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NEAR-EARTH OBJECT SURVEY SIMULATIONS WITH A REVISED POPULATION MODEL

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ABSTRACT

We carried out a set of simulations to reproduce the performance of wide-field NEO surveys based on the revised population model of Near Earth Objects (NEOs) constructed by Morbidelli (2006). This is the first time where the new model is carefully compared with discovery statistics, and with the exception of population model, the simulation is identical to the procedure described in Moon et al. (2008). Our simulations show rather large discrepancy between the number of NEO discoveries made by the actual and the simulated surveys. First of all, unlike Bottke et al. (2002)'s, Morbidelli (2006)'s population model overestimates the number of NEOs. However, the latter reproduces orbit distributions of the actual population better. Our analysis suggests that both models significantly underestimate Amors, while overestimating the number of Apollos. Our simulation result implies that substantial modifications of both models are needed for more accurate reproduction of survey observations. We also identify Hungaria region (HU) to be one of the most convincing candidates that supply a large fraction of asteroids to the inner Solar System.

Key words : minor planets, asteroids - solar system: general - surveys

I. INTRODUCTION

During the past few years, we have witnessed an exponential growth in the number of catalogued asteroids and comets. On January 12 2008, the number of kilometer sized NEOs (hereafter referred as 'NEO(+1 km)')($H \leq 17.75$) reported to the Minor Planet Center (MPC) is 732 (`http://www.cfa.harvard.edu/iau/lists/MPLists.html`). This roughly corresponds to about 70−85% of the predicted population, depending on the size of base model (See Rabinowitz et al., 2000; Stuart, 2001; Bottke et al., 2002).

Recent upgrades of CCDs and refurbishment of dedicated telescopes led to observational biases that are quite different from those asteroid surveys before the early 2000's. Therefore, it would be a timely investigation if we evaluate the performance characteristics of the current asteroid survey programs and their prospects, with most recent population models together with detailed survey simulations. In an effort to compare the numbers, orbit (a, e, i) and absolute magnitude (H) distributions of actual NEO population, Moon et al. (2008) constructed a set of improved survey simulators integrating four-dimensional theoretical population of 4668 NEOs (Bottke et al. 2002) and strategies of the past and present search programs. Their simulation could roughly reproduce the observed (a, e, i, H) distribution of the catalogued NEOs as of December 2005. Furthermore, their extended experiment provided excellent predictions for the discovery statistics as well as orbital distributions of NEOs (H <18)(hereafter, NEO(+18)) reported to the MPC for the year 2006. The close match between the simulated and the actual surveys implies that the simulation is a plausible approximation of reality. However, they also claimed that Bottke et al. (2002) population model can be further improved by substantial revisions because it exhibits small but clear mismatches in (a, e, i, H) distributions with those of the actual sample; the latter outnumbers in certain regions in semi-major axis (a), ellipticity (e) and orbital inclination (i). In the work presented here, we apply survey simulator that was presented in the previous work of Moon et al. (2008) with a revised population model (Morbidelli 2006, personal communication). We expect that our experiment could provide a stringent test for the precision of population models. We can also compare the magnitude (and hence size) and shape of the actual and model NEA (Near Earth Asteroid) population according to their families (Atens, Apollos, Amors, and IEOs;

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Inner Earth Objects). It may tell us about contribution from main-belt source regions derived by Bottke et al. (2002) and Morbidelli (2006). A brief introduction to the simulation method is given in the following section.

II. SURVEY SIMULATION

(a) Characteristics of NEO Surveys

The characteristics of the major asteroid search programs are reviewed in Table 1 of Moon et al. (2008) that covers all of important historical and existing survey programs. Our survey simulation is based on the monthly sky plots (See `http://scully.harvard.edu/~cgi/SkyCoverage.htm`; `http://www.ll.mit.edu/LINEAR/skyplots.html`) and a number of critical survey parameters provided in the table.

(b) Survey Periods

NEO discovery of major survey programs have been benefited from improvements in detector size and sensitivity as well as availability of larger apertures. Upgrades and replacements of telescope, CCDs, and post-processing software resulted in fainter limiting magnitude, larger field of view, and higher detection efficiencies. In order to reflect modifications in search strategies and technical development in the past, we defined five distinct episodes (from period I to period V) in which contributions from individual survey have been significantly changed in search volume (Moon et al. 2008).

(c) Ephemerides

In order to run each simulation code we input a list of fake NEOs with Keplerian orbital elements and absolute magnitude (H). To compute ephemerides for NEO population models, i.e., 4668 NEOs (Bottke et al. 2002) and 6239 NEOs (Morbidelli, 2006), for each night and for a period of 10 years, the JPL Horizons System (Giorgini et al., 1996) is utilized. With orbital elements and H distributions provided by William Bottke and A. Morbidelli observable quantities for each NEO such as position, distance, phase angle, and solar elongation were calculated throughout the ten year simulation. The apparent magnitude is calculated following the method of Bowell et al. (1989) assuming that a slope parameter (G) of 0.23.

(d) Survey Simulators

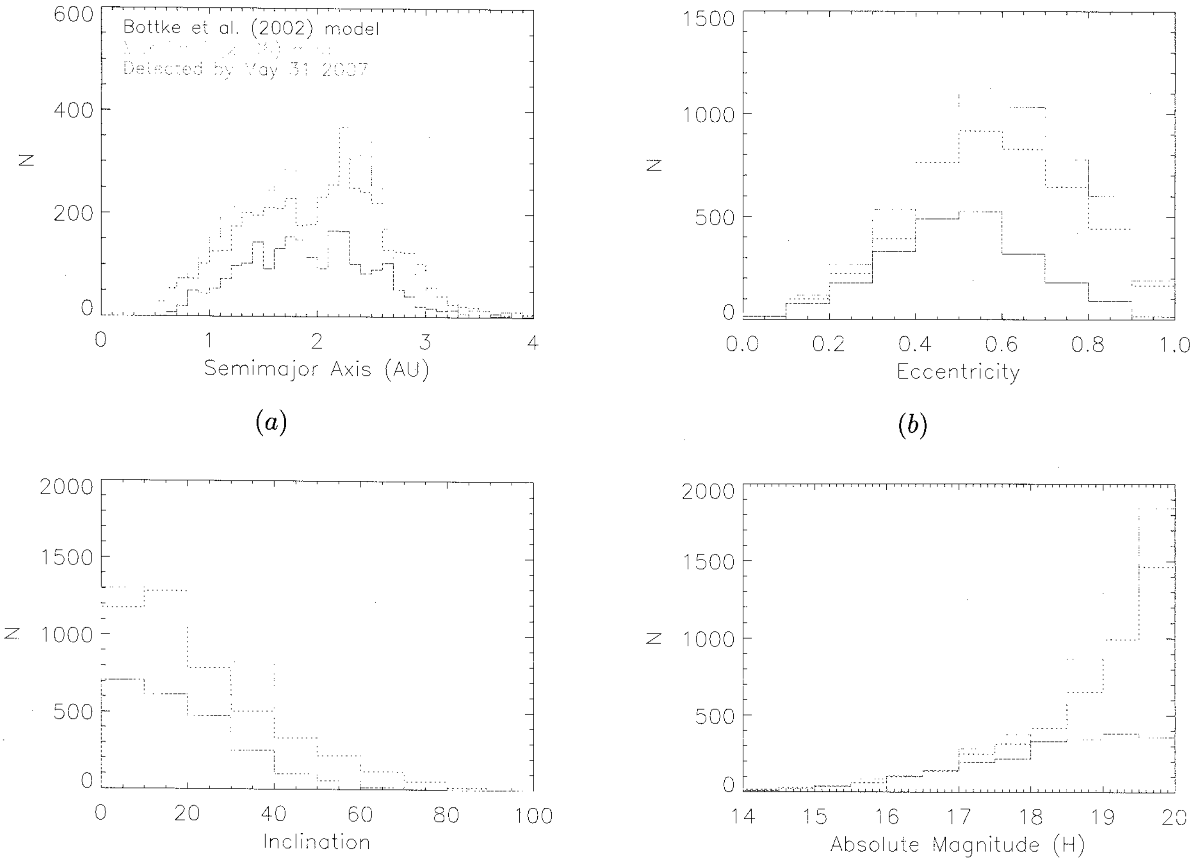
We use survey simulator constructed by Moon et al. (2008) employing 21 individual survey simulators (ISS) for each site and each period. We started simulations with period I and finished with period V, until December 31 2005, in order to directly compare the present result with Moon et al. (2008).

III. NEO POPULATION MODELS

At present, we have two NEO population models; Bottke et al. (2002) and Stuart (2003). The former was constructed by combining numerical integration work with model fit to relatively small sample of 138 NEAs discovered by Spacewatch (Bottke et al., 2002) while the latter was created by direct de-biasing of more extensive dataset (>1300 NEAs) from the LINEAR database (Stuart, 2003). Essentially, both models are distinct in the sense that the former assigns H and orbital elements (a, e, i) of constituent particles, whereas the latter does not distinguish individual objects; the Stuart (2003) model is one-dimensional projections of (a, e, i, H). Yet they are in overall agreement with small differences such as size of the population, and overabundance of higher inclination objects suggested by Stuart (2001). Recently, Morbidelli (2006, personal communication) revised the population model by applying bias corrections adapted by Stuart (2003) to Bottke et al. (2002)'s. In this paper, we employ the revised model provided by Morbidelli (2006) for our survey simulations. More detailed comparison of these two models are given below.

Bottke et al. (2002) population model: Bottke et al. (2002) constructed a theoretical model population which is based on two assumptions: (1) the H distribution follows a source independent law that is valid for $13 < H < 22$; (2) the NEO population is continuously supplied by five intermediate source (IS) regions: (a) the $\nu 6$ secular resonance in the main asteroid belt, (b) the 3:1 mean motion resonance at 2.5 AU, (c) the intermediate source Mars-crossers, (d) the outer main belt, and (e) trans-Neptunian disk. This model is established by taking a linear combination of (a, e, i) distributions from each IS with one parameter, source independent law for H distribution. Then, they obtained best fit model parameters based on observations. However, the limited number of Spacewatch NEOs could not afford sufficient coverage to normalize a wide-ranging probability distribution of NEOs in orbit parameters and H space, as Bottke et al. (2002) acknowledged. This population model provides 4668 fake NEOs with $H \leq 20$ including 961 NEO(+18)s.

Morbidelli (2006) population model In the early 2000's, Morbidelli et al. (2002) and Stuart (2003) independently computed NEO albedo distribution models assuming an albedo-dependent bulk density of the population. Their results are in overall agreement which evidences that current understanding of the population has attained a high level of accuracy. Recently, Morbidelli (2006, personal communication) applied bias corrections adapted by Stuart (2001) to the Bottke et al. (2002) population model and obtained an excellent match to LINEAR data. In order to fit the model population to the observed distributions of orbit elements (a, e, i), they included two additional high inclination



(*a*) (*b*)

(*c*) (*d*)

Fig. 1.— Comparison of orbit elements and H magnitude of two population models with $H < 20$ together with the actual NEO(+20) discovered by June 1 2007, for comparison. (a, e, i, H) distributions of BO(+20) and MO(+20) are shown in black dotted, and red histograms, while those of the actual objects are illustrated in blue.

sources such as Hungaria (HU) ($1.77 < a < 2.06$AU; $i > 15°$) and the Phocaeas (PH) ($2.1 < a < 2.5$ AU; above $\nu6$ resonance) to the five intermediate source regions suggested by Bottke et al. (2002). In this paper, we utilize the revised model provided by Morbidelli (2006, personal communication) that contains 6230 NEOs with $H \leq 20$ including 1139 NEO(+18)s.

We compare (a, e, i, H) distributions of two population models with $H < 20$ together with the actual NEO(+20)(NEOs witn H $<$ 20) discovered by June 1 2007, for comparison. For the sake of convenience, we define the Bottke et al. (2002) model with cutoff absolute magnitude (hereafter referred as H_{cutoff}) H_{cutoff} <18 as BO(+18), and H_{cutoff} <20 as BO(+20). In a similar fashion, we refer the Morbidelli (2006, personal communication) population model with H_{cutoff} <18 and H_{cutoff} <20 as MO(+18) and MO(+20), respectively. In all diagrams shown in this paper, including Fig. 1, orbit (a, e, i) and H distributions of BO(+20) and MO(+20) are shown in black dotted and red histograms, while those of the actual populations are illustrated in blue.

IV. SIMULATION RESULTS

Number of discovery: We performed survey simulations with Morbidelli (2006)'s population model. However, we failed to match the number of actual discovery with those detected by simulations (See Table 1). Number of the actual pop(+18)(NEO population with H $<$ 18) discovered (by actual surveys) in each time period (from period I to period V) are 234, 70, 122, 212, and 125, respectively, whereas the number of detected MO(+18)s (by simulations) are 249, 93, 132, 272, and 160, in the same time frame. The total number of NEO(+18)s found by observation was 763 as of December 31 2005, while the number of simulated discovery is 906. They differ by 143 which corre-

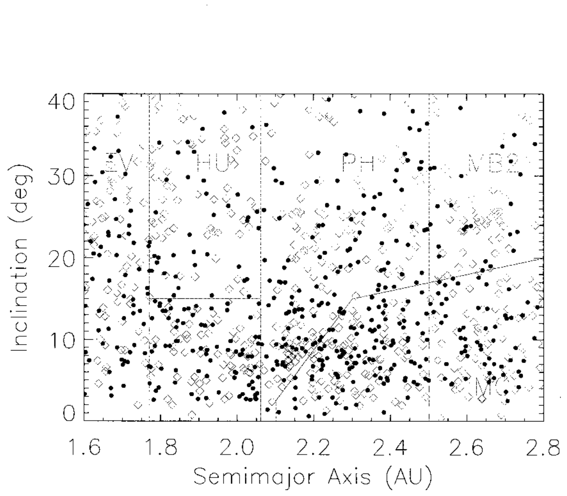


Fig. 2.— A graphical representation of (a, i) distributions of both real pop(+18)as of June 1 2007 (red diamonds) and model pop(+18)(black filled circles). The lines define boundaries between the evolved Mars-crossing population (EV)($a < 1.77$ or $1.77 < a < 2.06$AU; and $i > 15°$), Hungaria (HU)($1.77 < a < 2.06$ AU; $i > 15°$), the Phocaeas (PH) ($2.1 < a < 2.5$ AU; above $\nu6$ resonance), and the MB2 population ($a > 2.5$; above $\nu6$ resonance).

sponds to 18.7% of the known NEO(+18)s (i.e., (906-763)/763 = 143/763=18.7%). The ratio of the difference between the number of MO(+18) and BO(+18) to that of BO(+18) accounts for about 18.5% (i.e., (1139-961)/961=178/961~18.5%). This result indicates that the simulator detects fake objects with the number proportional to the ratio of the population size (i.e., 961/1139).

In Table 2, the contrast between the number of NEO(+20)s discovered by the actual observations and those detected by simulation is presented. It is revealed that our simulators overestimate as much as 580 NEO(+20)s than those reported to the MPC. This corresponds to about 29.9% of the number of NEO(+20)s detected in actuality ((2521-1941)/1941=580/1941 ~ 29.9%). The ratio of the difference between the number of MO(+20) and BO(+20) to that of BO(+20) is about 27.7%, hence the simulation result again reflects the difference between model populations (i.e. (5730-4487)/4487=1243/4487 ~27.7%). Note that Table 12 and Table 13 in Moon et al. (2008) show close agreement between the number of model population (Bottke et al. 2002) and the actual objects, yet Table 1 and Table 2 in this paper reveal significant disagreement between the revised model (Morbidelli 2006) and the actual population.

V. POPULATION MODEL vs. OBSERVATION

(a) (a, e, i, H) Distributions of the Entire Family

We find a significant disagreement between population models and the known sample in the (a, e, i, H) phase space. In order to examine the discrepancy, we compared orbit elements and H distributions of both Bottke et al. (2002) and Morbidelli (2006, personal communication) models.

Bottke et al. (2002) model: Morbidelli and Nesvorny (1999) demonstrated that the Mars-crossing asteroids are considered to have been produced by mean-motion resonances with Jupiter or Mars and also by three-body mean-motion resonances with Jupiter and Saturn (Nesvorny and Morbidelli 1998). In their vicinity, main belt asteroids slowly increase the orbital eccentricity until their orbits cross that of Mars, and finally become NEOs over several tens of millions of years (Migliorini et al., 1998), in the mean time, their semimajor axis and orbital inclination do not change. It was observed that the actual NEO population outnumbers in $a \sim 1.8 - 2$AU, 2.1-2.2AU, and 2.6-2.7AU, likewise, they are in excess in $i \sim 20° - 30°$ (See Fig. 1 and Fig. 2 of Moon et al., 2008). Bottke et al. (2002) referred to additional IS (Intermediate Source) residing Intermediate Mars-crossers (IMCs) region that are capable of transporting objects into NEA region. An (a, i) plot of the known and model pop(+18)s as of June 1 2007 is illustrated in Fig. 2. In order to further investigate the above assumption, we simply count the number ratio of the actual pop(+18) to BO(+18) in the locations that corresponds to additional IS regions. Here, we consider that each additional IS region has one-to-one correspondence to the locations where the actual NEAs outnumber fake objects in the (a, i) plane: the evolved Mars-crossing population (EV)($a < 1.77$ or $1.77 < a < 2.06$ AU; $i > 15°$), Hungaria (HU)(1.77AU $< a < 2.06$ AU; $i > 15°$), the Phocaeas (PH) ($2.1 < a < 2.5$ AU; above $\nu6$ resonance), and the MB2 population ($a > 2.5$; above $\nu6$ resonance). (The nomenclature used in Michel et al. (2000) is employed.) The number ratios, actual pop(+18) to BO(+18) in the EV, HU, PH+IMC, and MB2+IMC regions are, 0.76, 1.46, 0.84 and 0.88, respectively. Provided that the known pop(+18) as of June 1 2007 ($n = 813$) accounts for 84.6% of the underlying population ($n = 961$), they can be directly translated to 0.88, 1.69, 0.97, and 1.02 of the model. Likewise, the number ratios of pop(+20) to BO(+20) in each corresponding locations are 1.09, 1.42, 0.94, and 0.79, respectively, if we assume that the known pop(+20) as of June 1 2007 ($n = 2233$) accounts for 49.77% of the model (BO(+20); $n = 4487$). With this simple arithmetic, we may conjecture that Hungaria (HU) region has been supplying significant fraction of NEAs than the current model predicts.

Morbidelli (2006) model: Morbidelli (2006)'s NEO

TABLE 1.
NUMBER OF OBSERVED AND SIMULATED NEOS (H <18)

		PERIOD I		PERIOD II		PERIOD III		PERIOD IV		PERIOD V	
		obs	**model**	obs	**model**	obs	**model**	obs	**model**	obs	**model**
PCAS/PACS	**675**	85									
Others	**-**	39									
Subtotal	**-**	124	**128**								
AANEAS	**413**	27									
Others	**-**	12									
Subtotal	**-**	39	**46**								
LINEAR	**704**	10		51		97		136		53	
NEAT	**566**	14									
LONEOS	**699**	1		8		7		22		8	
CSS	**703**			4		5				25	
Others	**-**	12		5		5		6		3	
Subtotal		37	**48**	68	**86**	114	**127**	164	**189**	89	**117**
NEAT	**608**					4	**3**	15	**27**	3	**3**
	644							30	**43**	11	**17**
Spacewatch	**291**							2	**5**	1	**4**
	691	34	**27**	2	**7**	4	**2**	1	**8**	8	**4**
CSS	**E12**									10	**14**
	G96									3	**1**
Grand Total	**-**	234	**249**	70	**93**	122	**132**	212	**272**	125	**160**
763/**906**	+/-*		**+15**		**+38**		**+48**		**+108**		**+143**

* Cumulative difference between n(NEO_{obs}) and n(NEO_{model})

population model reproduces orbit distributions of the actual population better. We presented (a, e, i, H) distribution of two NEO population models, BO(+18) and MO(+18), and the actual NEO(+18)s discovered by June 1 2007. The actual pop(+18) outnumbers in $a \sim 1.8 - 1.9$AU by $\sim$ 15% and 2.6-2.7AU by $\sim$75% (See Fig. 3).

(b) (a, e, i, H) Distributions of NEA Families

Bottke et al. (2002) model: Moon et al. (2008) demonstrated that the simulator detected different proportions of NEA families from those discovered by the actual survey teams; as of June 1 2007, the discovery teams actually found 32 Atens, 388 Apollos, and 378 Amors with H < 18 whereas simulator detected 51 Atens, 464 Apollos, and 280 Amors (H < 18) in the same time frame. Thus, we may conjecture that Bottke et al. (2002) overestimates as much as 59% of Atens and 20% of Apollos, at the same time they underestimate 26% of Amors assuming that the shape of the population detected by simulation reflects that of the base model.

Now, we make comparisons of orbit and H distributions of BO(+18) with those of the actual NEO(+18)s. The actually discovered Apollos are in excess near a 2.6-2.7AU, however the distinction between virtual and the actual objects becomes most serious for Amors. As shown in Fig. 4(a), the model predicts less Amors in $a \sim$ 1.6-2.3AU and 2.5-2.9AU. On the other hand, it is surprising that the catalogued NEO(+18)s accounts for 420% of the Bottke et al. (2002) model near a 1.9-2.0AU. Further, they are abundant in $e \sim 0.2 - 0.6$, with 20%-70% excess of those predicted by Bottke et al. (2002) (Fig. 4(b)). Also, it should be noted that there is an overabundance of the actual Amors with higher inclination orbits (Fig. 4(c)). While the difference between model and the known sample is relatively small for H distribution, sizable excess is observed near $H \sim 15 - 17$ and $H \sim 17.5 - 18$, in the real world;

Table 2.
Number of observed and simulated NEOs ($H < 20$)

		Period I		Period II		Period III		Period IV		Period V	
		obs	**model**	obs	**model**	obs	**model**	obs	**model**	obs	**model**
PCAS/PACS	**675**	130									
Others	-	43									
Subtotal	-	173	**198**								
AANEAS	**413**	40									
Others	-	16									
Subtotal	-	56	**72**								
LINEAR	**704**	43		133		217		367		196	
NEAT	**566**	20									
LONEOS	**699**	1		14		32		56		31	
CSS	**703**			10		19				70	
Others	-	21		9		7		17		19	
Subtotal		85	**94**	166	**167**	275	**326**	440	**588**	316	**428**
NEAT	**608**					11	**6**	46	**56**	6	**31**
	644							111	**180**	31	**114**
Spacewatch	**291**							8	**12**	3	**18**
	691	62	**82**	12	**41**	18	**5**	17	**22**	34	**32**
CSS	**E12**									41	**38**
	G96									30	**11**
Grand Total	-	376	**446**	178	**208**	304	**337**	622	**858**	461	**672**
1941/2521	+/-*		**+70**		**+100**		**+133**		**+369**		**+580**

* Cumulative difference between n(NEO_{obs}) and n(NEO_{model})

the discrepancy becomes 70% in $H \sim 16.5 - 17$. In summary, it is most probable that the Bottke et al. (2002) model underestimates Amors with semimajor axis $a \sim$ 1.6-2.3AU and 2.5-2.9AU, with highly eccentric and larger inclination orbits. In addition, it is obvious that the model estimates excess number of Apollos.

(c) Morbidelli (2006) Model

As observed with the Bottke et al. (2002) model, the "actual" Amos outnumbers "fake" counterpart in certain locations in semimajor axis (for $H < 18$); $a \sim$ 1.2-1.4AU, 1.5-1.7AU, 1.8-2.2AU, and 2.5-2.9AU (Fig. 5(a)). In particular, they exceed by 300% in quantity near $a \sim$ 2.6-2.7AU. Likewise, there is a general deficit of fake Amors both in $e \sim 0.2-0.4$ and $e \sim 0.5-0.6$; the Morbidelli (2006) population model probably underestimate at least 50% of Amors ($H < 18$) with moderately eccentric orbits ($e \sim 0.5 - 0.6$) (Fig. 5(b)). On the other hand, distribution of orbit inclination shows an overabundance of the actual Amors ($H < 18$) with $i \sim 20° - 50°$, in Fig. 5(c). The present model systematically underestimates the population size of Amors ($H < 18$) while considerably overestimates that of Apollos (Fig. 5(d)).

VI. SUMMARY AND DISCUSSION

We made use of revised population model of 6230 NEOs provided by A. Morbidelli for detailed survey simulations. However, we failed to match NEO discovery rate of the actual and the simulated surveys. In this section, we summarize the main results of our simulation results.

Size of the population: The mismatch between the simulated and the actual surveys is statistically significant; they differ by ~18.5% for pop(+18), and ~ 29.9% for pop(+20). In Moon et al. (2008), survey simulations with the Bottke et al. (2002) population model accurately reproduced discovery statistics of actual sur-

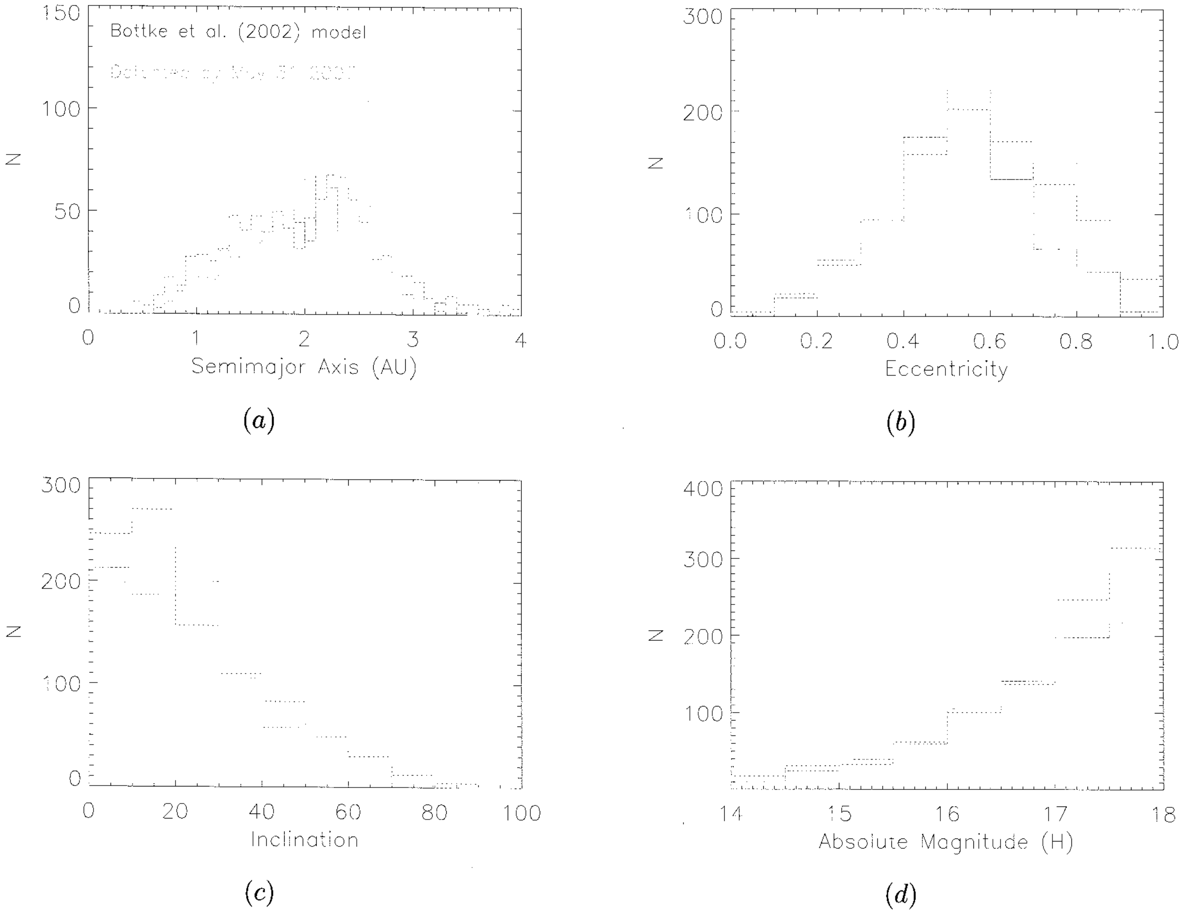


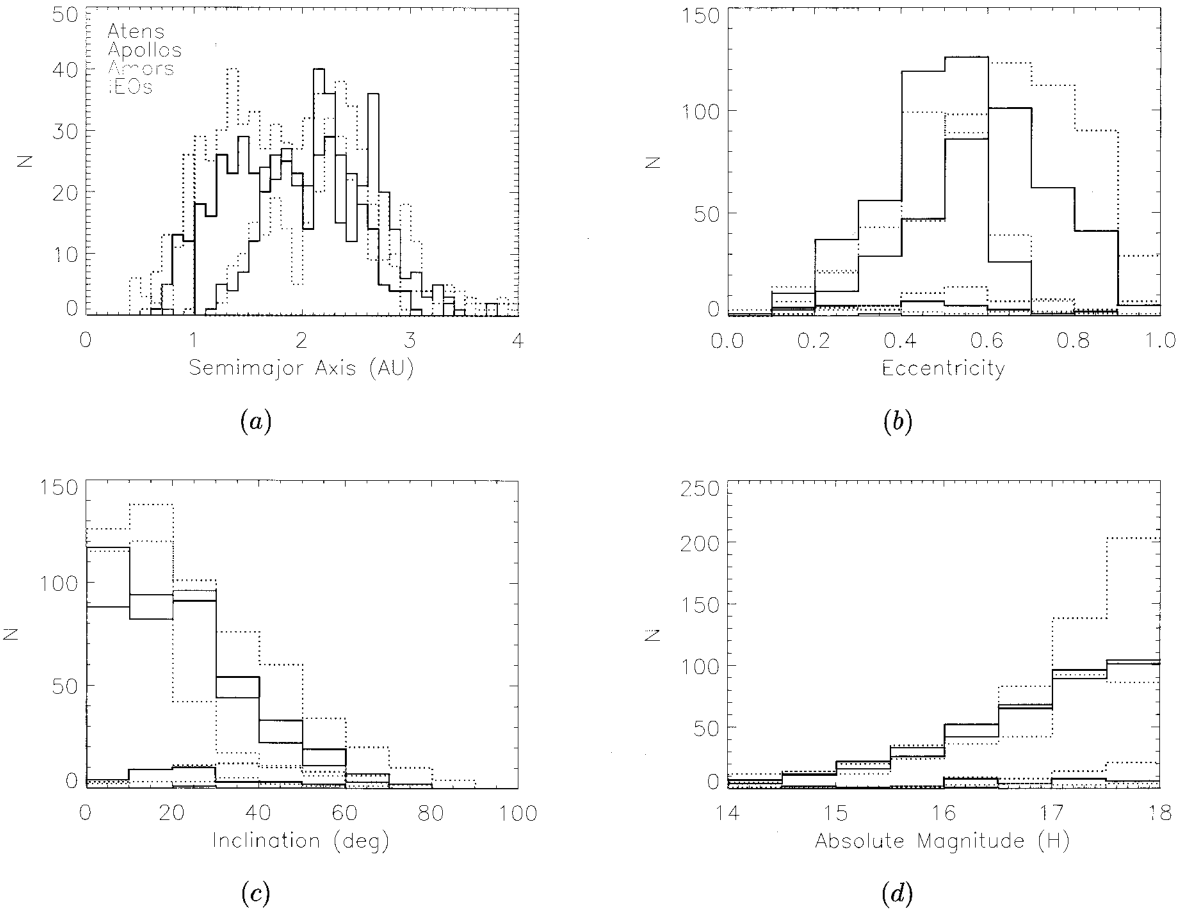
Fig. 3.— Distributions of (a, e, i, H) for BO(+18), MO(+18), and the actual NEO(+18)s discovered as of June 1 2007 is compared. BO(+18) and MO(+18) are shown in black dotted, and red histograms, respectively, while those of the actual objects are illustrated in blue.

veys. Our simulation suggests that Morbidelli (2006)'s NEO population model considerably overestimates size of the population. We may conjecture that, as far as population size is concerned, the Bottke et al. (2002) model is close to the real while the Morbidelli (2006) model better reproduces the overall shape of the orbit distributions of actual population.

(a, e, i, H) *distribution of the entire family*: We found noticeable contrast among (a, e, i, H) distributions of the actually known and underlying model populations (Bottke et al., 2002; Morbidelli, 2006). The actual objects outnumber in the almost identical locations in the semimajor axis (a ~1.8-2AU, 2.1-2.2AU, and 2.6-2.7AU) for both population models, yet Morbidelli (2006)'s model reveals modest improvements. On the other hand, however, only a slight overabundance of the known sample is observed in certain locations in the eccentricity and inclination distributions with Morbidelli (2006)'s NEO model population.

(a, e, i, H) distributions of NEA families: We suspect that Bottke et al. (2002) overestimates 59% of Atens and 20% of Apollos while on the other hand, it apparently underestimates 26% of Amors assuming that our simulated survey is a plausible approximation of the reality. Morbidelli (2006)'s model also predicts relatively small number of Amors. However, both NEO population models considerably overestimate the population size of Apollo asteroids.

Additional IS: It was clearly shown that the Bottke et al. (2002) model and the actual populations, either pop(+18) or pop(+20), show perceptible discrepancies, in the specific locations in the (a, e, i, H) space. Based not only on the survey simulation results but also on the comparison between the actual and model populations, Hungaria region (HU) is considered to be the most convincing candidates that provide a considerable proportion of NEAs than the present population model estimates. (Note that Morbidelli (2006)'s model



(*a*) (*b*)

(*c*) (*d*)

Fig. 4.— Comparison of the real and the Bottke et al. (2002) model population in (a, e, i, H) space. The real pop(+18)s discovered by June 2007 is shown in thick lines, whereas the population model (BO(+18)) is depicted in dotted lines. Each color corresponds to each family of NEAs; IEOs (cyan), Atens (black), Apollos (blue), and Amors (red).

included Hungaria (HU) and Phocaeas (PH) as additional IS.)

The physical properties and the dynamical evolution of NEA population cannot be understood without knowledge of their size, number, and orbit distribution. Our detailed analysis suggests that substantial revisions of the population model are required, either in the relative importance of NEO source regions (together with residence time probabilities, flux, and etc.), or inclusion of additional IS providing asteroidal and cometary bodies into the near Earth space.

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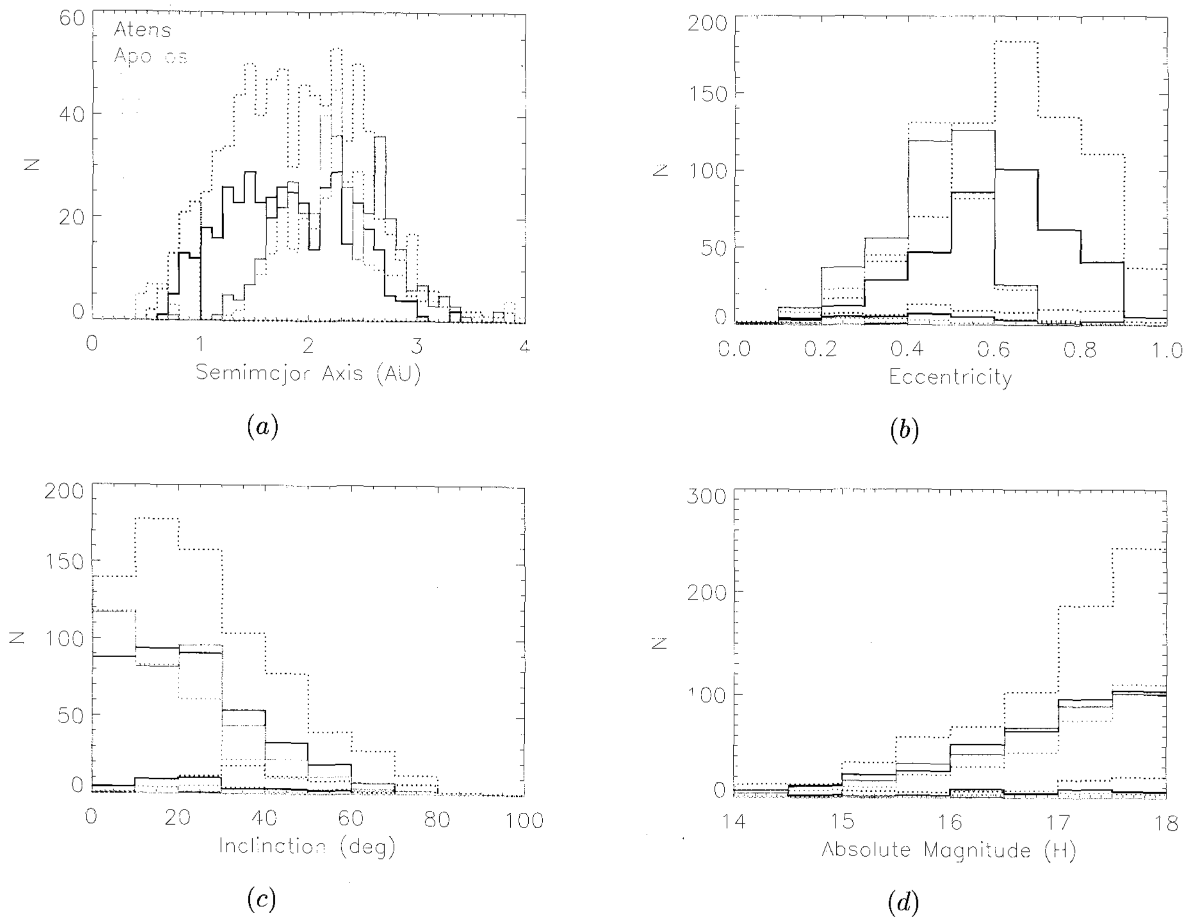

Fig. 5.— Comparison of the actual and the Morbidelli (2006) model population in (a, e, i, H) space. The thick lines represent the actual pop(+18)s discovered by June 1 2007, while the dotted lines depict the population model (MO(+18)). Each color corresponds to each family of NEAs; IEOs (cyan), Atens (black), Apollos (blue), and Amors (red).

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