a third check).
- JPL (Chesley) checks with the MPC, and requests more observations to reliable observers.

21 December 2004: the story gets complicated

- Tholen explains why June data are bad: first use of a new instrument, clock error (about 5 seconds!), misaligned CCDs, partial inability to handle trailing targets.
- Tholen models field distortion and reconstructs true time from numbered asteroids in the field, but remeasurement of all June nights takes a lot of time.
- We decide to wait for the June remeasurements before going public.

22 December 2004: new data, IP goes up

- One June night finally corrected.
- New observations start to flow in from Australia (McNaught).
- But IP has gone up! $IP \approx 0.01$, Torino Scale (TS) of 2, Palermo Scale (PS) approaching 1!
- We decide to wait for the correction of the other June night, and make a coordinated announcement at 17 UT on 23 December (we estimate that by that time we will have sufficient confidence in the data).
- JPL starts planning radar observations, possible in late January 2005.

23 December 2004: announcement

- Second June night corrected.
- More data from Australia.
- Announcement at 19:00 Italian time, one hour later than planned in order to have time to process the new data.

24 December 2004: new data, IP goes up (again!)

- Lots of observations flowing in.
- IP above 1%, PS above 1, TS= 4!
- Observations from the Northern hemisphere do not agree too well with those from the Southern one.

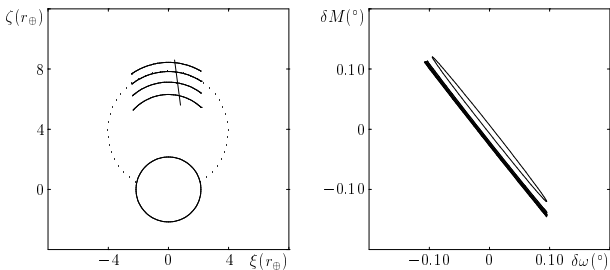
Probability continue to rise, then the all clear (almost...)

- 25 December: 1 in 43...
- 26-27 December: 1 in 37...
- In the meantime, the Indian Ocean tsunami.
- 27 December: Spacewatch March 2004 precovery, no collision in 2029...
- ...but let's not forget resonant returns and associated keyholes... (plenty of them!)

And the story goes on...

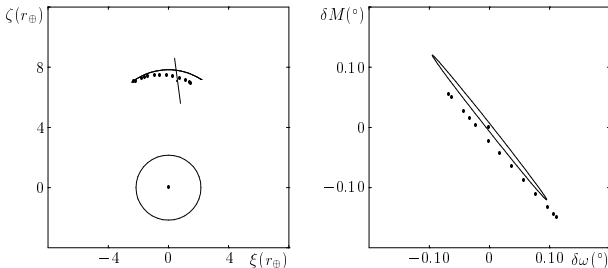
- A comment by Genny Sansaturio (28 December 2004): please, don't put another MN4 in my life in the next, say, 25 years... I could survive the impact but not the stress generated while ruling it out!
- Radar observations at the end of January 2005 definitely improve the situation...
- ...but one thing to keep in mind is that, without the Spacewatch March 2004 precovery, the probability in early January 2005 would have gone up to around 10%!
- Needless to say, we continue to keep an eye on Apophis. It has become an academic case, in fact a damnedly interesting one...

2004 MN₄ keyholes: theory



Left: LOV and theoretical keyholes for impacts in 2034, 2035, 2036, 2037 on the 2029 b -plane; Earth radius includes focussing, dots show the 6/7 resonance. Right: same keyholes, and pre-image of the Earth, in the $\delta\omega$ - δM plane; the origin is a “central” 2029 collision.

2004 MN₄ 2036 keyhole: practice



Left: LOV and 2036 theoretical keyhole, together with dots showing numerically found impact solutions; one of them is a “central” collision, the others are inside the “real” 2036 keyhole. Right: same impact solutions in the $\delta\omega$ - δM plane.

Additional slides

The detection of NEOs

Asteroids are detected as moving pointlike light sources.

Automated surveys: 4 ÷ 5 images, detect alignments.

A straight line does not allow orbit determination.

Key issues for surveys: limiting magnitude, efficiency of detection, sky area covered (geographical distribution of observatories).

NEO surveys

A number of large surveys, operating mostly in the U.S.A., are currently devoted to the discovery of NEAs. The most successful ones are the Catalina Sky Survey, LINEAR and Spacewatch.

In the near future, Pan-STARRS (4×1.8 m telescopes observing the same region of sky simultaneously) is likely to dominate the field. Each telescope will have a 7° FOV, and will be equipped with a CCD focal plane mosaic with 1.4 billion pixels.

In survey mode Pan-STARRS will cover 6 000 square degrees per night. The whole available sky as seen from Hawaii will be observed 3 times during the dark time in each lunation.