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.

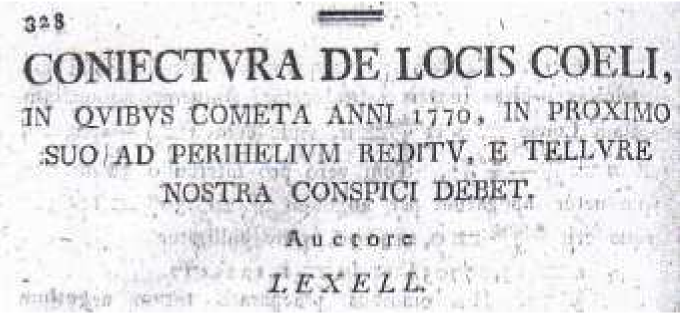
This comet passed exceptionally close to the Earth, and posed problems to those who tried to compute its orbit.

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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CONIECTVRA DE LOCIS COELI,

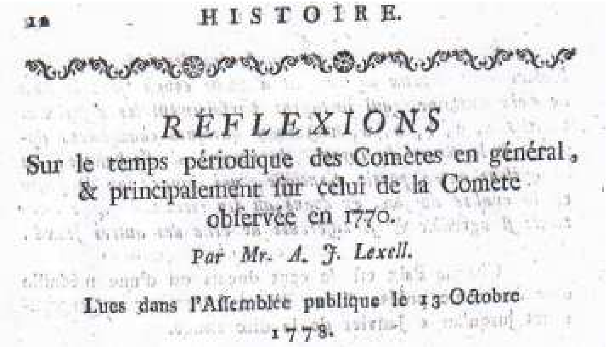
IN QVIBVS COMETA ANNI 1770, IN PROXIMO SUO AD PERIHELIVM REDITV, E TELLVRE NOSTRA CONSPICI DEBET.

Auctore

LEXELL.

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



RÉFLEXIONS

Sur le temps périodique des Comètes en général, & principalement ſur celui de la Comète obſervée en 1770.

Par Mr. A. J. Lexell.

Lues dans l'Aſſemblée publique le 13 Octobre 1778.

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

$$a = 3{,}14786 + 0{,}01\mu,$$
$$e = 0{,}7857161 + 0{,}0007260\mu,$$
$$\varepsilon = 356^\circ 15' 55'',51 - 12'',67\mu,$$
$$\varpi = 356.16.26{,}03 - 27{,}16\mu,$$
$$\varphi = 1.34.19{,}53 + 4{,}17\mu,$$
$$\theta = 131.53.56{,}00 + 83{,}00\mu.$$

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.

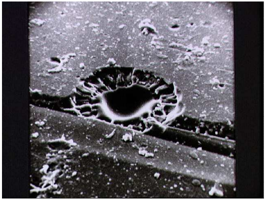
Sensitivity to initial conditions

− 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.

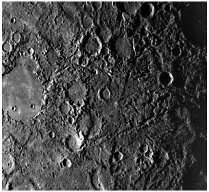
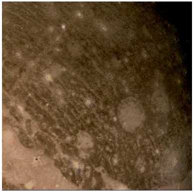
The problem

Collisions in the Solar System

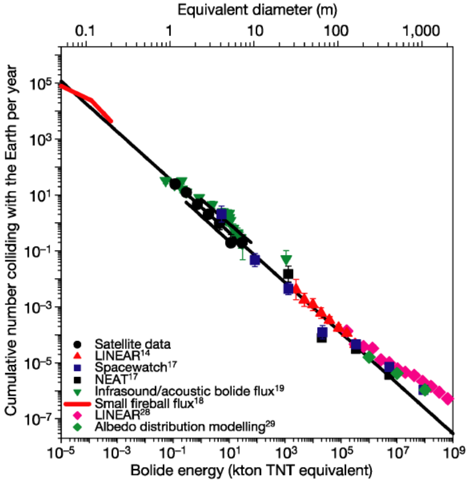

- Collisions are a key phenomenon in our Solar System.
- The growth of the terrestrial planets, of the cores of giant planets, and of planetary satellites has taken place through collisions.

Collisions in the Solar System

- The signature of collisions have been found everywhere in the Solar System by space probes.
- Collisions take place at all scales.

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



The impactor flux at the Earth

Typical timescales as function of impact energy:

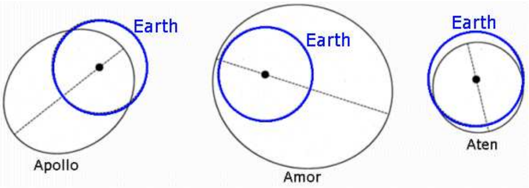
- 0.01 kT events: 1 day;
- 10 kT events: 1 year;
- 1 MT events: 100 years;
- 100 000 MT events: 1 000 000 years.

Near-Earth Objects (NEOs)

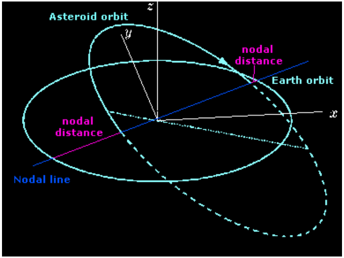
Near-Earth Objects are asteroids and comets on orbits with perihelion distance $q < 1.3$ Astronomical Units.

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 MOID



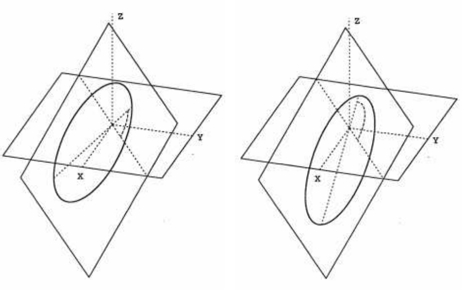
Although the orbits of many NEAs intersect (in projection) that of the Earth, this does not imply the possibility of very close approaches or collisions.

In three dimensions, what matters is the Minimum Orbital Intersection Distance (MOID), that is the minimum distance between the orbits of the NEA and of the Earth.

Potentially Hazardous Asteroids

NEAs brighter than absolute magnitude $H = 22$, roughly corresponding to a diameter of 110 m, and whose MOIDs are smaller than 0.05 AU (about 7 500 000 km) are referred to as Potentially Hazardous Asteroids (PHAs).

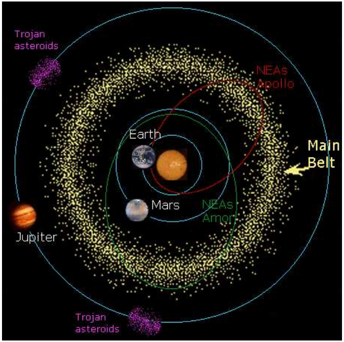
The secular variation of the MOID



Due to secular planetary perturbations, NEAs' orbits rotate within their plane; this causes the MOID to change over time.

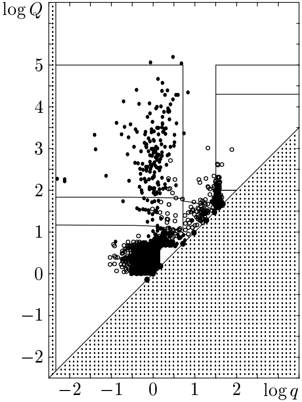
NEAs whose MOIDs are small and decreasing have to be especially monitored, as they are potential Earth impactors.

Main Belt Asteroids (MBAs)



NEAs represent a distinct population from normal, Main Belt Asteroids (MBAs), that move in the region between Mars and Jupiter.

Other populations of small bodies



Many other populations of small bodies are in heliocentric orbits, at various distances from the Sun.

Meteoroid streams

- Meteoroid streams are composed of small particles released from comets and from some Earth-crossing asteroids.
- We see individual meteoroids because their orbits cross that of the Earth, so that they can penetrate in the atmosphere and burn, producing an observable (visual, radar, TV) meteor.
- As particles are released at very low relative velocity, they remain near the orbit of the parent body.
- Because of the Earth-crossing condition, we expect their dynamics to be chaotic.

Recent developments: storm predictions

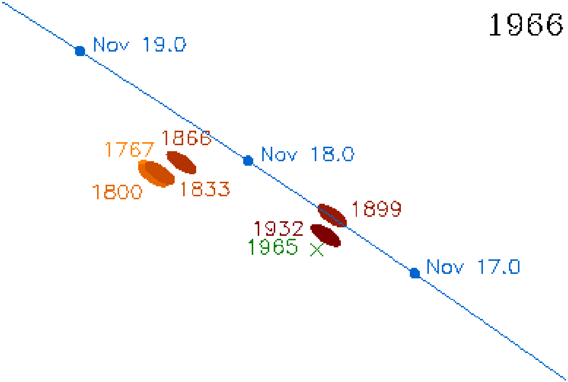
Over short time spans (tens of revolutions or less) the motion of meteoroids is nearly integrable, and their non-along-track dispersion is small. This effect may be enhanced by trapping in mean motion resonances.

Thus, meteoroids released since few revolutions remain close to each other, producing meteor storms at favourable Earth encounters.

The realization that relatively little computer time is needed to investigate the collective behaviour of recently ejected meteoroids has led to accurate storm predictions.

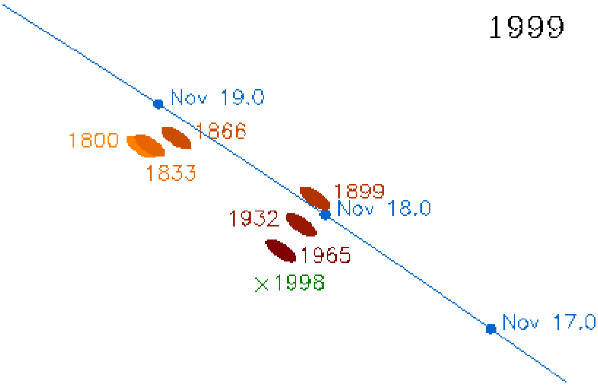
The problem has obvious analogies with that of impact monitoring.

Recent developments: storm predictions



The ecliptic crossings of various Leonids dust trails in 1966.

Recent developments: storm predictions



The ecliptic crossings of various Leonids dust trails in 1999.

A related problem: space debris

There is a certain degree of similarity between NEO impacts on Earth and space debris impacts on artificial satellites; there are, however, some important differences:

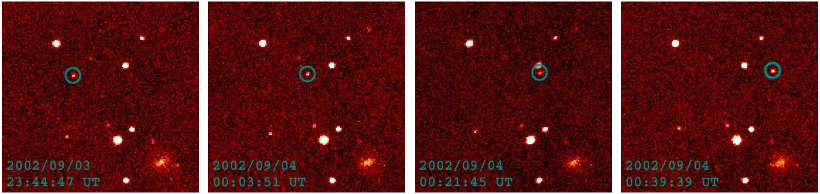
- nature and number of targets to be protected;
- maneuverability of targets;
- strong chaoticity of the motion in the NEO case;
- chain reaction effect in the debris case.

The solution

Steps to Decrease the Risk

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

Discovery of NEAs



Taking multiple images, somewhat spaced in time, of the same region of the sky allows to single out objects moving with respect to stars.

MBAs and NEAs are detected in this way.

NEAs move generally faster than MBAs.

The detection of NEOs

Asteroids are detected as moving pointlike light sources.

Automated surveys: $4 \div 5$ images, detect alignements.

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 $2 \div 3$ times during the dark time in each lunation.

Discovery of NEAs: current state

With automated surveys currently operating (Catalina, LINEAR, Spacewatch, LONEOS, NEAT) there has been rapid progress; as of November 2009 ≈ 900 NEAs with estimated diameter > 1 km have been discovered.

The total population estimate is tricky, but more than 3/4 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 3/4 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.

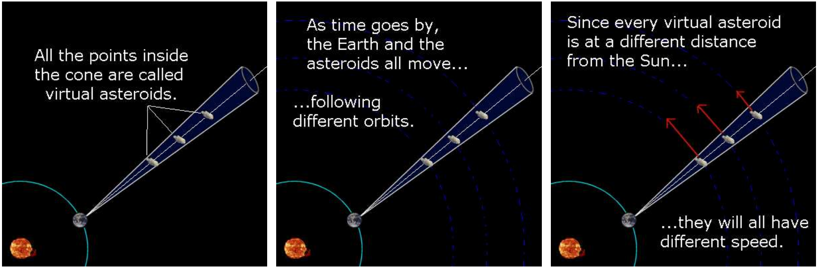
Orbit determination is more difficult for NEAs than for MBs.

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

Orbit Determination

A single detection does not allow to compute an orbit.

Orbit Determination

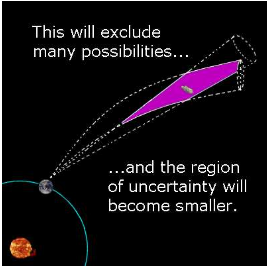


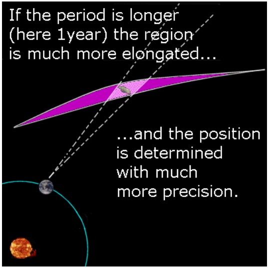
However...

Orbit Determination

...subsequent follow-up observations, with the help of Celestial Mechanics, allow the determination of an orbit.

Orbit Determination





The orbit becomes better and better determined as follow-up observations accumulate.

Orbit Determination

- 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.

Radar versus optical astrometry

When a NEA passes close to the Earth, radar observations become possible.
Radar astrometry is much more effective than optical astrometry because:

- NEA radar astrometry provides exactly the information (i.e., geocentric distance and its rate of variation) that optical astrometry does not;
- NEA radar astrometry can be extremely accurate.

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.

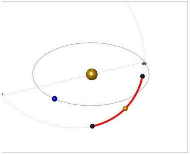
Virtual asteroids and impactors

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.

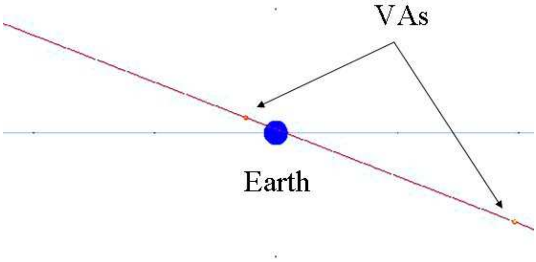
As the VAs proceed on their separate orbits the string stretches, mostly along track, until it wraps around a large portion of the orbit.

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 AN_{10}).

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 2$^{\rm nd}$ 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

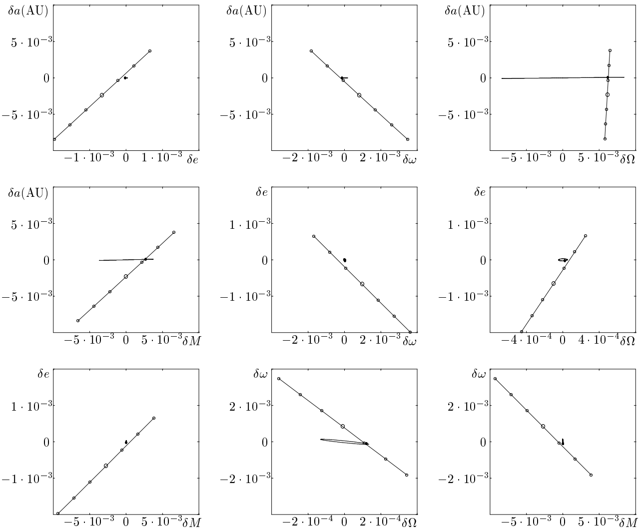
Direct collisions: 2002 NT_7

With a newly discovered NEA, VIs can be associated to direct impacts (i.e., without a prior Earth encounter).

In the summer of 2002 the observational record of 2002 NT_7 was compatible with a collision with the Earth taking place about 7.3 revolutions of the asteroid later, in early 2019.

The next plot shows the collision in the δa-δe, δa-$\delta\omega$, δa-$\delta\Omega$, δa-δM, δe-$\delta\omega$, δe-$\delta\Omega$, δe-δM, $\delta\omega$-$\delta\Omega$, $\delta\omega$-δM planes. The collision region in each subplot is an ellipse, and the collision point found numerically is the full dot. The line represents the LoV, along which the $\sigma = -3, -2, -1, 1, 2, 3$ values are denoted with small open circles, and the nominal solution ($\sigma = 0$) is denoted by the large open circle.

Direct collisions: 2002 NT_7

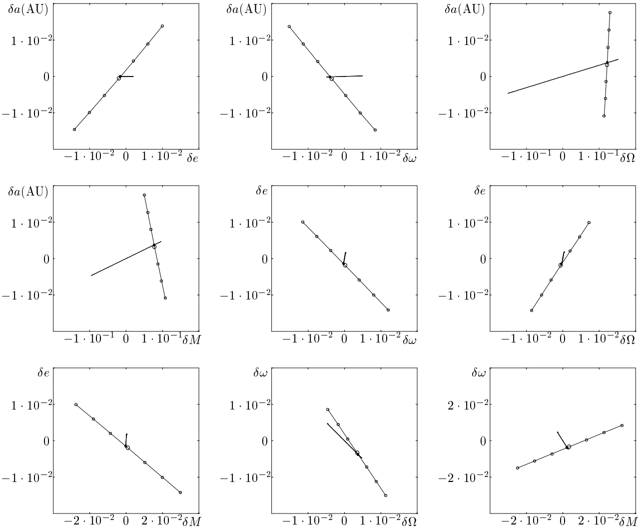


Direct collisions: 2003 EE_{16}

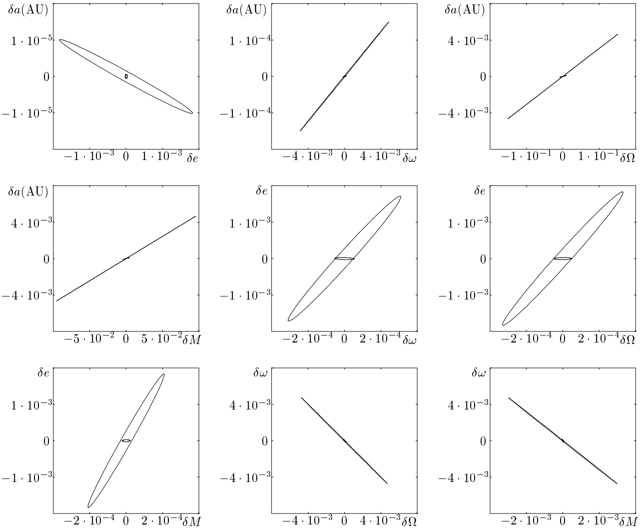
In March 2003 the the observational record of 2003 EE_{16} was compatible with a collision taking place about 2.9 revolutions of the asteroid later, in early 2008.

The next plot shows the collision. As it is easily noticeable (see also the subsequent slide, where the two cases are plotted together), the collision region for this low-inclination NEA is much larger than that of 2002 NT_7.

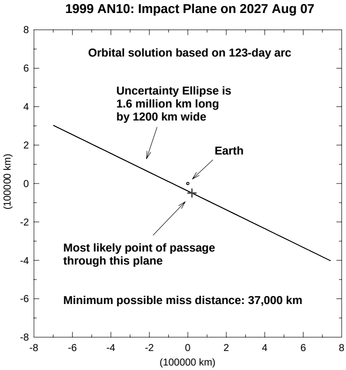
Direct collisions: 2003 EE_{16}



The two collision regions

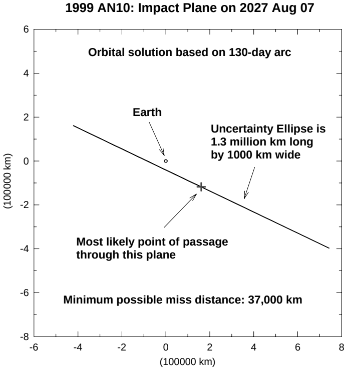


Uncertainty region on the *b*-plane



The uncertainy region, based on a 123 d observed arc, of 1999 AN_{10} projected on the *b*-plane of its Earth encounter on 7 August 2027 (from Chodas 1999).

Uncertainty region on the *b*-plane

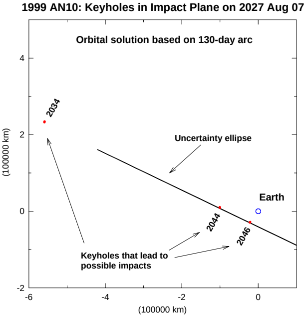


The same region, based on a 130 d observed arc, is smaller, and the nominal solution has moved (from Chodas 1999).

Keyholes

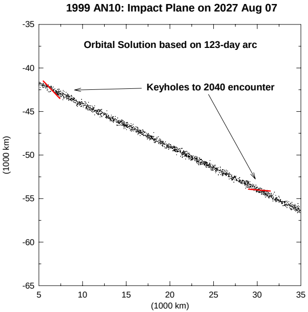
A keyhole (Chodas 1999) is a small region of the *b*-plane of a specific close encounter of an asteroid with the Earth such that, if the asteroid passes through it, it will hit the planet or have a very close encounter with it at a subsequent return.

Keyhole locations



The positions of keyholes in the *b*-plane of the encounter of 7 August 2027 of 1999 AN_{10}, 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 AN_{10}, for a very close encounter in 2040 (from Chodas 1999).

Öpik's theory of close encounters

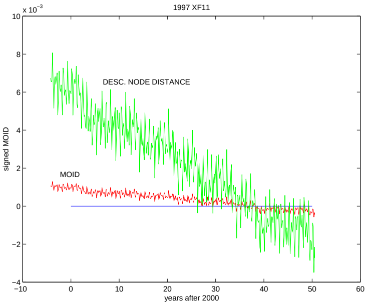
Model: restricted, circular, 3-dimensional 3-body problem; far from the planet, the small body moves on an unperturbed heliocentric keplerian orbit.

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 XF_{11}.

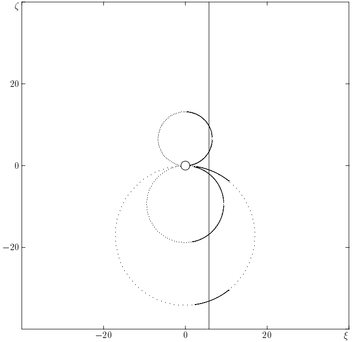
Problem for the modelling: there are large short-period variations superimposed on the secular trend.

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.

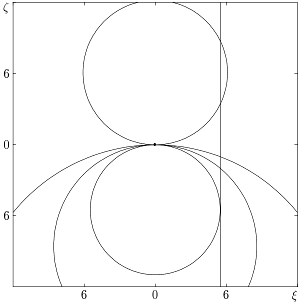
Our result: the locus of the b-plane points leading to a final orbit of given semimajor axis is a circle, whose radius and coordinates of the centre are functions only of the initial orbital parameters and of the given final semimajor axis.

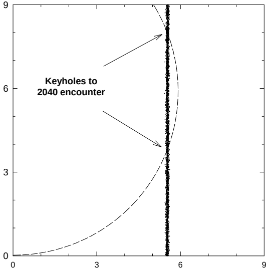
Keyhole locations



The location of keyholes, on the *b*-plane of the 7 August 2027 encounter with the Earth of 1999 AN_{10}, 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.

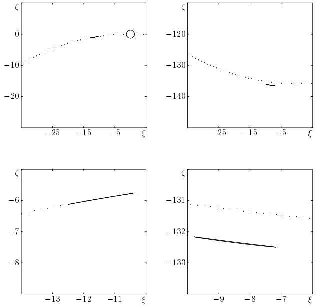
Shape and size of an impact keyhole

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.

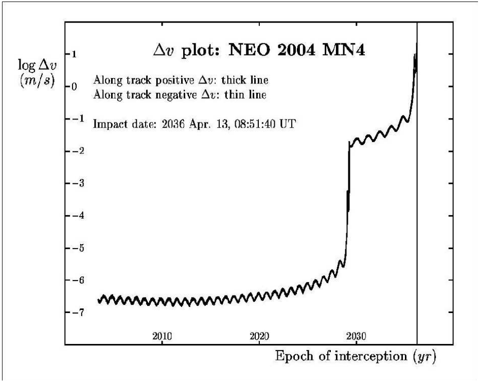
Geometric consequence: the pre-image of the Earth on the b-plane of the encounter preceding the collision is a thick arclet closely following the shape of the circle corresponding to the suitable orbital period.

Shape and size of an impact keyhole



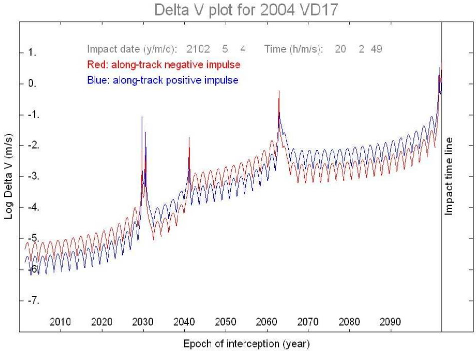
Keyholes on the 2028 *b*-plane of 1997 XF_{11}, for collision at the resonant return in 2040. Left keyhole: vertical compression between 15 000 and 21 000; right keyhole: vertical compression of about 124.

Keyholes are useful



The ΔV necessary to avoid the 2036 collision of 2004 MN_4 with the Earth (Carusi 2005); the 2029 encounter lowers ΔV by four orders of magnitude.

Keyholes are useful



The ΔV necessary to avoid the 2102 collision of 2004 VD_{17} with the Earth (Carusi 2005); even the very distant 2032, 2041 and 2067 encounters lower ΔV significantly.

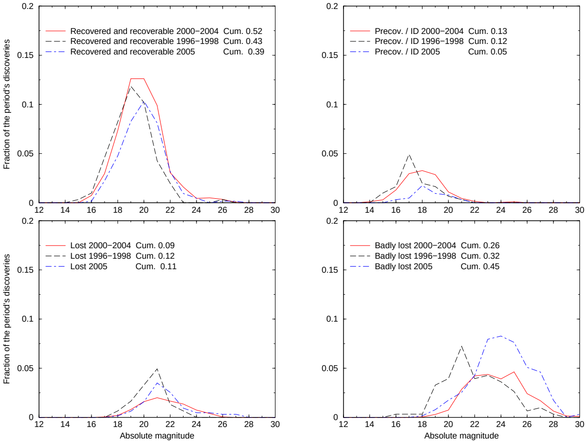
Current players

- Most NEA discoveries are due to NASA funded programs. NASA activities are coordinated by the NEO Program Office at the Jet Propulsion Laboratory.
- The Minor Planet Center (Cambridge, USA) is the international clearing house for observations and orbits of small solar system bodies, including NEOs. It is funded in part by NASA, and its activity is overseen by the International Astronomical Union.

Current players

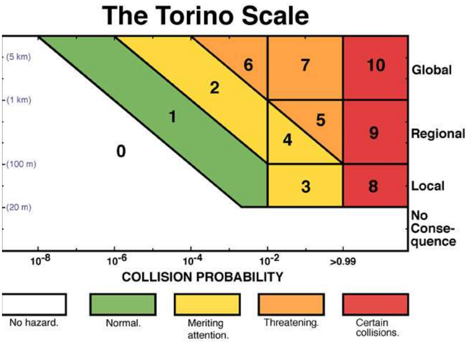
- In November 1999 the software robot CLOMON begun operations at the University of Pisa (Italy).
- In 2002 a second-generation impact monitoring software (Sentry) has been implemented at JPL.
- In 2002, CLOMON has been superseded by CLOMON2, with performances comparable to those of Sentry; the University of Valladolid (Spain) has joined that of Pisa, providing parallel operations of CLOMON2.
- The results of impact computations are available on the Web in the form of Risk Pages, updated daily.
- Cross-checking of CLOMON2 and Sentry has solved the problem of verification, and indeed has increased reliability.

The Spaceguard Central Node



The Priority List published daily by the Spaceguard Central Node has helped to secure many orbits......

The Torino Scale



The Torino Scale categorizes the Earth impact hazard associated with newly discovered NEOs. It is intended to serve as a communication tool for astronomers and the public.

The Torino Scale

THE TORINO SCALE

ssessing Asteroid/Comet Impact Predictions

Hazard	0	The likelihood of collision is zero, or is so low as to be effectively zero. Also applies to small objects such as meteors and bolides that burn up in the atmosphere as well as infrequent meteorite falls that rarely cause damage.
Normal	1	A routine discovery in which a pass near the Earth is predicted that poses no unusual level of danger. Current calculations show the chance of collision is extremely unlikely with no cause for public attention or public concern. New telescopic observations very likely will lead to re-assignment to Level 0.
by Astronomers	2	A discovery, which may become routine with expanded searches, of an object making a somewhat close but not highly unusual pass near the Earth. While meriting attention by astronomers, there is no cause for public attention or public concern as an actual collision is very unlikely. New telescopic observations very likely will lead to re-assignment to Level 0.
	3	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of localized destruction. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
	4	A close encounter, meriting attention by astronomers. Current calculations give a 1% or greater chance of collision capable of regional devastation. Most likely, new telescopic observations will lead to re-assignment to Level 0. Attention by the public and by public officials is merited if the encounter is less than a decade away.
Threatening	5	A close encounter posing a serious, but still uncertain threat of regional devastation. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than a decade away, governmental contingency planning may be warranted.
	6	A close encounter by a large object posing a serious, but still uncertain threat of a global catastrophe. Critical attention by astronomers is needed to determine conclusively whether or not a collision will occur. If the encounter is less than three decades away, governmental contingency planning may be warranted.
	7	A very close encounter by a large object, which if occurring this century, poses an unprecedented but still uncertain threat of a global catastrophe. For such a threat in this century, international contingency planning is warranted, especially to determine urgently and conclusively whether or not a collision will occur.
Collisions	8	A collision is certain, capable of causing localized destruction for an impact over land or possibly a tsunami if close offshore. Such events occur on average between once per 50 years and once per several 1000 years.
	9	A collision is certain, capable of causing unprecedented regional devastation for a land impact or the threat of a major tsunami for an ocean impact. Such events occur on average between once per 10,000 years and once per 100,000 years.
	10	A collision is certain, capable of causing a global climatic catastrophe that may threaten the future of civilization as we know it, whether impacting land or

The Palermo Scale

The Palermo Scale (PS) compares the intrinsic risk to the statistically expected energy flux from collisions at similar energy levels, integrated over the time interval until the potential collision.

It is expressed as the base 10 logarithm of the ratio between the risk associated to a specific potential collision and that coming from the collisions, at the same energy level, expected in the time span between “now” and the collision under consideration.

The story of Apophis

20 December 2004: 2004 MN_4

- CLOMON2 finds for 2004 MN_4 an IP of $7.7 \cdot 10^{-4}$ on 13/4/2029...
- ...but absolute magnitudes in June and December don't fit ($2.5 \div 3$ 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.

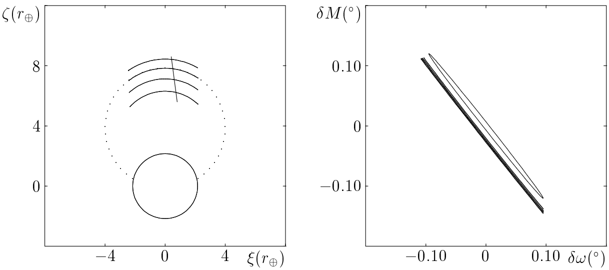
Probability continue to rise, then the all clear (almost...)

- 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...

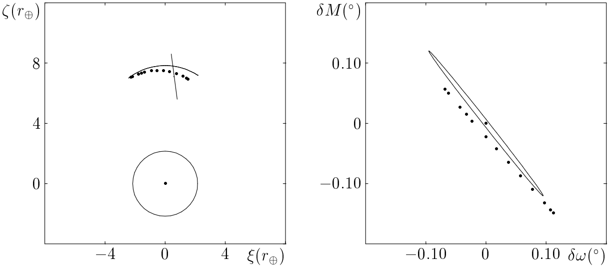
- A comment by Genny Sansaturio (28 December 2004): please, don't put another MN4 in my life in the next, say, 25 years... I could survive the impact but not the stress generated while ruling it out!
- Radar observations at the end of January 2005 definitely improve the situation...
- ...but one thing 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 MN_4 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 MN_4 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.