NEAR EARTH OBJECTS

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ABSTRACT

A survey of the field of NEOs is given with respect to the present status of detecting NEOs from the ground, the prospects to detect from space, and especially with Gaia. A realistic model of the NEO population with respect to orbits and sizes has been established, and this model has been used to assess the capabilities of various instruments from ground and from space. The contribution of Gaia will be to make an all-sky homogenous survey, including atypical orbits far from the ecliptic and observation when a NEO is close to the direction of the Sun where observation from the ground is difficult.

Key words: Gaia; Techniques: miscellaneous; Minor planets; Asteroids.

1. INTRODUCTION

A few days before the Paris symposium we were reminded of the danger from space (NASA 2004) by the close approach to planet Earth of a NEO. Toutatis, a potato-shaped asteroid about 4.6 km in its longest extent, passed within 1 550 000 km of the Earth's centre on Wednesday, September 29, 2004. This is closer than this asteroid has come to Earth since at least the twelfth century. Toutatis will not pass this closely again for the next 500 years. The passage is the closest Earth approach this century for a known asteroid of this size. Because of an extensive set of optical and radar observations, the orbit for Toutatis is one of the best determined of any asteroid and there is no chance that this object will collide with the Earth during any other encounter for at least 5 centuries. Thus, this NEO was expected.

With a size of 4 km it would have meant a disaster if Toutatis had hit the Earth. The distance of 1.5 million km is called 'close' although it is 100 times the diameter of the 'target' Earth. If a rifleman hits at a distance from the target of 100 times the target diameter it is not called 'close', but in case of a NEO the consequences of a hit are so severe that great effort is justified to find all NEOs and their orbits so that a hit can be predicted well in advance. It might then be possible to plan for mitigation of the event in manners depending on the state of technology at the time and on the political will to do something.

We shall give here up-to-date numbers for the detection of NEOs and for the prospects of improving the detections by ground-based observations and from space. The role of Gaia in this context is discussed.

A NEO is an object that can come close to Earth, and which can potentionally hit some time in the future. In practice, a NEO is defined as an object having a perihelion distance $q < 1.3$ AU and an aphelion distance $Q > 0.983$ AU. The majority of NEOs are Near Earth Asteroids (NEA) and only a few are Near Earth Comets (NEC). A large NEO is by definition an object with a diameter larger than 1 km, corresponding to an absolute magnitude of $H < 18$. The Spaceguard goal set in 1998 is to discover 90% of the large ones within 2008 and 90% of those with $H < 20.5$ beyond. By August 2004 about 750 had been discovered out of an expected total population of 1000.

A collision with a NEO about 300 m diameter corresponding to $H = 20.5$ mag is expected every 63 000 years. It will dissipate about 1000 megaton explosive effect corresponding to one hundred hydrogen bombs.

The absolute magnitude of a Solar System object is the visual magnitude at 1 AU from the Sun, 1 AU from the Earth and zero phase angle.

2. NEO DISCOVERIES

The NEA discoveries are tabulated in Table 1, based on more detailed data from NASA (2004). It appears that one observing programme, LINEAR, has made more discoveries of large NEAs than all others together.

LINEAR stands for Lincoln Near-Earth Asteroid Research and is operating from a site in New Mexico since 1996 according to NASA (2004). A one-meter aperture telescope with 2 square degree field of view was first used. From 1999 a second one-meter telescope was added to the search effort and in 2002, a third telescope of 0.5 meter aperature was brought on-line to follow-up observations for the discoveries made by the two one-meter

Table 1. Discoveries of NEAs, Near Earth Asteroids. The last line is the incomplete half year of 2004.

Year	New large NEAs		Cumulative total	
	LINEAR	Other instr.	Large	All
1995	0	10	196	347
6	0	6	202	392
7	3	12	217	445
8	34	18	269	650
9	48	19	336	878
2000	77	26	439	1240
1	59	30	528	1677
2	63	32	623	2163
3	40	26	689	2601
4*	17	14	720	2872

search telescopes.

The discovery rate for large NEOs is slowly decreasing from a maximum of 77 per year discovered in the year 2000 by LINEAR. This is consistent with the fact that about 75% of all large NEOs are now known. The present totals by mid 2004 are 720 large NEAs and 2872 of all sizes.

3. THE NEO POPULATION

A realistic model of the NEO population has been established by Jedicke et al. (2003). Most NEOs are believed to be fragments of larger bodies of the main belt destroyed or eroded by internal collisions and then progressively drifted into mean-motion and secular resonances. Subsequently they enter into Earth-approaching orbits from gravitational perturbations leading to an increase of the eccentricity (Morbidelli 1999).

Further works have lead to finding the orbital and size distribution of near-Earth asteroids. Five sources of objects from Mars to Jupiter orbits are thought to provide most of the NEOs in the inner Solar System. Free parameters in the resulting distributions are fitted to the observations of a well-characterized survey, namely Spacewatch, by assessing the bias effect between the theoretical and observed distribution. The size distribution is assumed to be orbit-independent.

A simulation of a population of 20 000 NEOs has been made from the model. The number of objects was selected so as to produce reliable statistical results and to provide a significant population in each of the main sources of NEOs. While the absolute number of objects is arbitrary, the distribution over the orbital parameters and magnitude is expected to be realistic.

4. OBSERVATIONS FROM GROUND AND SPACE

The LINEAR observing programme has been the most efficient so far. It is therefore interesting to note that the above model was tested by Morbidelli et al. (2002) with a pseudo-LINEAR simulator that simulates the average sky coverage of LINEAR and its average limiting magnitude of $V = 18.5$. In two years LINEAR increased the detected population of NEOs with $H < 18$ from 273 to 449. The pseudoLINEAR simulator took 2.14 year, a very satisfactory agreement.

The prospects for achieving the Spaceguard goal with a ground-based survey could then be assessed. With LINEAR alone, 10 years observing would give 65% completeness for large NEOs. An instrument with a limit of $V = 21.5$ would give 90% after 10 years, and this percentage could be obtained in just 3.5 years with the planned LSST with limit $V = 24.0$.

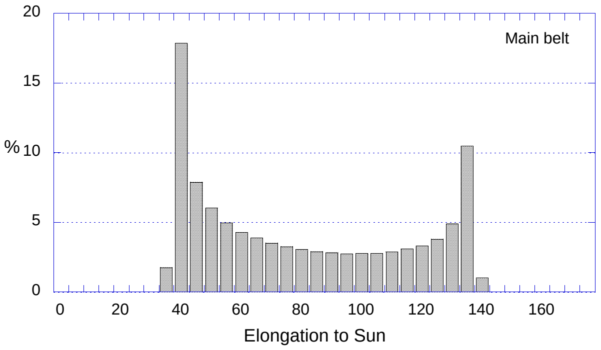

Figure 1. Distribution of the angular distances to the Sun when main belt asteroids brighter than $V = 20$ mag are observed by Gaia.

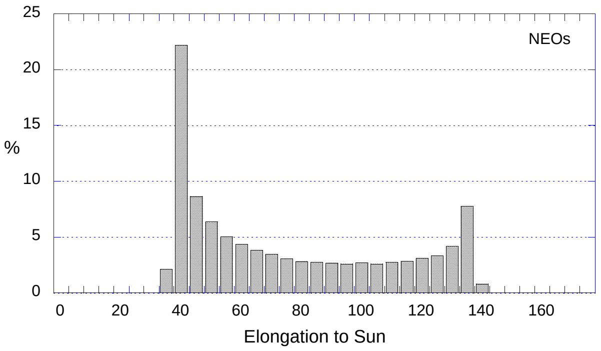

Figure 2. Distribution of the angular distances to the Sun when NEOs brighter than $V = 20$ mag are observed by Gaia.

Space-based surveys were assessed by Morbidelli et al. (2002) with the unsurprising conclusion that a space-based survey that duplicates the strategy of ground-based surveys will never be competitive in terms of cost. Such

Table 2. Probability of observing a NEO of a given absolute magnitude with Gaia. The columns gives the probability that repeated observations occur a certain number of times, from $n = 0$ (never observed) to $n > 25$. The figures refer to the spectroscopic telescope field. A limiting magnitude $V = 20$ has been adopted for the detection.

H	$n = 0$ %	$1 < n \leq 10$ %	$10 < n \leq 25$ %	$n > 25$ %
14	2	1	6	91
15	5	4	15	76
16	11	9	25	55
17	19	18	30	33
18	40	27	21	12
19	73	21	4	2
20	89	9	2	0
21	96	3	1	0

survey must take advantage of the location of the instrument in space by either observing at small solar elongations, or searching for NEOs from a point closer to the Sun than the Earth.

When seen from the Earth, NEOs are brighter and more frequent at small solar elongations, and looking from an observing site orbiting inside the Earth brings a further advantage. For instance, with an instrument reaching $V = 18.5$ the completeness on NEOs with $H < 18$ after 5 years observation would be 55, 80, and 96% from an orbit at the Earth, Venus and Mercury, respectively. This supposes an ideal situation with daily full sky coverage, except closer than 45 degrees from the Sun.

5. OBSERVATIONS WITH GAIA

Gaia can observe as close as 35 degrees from the Sun which is very difficult to do from the ground where observation around opposition is preferred. Figures 1 and 2 show the distribution of solar elongations with Gaia for the main belt asteroids and for the available realistic simulated population of NEOs. The scanning law of Gaia and the illumination conditions explain the high frequency of observations close to the Sun for a fixed limiting magnitude, here $V = 20$. The NEOs are especially favoured in this respect with about half of the observations packed within 10 degrees of the minimum angle while the other half is almost uniformly distributed between 50 and 145 degrees, the maximum allowed by the scanning law.

NEOs can be detected when they cross the focal planes of the Astro or Spectro telescopes of Gaia; these focal planes are shown elsewhere in the present book. The motion of a NEO is typically 30 mas s^{-1} which may be detected for objects even fainter than 20 mag with good accuracy. Detection in the Astro focal plane should be done in the data analysis on the ground, based on the motion in the first part of the focal plane.

Table 3. Number of detections of NEOs with Gaia per range of absolute magnitude. The second column gives the expected number of NEOs according to Mignard (2002). The column $n = 0$ gives the number of non-detected objects, followed by those detected over less than 10 crossings or more than 10. The figures refer to the spectroscopic telescope field. A limiting magnitude $V = 20$ has been adopted for the detection.

H	N_{NEOs}	$n = 0$	$1 < n \leq 10$	$n > 10$
14.5–15.5	70	3	3	64
15.5–16.5	160	18	15	127
16.5–17.5	360	70	70	220
17.5–18.5	810	320	220	270
18.5–19.5	1800	1300	380	120
19.5–20.5	4050	3600	360	90
20.5–21.5	9000	8600	270	90
Total	16250	13951	1318	981

Detection of the motion in the Spectro telescope will be based on the object detection on the first pair of sky mapper CCDs compared with that on the last pair. The two pairs of CCDs are separated by one minute of time so that the motion of typically 2 arcsec between them may be determined quite well. Whether the recognition of a moving object is better done by on-board data analysis or on the ground is being studied.

The result from a transit of the Astro or Spectro telescope is two positions each with a few milliarcsecond precision. Or, in other words: a position and a motion vector. The scanning law of Gaia will often provide two or more transits of the telescope fields following each other in an apparition. After each apparition usually follows a month without any field transits. In one apparition the transits in, e.g., the Astro field and the Spectro field are separated by about two hours.

The number of observations with Gaias Spectro telescope is illustrated by the Tables 2 and 3 where a limiting magnitude of $V = 20$ mag has been assumed. Table 2 gives the probability that repeated observations occur a certain number of times for NEOs with various absolute magnitudes. It appears that an object with $H = 18$ will be missed in 40% of the field transits and get between 1 and 10 observations in 27% of the transits.

Table 3 gives the potential number of detections by Gaia derived from the probabilities in Table 2 and the model for the luminosity function of NEOs. A total number of 90 field transits will result for a star from a 5 year mission, but we have for Tables 3 assumed a more conservative number of 65 observations. The total number of objects detectable $(n > 0)$ is just above 2000 and only half will have a good coverage during the mission.

The contribution of Gaia with a detection limit of $V = 20$ mag to the detection of new objects will be marginal. Fainter objects may be detected but the completeness will be too low to have a real scientific impact. Hence, the importance of the observations of NEOs by Gaia lies elsewhere. Gaia is unique thanks to:

- The capability of observing close to the Sun, where ground-based surveys are biased. This not only extends the orbital coverage for eccentric orbits, but allows one to detect objects with $a(1 + e) < 1$, which is difficult to achieve from the Earth;
- the application of a homogenous method of observation and analysis to all Solar System objects;
- multi-colour photometry will be obtained for many of the objects;
- the realization of an all-sky coverage, allowing to find NEOs on atypical orbits;
- the accurate orbit determination. The *a priori* knowledge of orbital parameters, even approximate, will ease considerably the identification over successive crossings, increase the rate of observation and permit a very precise orbit determination, much better than those derived from ground-based astrometry. A precise knowledge of the orbital elements is a key factor to investigate the origin and evolution of the NEOs.

6. CONCLUSIONS

The main results reached from the crossing of a realistic NEO population with the scanning law and detection capabilities of Gaia are as follows.

- The detection of objects smaller than $\sim$ 500 m in diameter, corresponding to an absolute magnitude $H = 20$ will have a low success rate, as most of the time these objects will be fainter than the limiting magnitude expected from the Gaia detection chain. A limiting magnitude of $V = 20$ has been assumed; possibly Gaia can go a bit fainter for NEO detection, but not much.
- Objects brighter than $H = 18$, corresponding to a diameter of $\sim$ 1 km will be observed many times during the mission and a 50% survey can be expected for objects of this size and larger.
- The survey will be virtually complete at $H = 16$, that is to say for a diameter of about 2 km.
- Many observations will be obtained at small angular distances from the Sun, making the Gaia survey complementary to the ground-based surveys.
- This feature will allow an exploration of the virtually unknown world of asteroids circling the Sun constantly within the Earth orbit.
- The velocity will be typically 30 mas s^{-1}, allowing quick recognition of the motion during a single field-of-view crossing.

A study should be made of the detection of new NEOs with Gaia with respect to determination of an approximate orbit from the observations obtained within the several hours of one apparition. The number of observations is quite high in an apparition of a NEO near the direction to the Sun due to the Gaia scanning law. At the same time these NEOs are more likely to be new than elsewhere because they can hardly be seen from Earth. An approximate orbit could be used for an alert to obtain further observations from the ground. Such a special study has not yet been made.

ACKNOWLEDGEMENTS

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