Icarus **143**, 421–424 (2000)
doi:10.1006/icar.1999.6282, available online at http://www.idealibrary.com on IDEAL®

NOTE

Estimated Abundance of Atens and Asteroids Evolving on Orbits between Earth and Sun

Patrick Michel

Osservatorio Astronomico di Torino, I-10025 Pino Torinese, Italy, and Observatoire de la Côte d'Azur, B.P. 4229, 06304 Nice Cedex 4, France
E-mail: michel@to.astro.it

and

Vincenzo Zappalà, Alberto Cellino, and Paolo Tanga

Osservatorio Astronomico di Torino, I-10025 Pino Torinese, Italy

Received May 20, 1999; revised September 2, 1999

The so-called Aten asteroids, evolving on orbits with semimajor axis $a < 1$ AU and aphelion distance $Q > 0.983$ AU, spend most of their time inside Earth's orbit. Currently, they account for about 7% of the observed near-Earth asteroid population and 13% of the Earth-crossing one. However, observational biases play against their discovery; thus the present number of Atens is probably severely underestimated. Another still unobserved population of asteroids, which we call IEO (inner-Earth objects), could also exist and evolve entirely inside Earth's orbit. Orbital numerical integrations of known source populations of Earth-crossers indicate that the real fraction of Atens and IEOs in the Earth-crossing population depends on the considered objects' diameters and could be close to 20% considering only the multikilometer bodies. Moreover, the fraction of IEOs could be as large as half that of Atens. Since these asteroids can also impact Earth, their threat should seriously be taken into account.

Key Words: **asteroids, dynamics; orbits; resonances.**

1. Introduction. Near-Earth asteroids (NEAs) are conventionally divided in three groups: Aten, Apollo, and Amor. Only the first two groups evolve currently on orbits which can intersect Earth's, while Amors have trajectories which only allow close approaches to our planet, having by definition perihelion distances arbitrarily limited to $1.017 < q < 1.3$ AU.

Although the first Amor asteroid was discovered in 1898, the discovery of (2062) Aten, which gave its name to the group, occured only in 1976 (Helin and Shoemaker 1979). This is due to the biases which affect observations from Earth, as most searches are concentrated toward sky zones 180° away from the Sun, i.e., the region where Atens spend the least of their time. Several studies have been devoted to this observational problem but a general plan for a specific search strategy has not yet been constructed. Up to June 1999, 54 Aten asteroids have been observed (from the Minor Planet Center, see http://cfa-www.harvard.edu/iau/lists/Unusual.html). They constitute only 7% of the whole observed NEA population and 13% of the Apollo–Aten one. Nevertheless, no recent study has been attempted to confirm whether this percentage reflects the real abundance of these objects, and in fact it has already been suggested that their number might be twice as large (Hills and Leonard 1995). Although several searches have been specifically dedicated to the discovery of a hypothetical planet orbiting between the Sun and Mercury (Campins *et al.* 1996), the region completely inside Earth's orbit ($Q < 0.983$ AU) has never been systematically explored.

Since no asteroid has been discovered yet in this region, no name has been officially decided for this potential group, and we call them IEOs for inner-Earth objects. Note that a threat from IEOs cannot be disregarded on the long term, since different dynamical mechanisms, such as close approaches to Venus or secular mechanisms, can reinject them on an Earth-crossing orbit. The impact hazard issue of course is relevant also for Atens, since those observed have an impact probability with the Earth twice that of Apollos (Bottke *et al.* 1994). Moreover, the membership of individual asteroids to the different groups is often temporary, since NEAs' orbits are chaotic and after one planetary encounter, they can evolve from one group to the other (Milani *et al.* 1989). It is therefore necessary to take seriously into account the impact threat from Atens and IEOs, and more generally to assess in the best possible way the demography of the region between the Earth and the Sun. In other words, it is important to estimate whether a statistically significant amount of small bodies exist permanently in these groups and if the real abundance of Atens and IEOs can be expected to be larger than presently estimated from observations. This would then confirm whether observational biases from the ground are too strong against these objects.

According to present inventory (from the Minor Planet Center), the observed Apollo/Aten ratio is about 7. This ratio is highly uncertain given the severity of observational biases. The average fraction of Atens derived from the orbital evolutions of known source populations of Earth-crossing asteroids could then give a better estimate of the actual fraction. The reason is that the orbital distribution in the Apollo–Aten–IEO region obtained by simulating the flux of incoming objects is not affected by observational biases. The fraction of Aten asteroids can thus be estimated by integrating numerically over their lifetimes the orbits of a representative sample of objects initially located in different known sources. In a steady-state scenario, starting from a source population, we can then estimate the plausible distribution in the different orbital groups by computing the total residence time of the integrated objects in the corresponding regions.

Note however that there are strong differences in the dynamical mechanisms leading to Earth-crossing orbits from different sources. In turn, the relative role played by different sources can be different for Earth-crossers of different sizes. Migliorini *et al.* (1998) have shown that Mars-crosser asteroids are certainly the dominant source of multikilometer Earth-crossers, and Gladman *et al.* (1997)

0019-1035/00 $35.00

TABLE I
Estimated Ratios of Apollos, Atens, and IEOs.

Population	Apollo/ (Aten + IEO)	Apollo/ Aten	IEO/Aten
Observed	6.65	6.65	0
Computed from MB Mars-crossers	3.85	6.15	0.6
Computed from Apollo + Aten	2.89	4.95	0.71

Note. The *observed* row indicates the observed ratios on June 1999 (from the Minor Planet Center). The MB Mars-crosser group is the most abundant group of Mars-crossers and the dominant source of multikilometer Earth-crossers (Migliorini *et al.* 1998). Apollo + Aten are a representative sample of the observed Apollo–Aten population. The ratios are computed from the residence times in the Apollo, Aten, and IEO regions of these initial populations over their whole evolutions (see text for details).

have shown that the dominant source of meter-sized Earth-crossers should be main belt objects injected through collisions or nongravitational mechanisms (Farinella and Vokrouhlický 1999) in mainly the 3/1 mean-motion resonance with Jupiter (at $a = 2.5$ AU) or in the ν_6 secular one with Saturn. This is due to the fact that the dynamical lifetimes of objects injected into these resonances are very short (<2 Myr). Therefore, to sustain the population of Earth-crossing asteroids in a steady state, the number of bodies injected into resonance per unit time would be much too large for multikilometer asteroids (Menichella *et al.* 1996, Gladman *et al.* 1997). Conversely, large main belt asteroids slowly diffusing through high-order resonances can sustain the multikilometer Mars-crossers who in turn sustain the multikilometer Earth-crossers (Migliorini *et al.* 1998). For a certain size range of the bodies, the three sources (Mars-crossers and main belt asteroids injected in the 3/1 and ν_6 resonances) should be considered to give the resulting inventory and orbital distribution of objects of the corresponding sizes in the Apollo–Aten–IEO region. Further studies are required to determine the contribution of each source in this size range. In this paper, we prefer to concentrate on multikilometer bodies. Indeed, it is already possible to make an estimate of the real fraction of multikilometer Atens and IEOs, since most of them should come from the Mars-crosser source. Under Conclusions, we will also give the ratios computed from the other sources (3/1 and ν_6 resonances) separately, making it possible to analyze the sensitivity of the results as a function of the different source regions.

2. Results. We have thus considered as initial population a representative sample of the most abundant Mars-crosser group called MB by Migliorini *et al.* (1998). These objects have initially a semimajor axis $a > 2.06$ AU (location of the 4/1 resonance with Jupiter) and an inclination such that they are below the ν_6 secular resonance. Migliorini *et al.* (1998) showed that they are the dominant source of multikilometer Earth-crossers. The dynamical mechanisms responsible for their transfer into the Earth-crossing region is analyzed by Michel *et al.* (1999). Roughly, as a result of close encounters with Mars, many MBs approach the ν_6 resonance such that the secular oscillation amplitude of their eccentricity slowly increases and they become Earth-crossers with $q \sim 1$ AU before having a chance to enter deeply into the resonance. Encounters with the Earth are then very efficient and transport the bodies along the $q \sim 1$ AU curve. They can thus finally enter the Aten and IEO regions as a consequence of planetary close approaches and/or secular mechanisms. Most of the other MBs are driven to the Earth-crossing region due to the injection through Mars encounters in the 3/1 or other resonances.

We then used the numerical integrations of the orbits of 324 MBs performed by Migliorini *et al.* (1998), and in order to have better statistics, we have added the evolutions of 203 other MBs that we numerically integrated over their lifetime using the swift_rmvs3 numerical integrator (Levison and Duncan 1994). Our sample of 527 objects is thus fully representative of the orbital distribution of the whole observed population composed of 885 bodies. We have then computed the total times spent by these bodies in the Apollo, Aten, and IEO regions respectively over their lifetime. In a steady-state scenario, these residence times in the orbital element space would represent the expected orbital distribution of objects coming from the source population. Indeed, the probability of existence of an object in a given region is proportional to the time spent by the integrated bodies in this region. Hence, the ratio of the total residence time in the Apollo

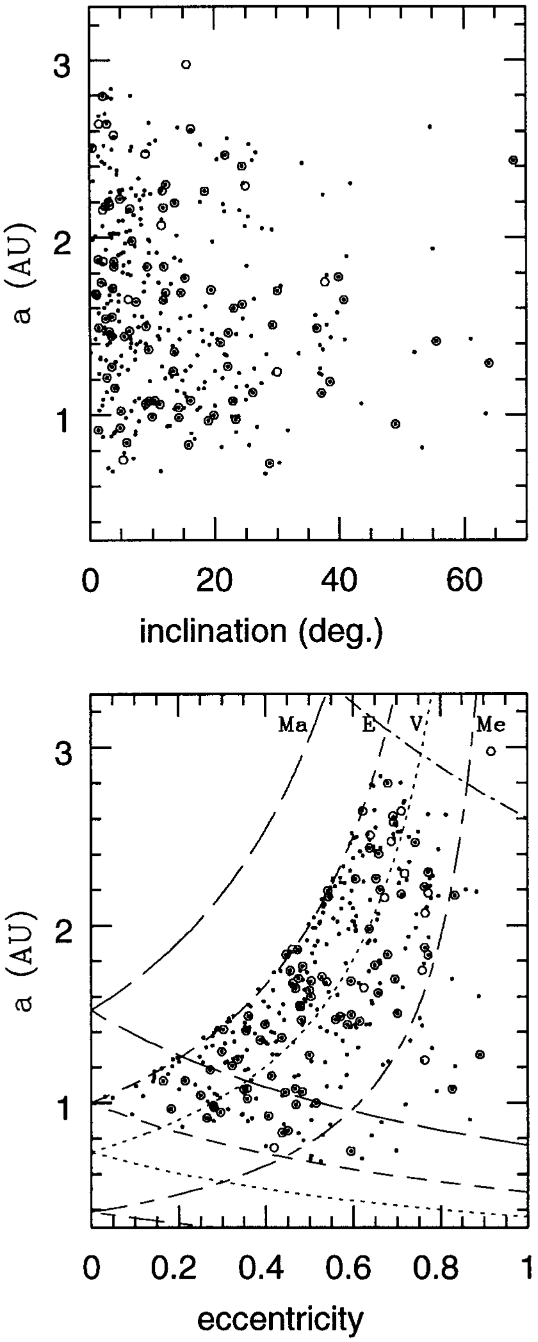

FIG. 1. Current orbital distribution of observed Apollos and Atens in the (a, i) (top) and (a, e) (bottom) planes, where a is the semimajor axis (in astronomic units), e is the eccentricity, and i is the inclination (in degrees). The initial conditions of the 81 Apollos and 12 Atens integrated in the present work are marked by blank circles. The curves correspond to the planet-crossing lines and labels indicate planets' names (Ma for Mars, E for the Earth, V for Venus, and Me for Mercury).

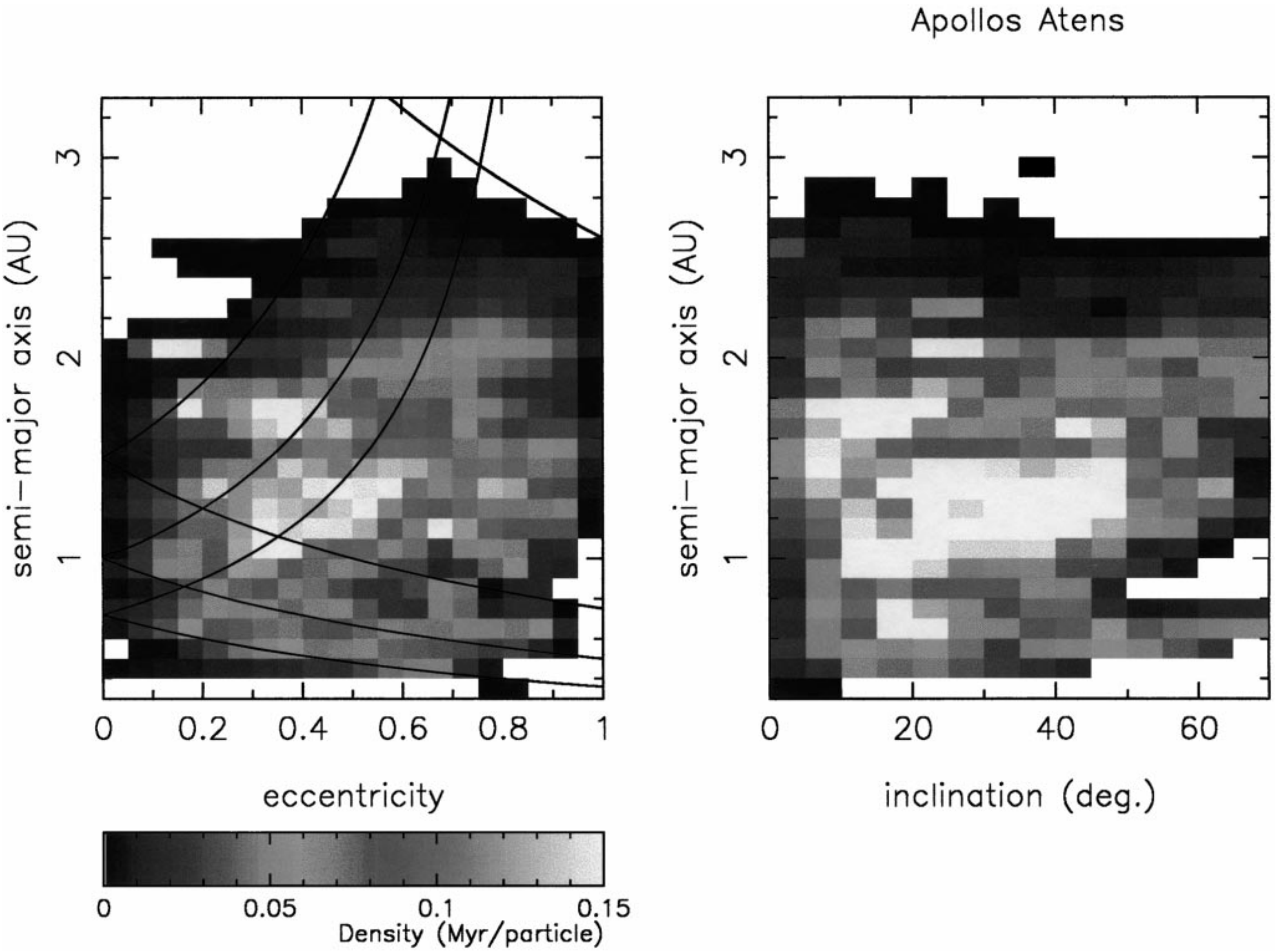

FIG. 2. Mean residence times of the Apollo–Aten sample over 60 Myr in the (a, i) (top) and (a, e) (bottom) planes, where a, e, and i are the usual orbital parameters. The (a, e, i) space has been divided into cells of equal sizes: 0.1 AU in a, 0.05 in e, and 5° in i. The total time spent in each cell by our sample has been computed and normalized by the number of integrated objects. These diagrams are thus projections in the (a, e) and (a, i) planes of the computed density distribution in the (a, e, i) space. The color scale gives the average time (millions of years per particle) spent in the different cells, the darkest being the shortest. Blank zones correspond to unvisited regions.

region over that in the Aten and IEO regions should give a better estimate of the ratio of Apollos versus Atens and IEOs in the real population. Table I shows that the estimated Apollo/Aten ratio is smaller than that observed. Moreover, IEOs are now an existing group and its abundance should be as large as 0.6 times that of Atens.

In order to analyze the evolutions of Apollos and Atens and the change of their observed ratio as a result of their evolutions, we have then used the orbital evolutions of a sample of 81 Apollos and 12 Atens computed over 60 Myr by Gladman *et al.* (1999) with the same numerical integrator. Initial conditions were taken from Bowell's catalogue (Bowell *et al.* 1994) and were selected on the basis of orbit quality. The orbital distribution of this sample does not show any obvious difference with the current distribution of the whole observed population (see Fig. 1). In particular, it contains fractions of Apollo and Aten asteroids initially similar to that observed. Starting from this population, the integrations do not simulate a steady-state scenario since our sample decays with time and does not receive a continuous feeding as the real population does. Nevertheless, it is still interesting to study whether the initial ratio changes as the population evolves. For this purpose, we have then computed the total time spent by our integrated sample in the Apollo, Aten, and IEO regions, respectively, and the ratios between these times. As shown in Table I, the resulting ratios of Apollos over either Atens + IEOs (2.9) or only Atens (4.95) are much smaller than the initial ratios, which means that many Apollos become Atens and IEOs during their evolutions and that a greater amount of time is spent in these groups. A significant fraction of IEOs appears and constitutes about 41.7% of the population with $a < 1$ AU. During their evolutions, 27.2 and 14.8% of Apollos go into respectively the Aten and IEO regions but these percentages cannot be considered as good estimates since once in the Aten region, an asteroid can still quickly go back into the Apollo group as a result of close planetary encounters or secular mechanisms. Estimates must be weighted, as we have done, by the average time in which bodies can remain in a region.

Figure 2 shows the residence time in different regions of the (semimajor axis: eccentricity or inclination) planes, normalized by the number of integrated particles. These plots show the amount of time (in millions of years) a particle spends on the average in the various regions of the orbital element space, and thus represent the expected orbital distribution of the bodies that come from our initial sample of observed Apollos and Atens. One can see that there is a concentration in the region $0.8 < a < 1.2$ AU and $0.2 < e < 0.7$ and a fairly high portion of time spent in Aten and even IEO regions. Note that in these regions, a quite large fraction of time is spent on highly inclined orbits against which observational biases are strong. Consequently, ground-based observations may miss a large component of Aten asteroids evolving on those orbits. In addition, Atens and IEOs may have a longer dynamical lifetime than the 9-Myr median lifetime of our Apollo sample, which is similar to that of the whole NEA population (Gladman *et al.* 1997, 1999). Actually, the median lifetime of the 12 integrated Atens is about 27.9 Myr, i.e., a factor of 3 greater than that of the NEA population. It has already been suggested that asteroids with semimajor axes a smaller than 2 AU have dynamical lifetimes longer than those with $a > 2$ AU, the latter being closer to mean-motion resonances with Jupiter capable of driving them directly into the Sun (Gladman *et al.* 1997). Here, we find that asteroids lucky enough to survive and evolve in the Aten and IEO regions can have a longer dynamical lifetime since their distance to dangerous resonances (at $a > 2$ AU) is increased and they can be temporarily protected against planetary close approaches thanks to efficient protection mechanisms, such as the Kozai resonance, which exist in these regions (Michel and Thomas 1996, Michel 1997). During their evolutions, Atens can go into several regions and transit to IEO or Apollo states thanks to planetary close approaches and secular resonances with terrestrial planets. Note that in the population observed, some Apollos may thus have spent some time as Atens in the past, justifying that we consider both groups in our initial sample.

3. Conclusion. In conclusion, considering initially the source population of the multikilometer objects to estimate the abundance of Atens and IEOs, we obtain a fraction of Atens and IEOs higher than that presently observed. However, the fraction of Atens depends much on the source population considered and therefore may be different for meter-sized bodies than for kilometer-sized bodies. Using the integrated orbital evolutions of thousands of particles initially placed in the 3/1 and ν_6 resonances (Gladman *et al.* 1997), we find much higher Apollo/(Aten + IEO) ratios (21.7 from the 3/1 and 7.5 from ν_6), since most objects never leave these resonances and are characterized as Apollos on their way to the Sun. These ratios are thus even higher than that observed, showing that if Apollos coming from these sources are really very abundant, they are also severely underrepresented in the population observed. Nevertheless the IEO/Aten ratio does not depend dramatically on the source. We find a similar abundance of IEOs coming from the 3/1 resonance (0.5 times that of Atens) and the Mars-crosser population (0.6 times that of Atens). The ν_6 source gives a smaller but still nonnegligible IEO/Aten ratio of $1/4$. Consequently, all sources indicate the existence of an IEO population and two of them give about the same ratio. Extensive observational programs aimed at improving the known inventory of the NEA population at small sizes are thus required to shed light on this issue.

ACKNOWLEDGMENTS

We thank P. Farinella for useful suggestions. We also thank D. Richardson and an anonymous referee for their constructive reviews of the manuscript. P.M. has worked on this project while staying at the Turin Astronomical Observatory thanks to an external fellowship of the European Space Agency.

REFERENCES

Bottke, W. F., M. Nolan, R. Greenberg, and R. Kolvoord 1994. Collisional lifetimes and impact statistics of near-Earth asteroids. In *Hazards Due to Comets and Asteroids* (T. Gehrels, Ed.), pp. 337–357. Univ. of Arizona Press, Tucson.

Bowell, E., K. Muinonen, and L. H. Wasserman 1994. A public-domain asteroid database. In *Asteroids, Comets, Meteors* (A. Milani, M. Di Martino, and A. Cellino, Eds.), pp. 477–481. Kluwer, Dordrecht.

Campins, H., D. R. Davis, S. J. Weidenschilling, and M. Magee 1996. Searching for vulcanoids. In *Completing the Inventory of the Solar System* (T. W. Rettig and J. M. Hahn, Eds.), pp. 85–96. A.S.P., San Francisco.

Farinella, P., and D. Vokrouhlický 1999. Semimajor axis mobility of asteroidal fragments. *Science* **283**, 1507–1510.

Gladman, B. J., P. Michel, and Ch. Froeschlé 1999. The near-Earth object population. *Icarus*, submitted.

Gladman, B. J., F. Migliorini, A. Morbidelli, V. Zappalà, P. Michel, A. Cellino, Ch. Froeschlé, H. Levison, M. Bailey, and M. Duncan 1997. Dynamical lifetimes of objects injected into asteroid belt resonances. *Science* **277**, 197–201.

Helin, E. F., and E. M. Shoemaker 1979. The Palomar planet-crossing asteroid survey, 1973–1978. *Icarus* **40**, 321–328.

Hills, J. G., and P. T. Leonard 1995. Earth-crossing asteroids: The last days before Earth impact. *Astron. J.* **109**, 401–417.

Levison, H., and M. Duncan 1994. The long-term behavior of short-period comets. *Icarus* **108**, 18–36.

Menichella, M., P. Paolicchi, and P. Farinella 1996. The main belt as a source of near-Earth Asteroids. *Earth Moons Planets* **72**, 133–149.

Michel, P. 1997. Overlapping of secular resonances in a Venus horseshoe orbit. *Astron. Astrophys.* **328**, L5-L8.

Michel, P., and F. Thomas 1996. The Kozai resonance for near-Earth asteroids with semimajor axes smaller than 2 AU. *Astron. Astrophys.* **307**, 310–318.

Michel, P., F. Migliorini, A. Morbidelli, and V. Zappalà 1999. The population of Mars-crossers: Classification and dynamical evolution. *Icarus*, submitted.

Migliorini, F., P. Michel, A. Morbidelli, D. Nesvorný, and V. Zappalà 1998. Origin of multikilometer Earth- and Mars-crossing asteroids: A quantitative simulation. *Science* **281**, 2022–2024.

Milani, A., M. Carpino, G. Hahn, and A. Nobili 1989. Dynamics of planet-crossing asteroids: Classes of orbital behavior, project Spaceguard. *Icarus* **78**, 212–269.