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The Near Earth Objects: possible impactors of the Earth/Les astéroïdes geocroiseurs : impacteurs potentiels de la Terre

Relevance of the NEO dedicated observing programs

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Abstract

The study of NEOs (Near Earth Objects) has considerably been developed in several ways under the huge impulse of the research on the risks of an hazardous collision with the Earth. In this context observations play a very important role. This article attempts to underline their importance in improving our knowledge of these objects and the necessity of organizing dedicated programs. It develops the objectives of these observations, describes methods to perform the detection of new objects, discusses their follow-up and the necessity of finding using archives. It also gives information about the fit of the observations in order to improve the knowledge of the orbits of NEO and about the effect of the planetary theories taken into account in the model. ***To cite this article: W. Thuillot et al., C. R. Physique 6 (2005).***

Résumé

Importance des programmes d'observation des objets géocroiseurs. L'étude des objets géocroiseurs (NEO ou Near Earth Objects) s'est considérablement développée sous de multiples aspects sous l'impulsion notable des recherches concernant les risques de collision avec la Terre. Les observations jouent dans ce contexte un rôle primordial. Cet article s'attache à souligner leur importance pour accroître notre connaissance de ces objets et la nécessité d'en organiser des coordinations spécifiques. Il développe les objectifs de ces observations, explicite des méthodes pour réaliser la détection de nouveaux objets, discute de leur suivi et de l'archivage des données, donne des informations sur leur utilisation pour améliorer la connaissance de leurs orbites et sur l'influence du choix des théories planétaires prises en compte dans le modèle. ***Pour citer cet article : W. Thuillot et al., C. R. Physique 6 (2005).***

Keywords: Asteroids; NEO; Detection surveys; Follow up; Observations

Mots-clés : Astéroïdes ; NEO ; Objets géocroiseurs ; Surveillance ; Suivi ; Observations

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1. Introduction

The study of the NEOs (Near Earth Objects) is a very active domain of research nowadays and observational data are obviously very appropriate for permitting improvements in this domain. We need to increase the amount of these data and their quality for different purposes. The detection of new objects is obviously the first task to be carried out in order not only to identify the potentially hazardous objects, but also in order to get a better knowledge of their dynamical behaviour. A second and very important task is follow-up observation. This task can only will lead to the improvement of the orbital elements of the detected objects and to the physical characterization by measuring several parameters. It requires dedicated astrometric, photometric and spectroscopic measurements through a network of observation stations. Finally, the best determination of orbital elements requires a search in archived observations where the objects could have already been observed.

If all these steps have been taken, the collected data can allow us to compute a realistic orbit of a NEO and to assess the risk of collision or, at least, to estimate the uncertainty of its least distance to the Earth and of its epoch. In the following sections we develop these topics and we describe some numerical experiments done to evaluate several effects which may act on this uncertainty: influence of the density of observations, of the spanning time span of observations and of the effect of the planetary ephemerids that are used in gravitational perturbations.

2. Surveys and detection programs

The current observational programs set to catalogue NEOs (NEAs, Near Earth Asteroids and NECs, Near Earth Comets) use dedicated ground-based telescopes equipped with CCD detectors. Possible NEOs are identified by automated computer software packages. Not surprisingly, those detection programs which search the largest amount of sky each month have had the most success in finding new NEOs. For more than ten years, a large majority of NEOs has been discovered by search programs based in the United States. Table 1 shows the corresponding statistics.

The yearly discovery rate of the American programs increased strongly from 26 in 1995 to 421 in 2003 while other programs never exceeded 20 discoveries per year. LINEAR contributed mainly to the success of the American programs. The other American programs NEAT, Spacewatch, LONEOS and Catalina had sometimes strongly variable discovery rates. The variations were due to technical changes concerning the telescope and CCD camera used, the automatic detection software and sometimes the obligation to share observation time with other programs. The American survey programs are coordinated through the NASA NEO program Office at the Jet Propulsion Laboratory (JPL) [1]. NASA's search program is designed to discover 90 percent of the NEO population (1 km in diameter or larger) within 10 years. There have never been comparable national search programs in other countries, which is one of the major reasons for the few detections outside the United States.

Most American search programs have changed or upgraded their telescopes since 1995 and added a separate telescope for the follow-up of NEOs which allows us also to determine more precisely their astrometric positions. We give a very brief description of the telescopes presently used for detection.

The by far most successful detection program LINEAR (Lincoln Near-Earth Asteroid Research) [2] is run by the Lincoln Laboratory of the Massachusetts Institute of Technology (MIT) in cooperation with the US Air Force. The observing site is Socorro, New Mexico. Two one-meter aperture wide field Air Force telescopes (GEODSS) specially designed to optically observe Earth satellites are used. The field of view is 2 square degrees. The NEAT (Near-Earth Asteroid Tracking) team [3,4] uses an AMOS (Air Force Maui Optical and Supercomputing) 1.2-meter telescope in Haleakala, Maui, Hawaii and the 1.2-meter

Table 1
Number of NEA discoveries by detection programs, total number of NEAs and NEOs (from A. Chamberlin, NASA). We denote Li for Linear, N for NEAT, S for Spacewatch, Lo for LONEOS, C for Catalina

Year	Li	N	S	Lo	C	Other	⩾1 km	Total NEA	Total NEO
1995	0	0	26	–	–	6	196	347	385
1996	1	10	28	–	–	6	202	392	430
1997	17	11	14	–	–	11	217	445	483
1998	135	11	36	7	3	13	269	650	688
1999	161	0	19	13	30	5	336	879	918
2000	258	15	26	38	13	12	440	1241	1281
2001	277	92	22	42	0	4	531	1678	1724
2002	286	145	22	21	1	11	627	2163	2211
2003	235	68	56	54	8	17	694	2601	2650
2004*	277	25	62	35	65	7	748	3130	3179

* Incomplete.

Oschin telescope at Mt. Palomar, California which previously performed the two Palomar Sky Surveys. The telescope in Hawai has a field of view of 1.4 square degrees. Spacewatch is the oldest NEO detection program started in 1984 by T. Gehrels at Kittpeak, Arizona. At present, a 0.9-meter telescope is used with a field of view of 2.9 square degrees [5]. The telescope is used also for detecting objects in the outer solar system. LONEOS (Lowell Observatory Near-Earth Object Search) [6] uses a 0.6-meter Schmidt telescope in Flagstaff, Arizona. It covers a field of view of 2.9 square degrees [6]. The Catalina Sky survey operates a 0.7-meter Schmidt telescope at Mt. Bigelow near Tucson, Arizona. Its field of view is 2.9 square degrees [7].

Currently, there are three somewhat regular NEO detection programs outside the United States, the Asiago DLR Asteroid Survey ADAS [8], the Campo Imperatore Near-Earth Objects Survey CINEOS [9] and the Japanese Spaceguard Association (JSGA) survey [10]. The telescopes of these three detection programs are not fully dedicated for NEO search. CINEOS observations are performed by a Schmidt telescope (60/90/183 cm) at Campo Imperatore Observatory on Gran Sasso Mountain, 130 km from Roma (Italy). The field of view is $52' \times 52'$. ADAS uses the 60-cm Schmidt telescope in Asiago near Padova (Italy), with a field of view of $49' \times 49'$. The two European telescopes for NEO search have much smaller field of views and apertures as compared to the American telescopes. Therefore, even the full dedication of the European telescopes for NEO detection would not significantly increase the European contribution. The Japanese Spaceguard Association uses a 1-meter Cassegrain telescope with a field of view of 2.5×3.0 degrees partially for NEO detection [10] at the Bisei Spaceguard Center in the Okayama region. In France, a Schmidt telescope which is located near Caussols (Observatoire de la Côte d'Azur) searched for NEOs until 1999. It was not built for NEO detection purposes, however, the famous 4179 Toutatis was discovered in one of its photographic plates. During the last 5 years a CCD camera has been used but it was covering only a small part of the field. Twelve NEOs were discovered with this telescope which is no longer operating. However, using a mosaic of CCDs it may be possible at this time to reach an efficiency similar to the NEAT program.

Why is LINEAR so successful in discovering NEOs? A priori, the observing site, the aperture and field of view of the telescopes do not appear to give a significant advantage for the LINEAR search program. The number of NEO detections depends on the area of the sky scanned during a given time and on the limiting magnitude reachable by the instrument. Dynamical models for assumed NEO populations do not indicate regions of the sky where a significantly higher density of NEOs can be expected.

According to the above technical data for the different search telescopes, the limiting magnitudes of the LINEAR telescopes do not give a decisive advantage for this search program. Other telescopes reach even fainter magnitudes. The success must be, therefore, due to an optimized sky coverage and also to efficient software which finds and extracts a maximum number of NEOs from the CCD images.

While the detection rate of NEOs between 1995 and 2001 strongly increased, it seems to become constant now. New generations of telescopes reaching much lower magnitudes may change this situation in the future. The goal to detect all 1 km sized or larger NEOs has not yet been reached. Since 2000, the year of a maximum of 104 discoveries, the rate has decreased slightly on the mean, but is far from being exponentially decreasing.

3. Follow up programs for the dynamics

Once the objects are detected, follow-up observations are required and this is hard to organize. Nevertheless all the objects need further astrometric and photometric measurements in order to be fully characterized and to be identified on several oppositions. Unfortunately, many objects are even lost after their detection. One of the reasons is that a detection by a survey program will only lead to few measurements; and the resulting short orbital arc is not sufficient to get accurate enough ephemerides. Another reason may be due to the faint magnitude of some NEO detected by the surveys which remain beyond the limiting magnitude of the instruments available for their follow-up observations.

In October 2004 for example, the orbits of more than 263 000 objects have been computed by T. Bowell; his database (ftp://ftp.lowell.edu/pub/elgb/astorb.txt) indicates that more than 400 have been poorly observed, and many are even certainly lost. This situation is particularly uncomfortable if the object is a NEO.

We can estimate the effect of the degradation of the precision in the determination of an orbit due to the lack of observations. Considering for example the NEO object 4179 Toutatis, we have first computed a nominal orbit by using a fit of all the available observations extracted from the MPC database [11] and a numerical integration using 2004 as the year of the initial conditions.

In order to test the influence of the availability of observations we computed several orbits of 4179 Toutatis with different sets of observations. This NEA passed close to the Earth in 2004 (perihelion), and thus led to series of observations all around the world. We have simulated the lack of observations, or the influence of bias such as the limiting magnitude in the calculation of the position of the object. Then by fitting the remaining set of observations, we obtain another orbit to be compared to the nominal one.

Therefore, several fits of the orbit have been carried out, taking into account:

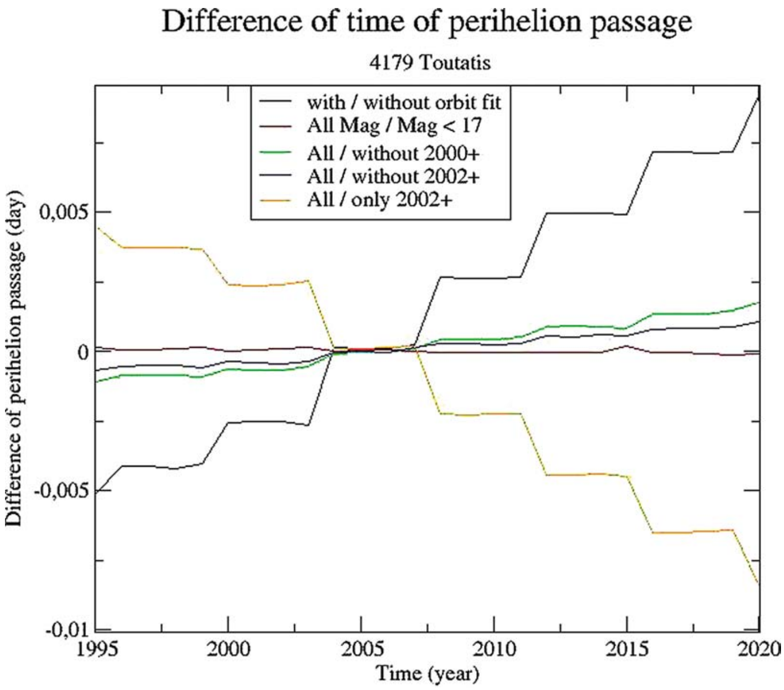

Fig. 1. Computed orbits of 4179 Toutatis: differences of time of perihelion passage obtained by comparing several biased orbits with a nominal orbit.

- all the available observations (marked as 'All' in Figs. 1–3 hereafter called the 'nominal solution');
- all observations until year 2000 (marked as 'without 2000+');
- all observations until year 2002 (marked as 'without 2002+');
- only those observations providing the magnitude of the object ('All Mag');
- among these above observations, only those with a limiting magnitude of 17.

Then the propagation of the orbit is performed, and the differences of orbital elements as well as Cartesian coordinates are plotted in Figs. 1–3. The maximum differences to the nominal solution are found close to perihelion (1996, 2000, 2008, 2012, except 2004), where the heliocentric velocity of the body is maximum. Therefore a small error in the observations (or a lack of observation) implies a large error on the position of the body itself which in fact is mainly an error of longitude. The difference between two solutions is maximum because of the time lag between two perihelion returns. The asteroid is found to be in advance or late compared with the nominal solution (Fig. 1). This has to be compared to the motion of the Earth on its orbit. A delay of 0.005 day of the return of Toutatis corresponds to a planet displacement of 13 000 km, therefore far more than one planet radius. This value is reached in 16 years, but this is not a realistic case as it is done only with the 2004 data. A more realistic test is to use all the data except those from 2004, which simulates the recent discovery of the asteroid and the use of its observation during a few previous oppositions to predict an impact. In this case, the error is still of the order of 2000 km, which is still rather big. It is clear that if we want to predict something useful we have to use the 2004 observations. It is important to stress that using classical astrometry makes it impossible to predict with a high accuracy an impact on Earth. It is fundamental for that goal to use radar data with a meter level accuracy.

The difference of orbital elements can seem to be low (Fig. 2), but by converting them into Cartesian coordinates, one found a few thousands of kilometres of difference (Fig. 3), at least. This is far from being negligible, especially in the case of an impact calculation, where the position of the impact has to be accurately found.

We can see that the highest differences to the nominal solution are found for the calculations that take into account the most recent observations only. This stresses the need to have as many available past observations as possible. The error of the position of the object almost doubles between the solution including observations up to 2000 and that involving all the observations up to 2002. Interestingly, the number of observations done between 2000 and 2002 is the same as the number of observations performed up to 2000. This does not mean that the accuracy is proportional to the number of observations, but only underlines the fact that, to derive a reliable orbit, many of observations on a large time scale are necessary.

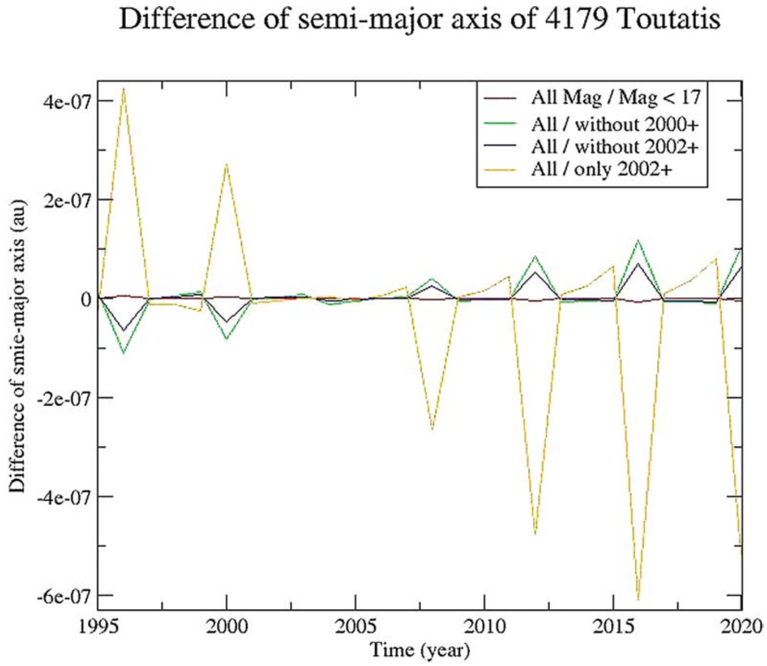

Fig. 2. Computed orbits of 4179 Toutatis: differences of semi-major axis obtained by comparing several biased orbits with a nominal orbit.

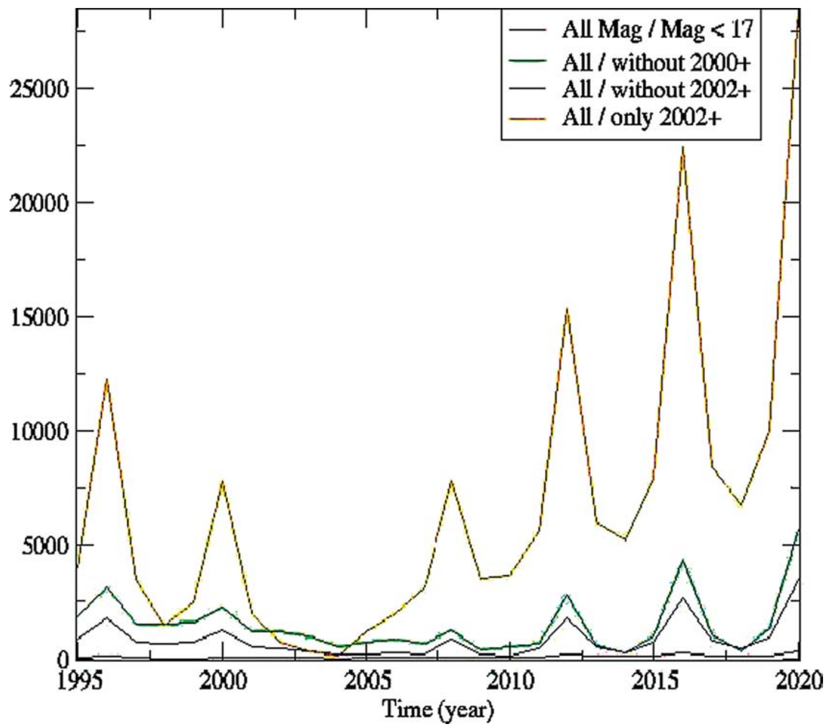

Fig. 3. Computed orbits of 4179 Toutatis: differences of position in space obtained by comparing several biased orbits with a nominal orbit.

Considering only the brightest observations has only a minor effect, compared to the solution including all the available magnitude estimates. A reason for that is that the faintest observations are done when the asteroid is far from perihelion. The distance between the Earth and the asteroid is then larger, and then astrometrical errors much more important. Many NEOs are discovered when they are as close as 0.1 AU to the Earth, but most of the time this asteroid stay as far as 1 to 3 AU. Therefore the observations made during Earth close encounter are at least 10 times more important.

At aphelion the heliocentric velocity is minimum, the position of the NEO changes slowly compared to the situation at perihelion. The positional errors are then less relevant than at any other point of the orbit.

The dedicated NEO programs of observation lead to discoveries of new objects which require much more observation time than is allowed by the survey programs. The Minor Planet Center maintains Web pages mainly to stimulate observations just after discoveries to avoid the loss of these objects. This is also done by the Spaceguard Central Node in Italy. The Lowell observatory also supports this kind of work by maintaining a critical list of asteroids. This list helps observers to choose the asteroids to observe in order to maximize the orbit improvement. It is important to note that the observers are organised in an insubstantial network compared to the huge resources of the detection programs. At this time, no really dangerous object has been found, but in case we would have to carry out a fast follow-up program for such objects, all the work done by these centres will be of precious benefit to coordinate observers and to collect observations. As illustrated in the previous numerical experiment the orbital precision is improved by increasing the density and the spread of the astrometric observations. Therefore the accurate computation of close approaches to the Earth and the improvement of their prediction require also the search for past observations if they exist. Jointly with a follow-up program of observation, 'data mining' can then highly improve the quality of NEOs ephemerides by imposing some strong orbital constraints on a long time interval.

4. Astrometry and orbitography

The determination of accurate orbits of NEOs requires not only the use of accurate astrometric measurements but also their adjustment with a model involving all the forces acting on the objects: gravitational forces (central force, planetary perturbations) and non-gravitational ones like the radiation pressure and the Poynting–Robertson drag. Among these forces we wondered how large would be the effect of different choices of planetary ephemerides.

At the present time two main methods are used to compute planetary ephemerides: numerical integrations made at JPL by Standish [12], widely used, and analytical theories developed at IMCCE by Bretagnon and his colleagues [13]. Both now include small effects such as, for example, some relativistic effects or the effect of the Solar oblateness. However, in these models, the perturbations by the largest main-belt asteroids remain hard to accurately assess since we have a very poor knowledge of their masses. Nearly 300 asteroids are required to be included in the computation of the perturbations. Apart from the largest, their masses can only be estimated by taxonomic considerations and assumptions on the respective density of each class. The accuracy of the determination of the mass of even the largest ones is not better than 10%. This lack of information led Standish and Fienga [14] to estimate the accuracy of the ephemerides of the four inner planets at a 2–3 km level over more than two decades. The theory of motion of Mars, which is the most sensitive to the gravitational action of asteroids, appears to be the less accurate of the planetary dynamical models. Therefore this feature may influence the computation of the orbit of Mars crosser objects and the modelling of their long term behaviour.

In order to estimate the maximum effect of such uncertainties in the computation of asteroids orbital motion, we made a selection of several Mars and Earth crosser asteroids and we carried out several numerical experiments. Two kinds of calculation were made.

The first experiment is a long term numerical integration of the orbit of 4179 Toutatis by using initial conditions extracted from a fit of the osculating elements given by the Minor Planet Center on the whole set of collected observations. The algorithm is a 15th order Radau algorithm by Everhart [15]. Eight perturbing planets are considered as well as non-gravitational forces described previously.

Fig. 4 shows the differences of position of the asteroid from two different computations. Each one takes into account a different planetary theory from JPL, DE405 and DE406. Standish [12] gives details on their estimated precision. We can see that the shift between the two orbits increases with the time, the initial conditions taken in 2004. The time span of the DE405 theory did not allow us to conduct the numerical integration further than the year 2199 AD. The comparison with DE406 is thus restricted to the period 1600–2199 AD. The difference of position of Toutatis begins to be significant (i.e., larger than a few kilometres) after 200 years (backwards or forwards in time), and reaches a maximum around 300 years in the past, but no comparison with the future motion is available, because of the restriction of the DE405 theory.

Fig. 5 shows the difference of position for several NEA that are also Mars crossers, for planetary ephemerides SLP96 from IMCCE and DE403 from JPL. We can see that the differences are much larger than when comparing DE405 and DE406, with a rapid increase to 50 km on average after 10 years. Such differences are not that relevant in the case of a 1 km diameter object or more, able to cause a global catastrophe. However, it must be emphasized that even by using the best data, it is hard to reach an accuracy better than a few tens of kilometres. This could be important for a small size asteroid impact causing damage similar to the Tungunska event.

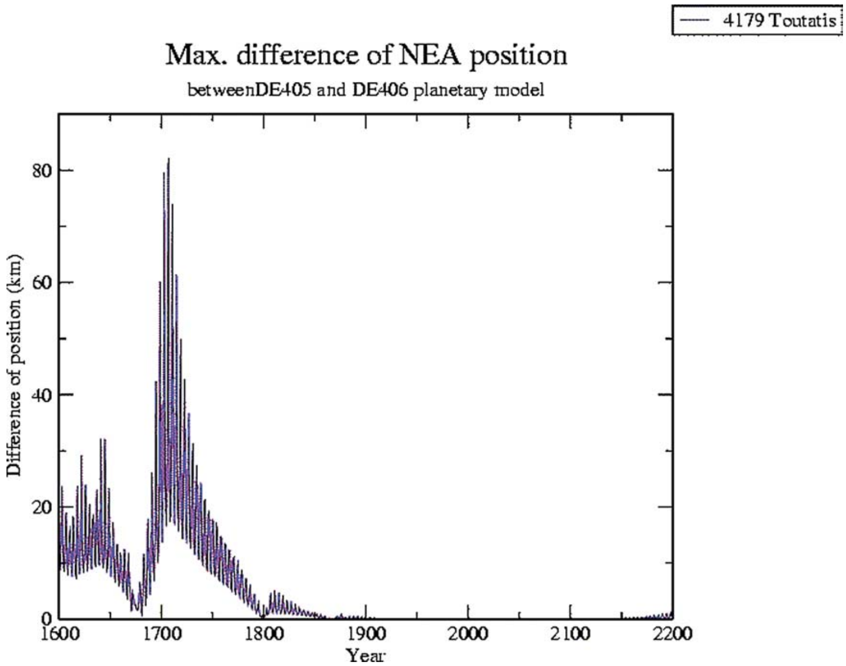

Fig. 4. Shift of orbits of 4179 Toutatis due to the use of two different planetary ephemerides.

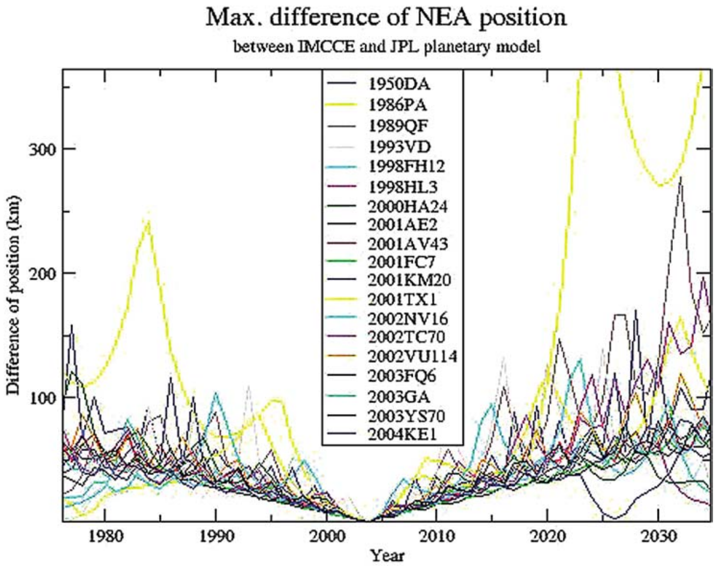

Fig. 5. Shift of orbits of several Mars crossers due to the use of two different planetary ephemerides.

5. Follow up programs for the physical characterization

By physical properties of a minor body we design the data obtained through observation and related to its intrinsic basic aspects such as colour, light curve, visible and near-IR spectra, thermal albedo, modelled shape and spin from radar measurements.

Continuous observational efforts must be made in order to improve both physics and internal structure of NEO population. Such programs have already been realised in the past, sporadically, for particular objects among NEOs [16,17]. Such programs provide interesting results namely the complex rotation of 4179 Toutatis and the bi-lobed shape of 4769 Castalia from Hudson and Ostro [18]. Even if these results were presented as 'unusual', nowadays the astronomical community agrees with these conclusions (with a non-negligible importance) in the large picture featuring the minor bodies of the solar system.

Peculiar programs concerning NEOs are also offered as ground-based support of space missions, for example by Binzel et al. [19] or Sekeguchi et al. [20]. Comparative planetology and laboratory results allow to refine the knowledge of the NEO-targets, and to offer good models to explain both their physical and mineralogical feature.

Systematic spectroscopy programs of NEO population only started in the 21st century, and first outcomes of these efforts are reported by Binzel et al. [21]. In terms of taxonomy, the results reveal that the NEO population is quite distinct from that of the Main-Belt [22]. No systematic program concerning NEOs colors was reported, and only few ground-based instruments allow observations in thermal region (10–20 µm) [23]. NEOs light curve parameters are stored into a European database (http://earn.dlr.de/nea/database.htm), but this work is far from being achieved.

Technological acquirements in building detectors and instruments now allow the observations and follow-up of faint fast-moving objects in the sky. Nevertheless, the absence of medium and large aperture telescopes devoted to NEOs physical observations makes systematic studies difficult; these programs must compete each semester with programs of various astronomical topics.

The remote observing technique could be the right choice to acquire the scientific information of a given NEO. With this aim, the Paris Observatory has initiated the project of the remote observing centre CODAM [24], in order to offer alternatives and flexibility of scheduled observational programs. This project was started in 2002. As of today, more than thirty nights of observation have been reported. Part of the awarded time was devoted to NEOs near-IR spectroscopy. This work which is part of the remote project will continue by identifying the telescopes allowing remote observing, in order to offer a wide coverage in longitude for monitoring, in the case of this article, and clearly materialize defined NEO programs.

6. Conclusion

In this article we give a short overview of several topics related to the observations of NEOs. Detection is mostly the task of large surveys and in these domains the American programs are obviously well in advance. However, follow-up programs for dynamics as well as for physical characterization are very important. Such dedicated programs of observation, with large longitude coverage, are still necessary to make the observations more dense and continuous, namely when a NEO is just discovered or when such an object passes close to the Earth. We hope that in a near future more robotic telescopes could be used for these programs which will be able to make systematic follow-up observations. Furthermore, supplementing a rich set of observations by extracting older records from catalogues or archives will allow us also to refine the orbits, and the advent of the Virtual Observatory projects will be of a great help for this purpose. Besides the increasing number and the higher quality of the observational data, the dynamical considerations are also important for the better understanding of the motion of the NEOs and we show here that the choice of a planetary theory can have a non-negligible effect on the computed model to study the long term behaviour of a NEO.

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