TRACKING NEAS FROM THEIR SOURCE REGIONS TO THEIR OBSERVED ORBITS. W. F. Bottke, Jr., *CRSR, Cornell University, Ithaca NY 14853-6801, USA, bottke@astrosun.tn.cornell.edu*, A. Morbidelli, J.-M. Petit, B. Gladman, *Obs. de la Cote d'Azur, B.P. 4229, 06034 Nice Cedex 4, France*, R. Jedicke, *LPL, U. Arizona, Tucson, AZ 85721, USA*.

Abstract. Recent work [1] has allowed us to deduce the debiased orbital and size distributions of the NEA population ($H < 22$). We estimate that approximately 28%, 66%, and 6% of the NEA population reside on Amor, Apollo, and Aten orbits, respectively, and that there are ~ 750 NEAs with $H < 18$ (i.e., $\sim$ 1 km in diameter). Assuming these are steady state values, we can use numerical integration to determine the inflow/outflow rate of bodies from the 3:1 resonance, the ν_6 resonance, and the Mars-crossing asteroid population. These values in turn allow us to estimate the steady state asteroid population in those regions.

Terminology. The starting point for all NEAs is the main belt, which we call the "ultimate source" (US). Asteroid fragments, liberated during collisions in the main belt, are directly injected [2] or slowly moved via radiation drag [3] into both mean-motion and secular resonances, where resonant perturbations proceed to pump up the eccentricities (and inclinations) of entrained objects until they reach the NEA region. We refer to the important 3:1 and ν_6 resonances in the inner main belt as "intermediate sources" (IS) of NEAs. The Mars-crossing asteroid population, replenished predominantly via numerous weak main-belt resonances in the main belt [4], is also an IS of NEAs. Most NEAs coming from the Mars-crossing region originally have orbits with $2.0 < a < 2.8$ AU, $i < 16°$, and perihelion $q < 1.3$ AU [5]. We call this the "MC" region. The near-Earth asteroid (NEA) region, with perihelion $q \leq 1.3$ AU and aphelion $Q \geq 0.983$ AU, is considered the "target region" (TR). Material in the TR can collide with the Sun, a planet, or be ejected via a close encounter with Jupiter. We collectively call these endstates the "sink". Nearly all asteroids in the IS regions pass through the TR before going to a sink.

The Steady State NEA Population. To understand the orbital paths taken by NEAs from the IS regions, we tracked thousands of test bodies started in each IS (i.e., the 3:1, ν_6 resonances and the MC region) across a network of (a, e, i) cells in the TR. Each (a, e, i) cell was (0.06 AU $\times 0.02 \times 5°$) in volume. The test bodies were numerically integrated using the symplectic N-body code "swift-rmvs3" [6]. Gravitational perturbations from planets Venus through Neptune were included. Test bodies entering the TR were followed until they entered the sink. The nominal length of the integrations was 100 Myr. The steady state orbital distribution of NEAs coming from each IS was determined by calculating the cumulative time that particles spent in each cell and then normalizing the resulting numbers by the total time spent in all cells. The resultant "residence time" probability distribution ($R_{IS}(a, e, i)$) indicates where asteroids from each IS statistically spend their time in the TR [1] [7].

To determine the orbital distribution of the NEAs, we linearly combined all three R_{IS} distributions and compared them to NEA data. Since real NEAs are biased by observational selection effects, we modified our dynamical results with bias estimates determined for the Spacewatch NEA survey [8] and fit our new distribution to only those NEAs discovered by Spacewatch. Our biased NEA orbital distribution is:

$$n = B\,(a, e, i, H)\; N_{NEA}\,(< H) \sum^{IS} \alpha_{IS}\; R_{IS}\,(a, e, i)$$

where B is the bias estimate, N_{NEA} is the absolute magnitude distribution depending on some parameter k (i.e., $N(< H) \sim 10^{kH}$), and α_{IS} is a weighting factor. Our best-fit case for n yielded $(\alpha_{3:1}, \alpha_{MC}, \alpha_{\nu_6}) = (0.44, 0.27, 0.29)$ and $k = 0.41$.

By removing the biases from n, we obtained the debiased orbits and sizes of the NEAs. We predict there are ~ 750 NEAs with $H < 18$, about a factor of 2 lower than previous estimates but within cited error bars [9]. Since 299 $H < 18$ NEAs have been discovered as of August 1999 [10], observational completeness in this range is ~ 40%.

The Flux Entering the IS from the US. We use the NEA population to estimate the inflow and outflow from each IS, assuming everything is in steady state. The route followed by asteroids from the main belt to the sink is:

$$\text{US} \longrightarrow \text{IS} \longrightarrow \text{TR} \longrightarrow \text{Sink.}$$

Most asteroids moving out of the IS spend a short time in the TR before going to the sink. The few asteroids that are long-lived, however, dominate the steady state population in the TR. The outflow flux going from the TR to the sink is the ratio of the number of asteroids in the TR (N_{TR}) over the mean lifetime spent in the TR ($\langle t_{TR} \rangle$).

For example, lets assume that out of 7 test bodies leaving the IS, 4 live in the TR for 1 Myr (short-life), 2 for 3 Myr (med.-life), and 1 for 9 Myr (long-life). Lets also assume the TR is originally empty. Using this information, we construct the steady state (SS):

Time (Myr)	1	2	3	4	5	6	7	8	9	SS
# short-life	4	4	4	4	4	4	4	4	4	4
# med.-life	2	4	6	6	6	6	6	6	6	6
# long-life	1	2	3	4	5	6	7	8	9	9

The steady state number of bodies is $N_{TR} = 4 + 6 + 9 = 19$, whereas $\langle t_{TR} \rangle$ = (4 $\times$ 1 Myr + 2 $\times$ 3 Myr + 1 $\times$ 9 Myr) / $(4 + 2 + 1) = 19/7$ Myr. Therefore, the inflow-outflow rate from the TR is 19 / (19 / 7 Myr) = 7 bodies per Myr.

Since the TR inflow/outflow rate must equal the IS inflow/outflow rate, our numerical integration results from above and our predicted NEA population (i.e., 750 asteroids with $H < 18$) can be used to deduce the rate of material flowing into the IS from the US (i.e., Flux$_A$):

Parameter	$3:1$	MC	ν_6
$\langle t_{TR} \rangle$ (Myr)	2.85	4.51	8.2
α_{IS}	0.44	0.27	0.29
$N_{TR}(H < 18)$	330	200	220
Flux$_A$ (Body/Myr)	116	44.3	27

The primary mechanisms producing Flux$_A$ are (i) collisional injection into resonances and (ii) the Yarkovsky effect. The importance of (i) and (ii) vary with asteroid size and parent body location, as we shall discuss in more detail below.

Estimating the Steady State IS Population. Flux$_A$ yields the inflow of material into the IS. If a steady state exists, this value must be equal to the outflow from the IS, which is the same as the outflow going through the TR into the sink. We call the flux of bodies leaving the IS to go to the sink Flux$_B$:

$$Flux_B = \tau_{IS}\, N_{IS}\, (H < 18)$$

where $N_{IS}\,(H < 18)$ is the number of bodies in the IS (represented by our test bodies) and τ_{IS} is the slope of the fractional decay rate of test bodies in the IS. To get τ_{IS}, we plotted the fractional decay rate for each IS and measured its slope prior to the median lifetime of the test bodies. In all three cases, the slope was exponential.

With τ_{IS} in hand, we can determine N_{IS} using the fact that Flux$_A$ = Flux$_B$:

Parameter	$3:1$	MC	ν_6
τ_{IS} (Myr^{-1})	0.38	0.02	0.33
$N_{IS}(H < 18)$	305	2200	82

We conclude that the steady state number of $H < 18$ asteroids in each IS (3:1 resonance, MC region, and ν_6 resonance) is 305, 2220, and 82, respectively.

Comparison with Observed Asteroids. We now compare our results with observational data in the MC region. Integrating the known MC asteroids for 100 Myr [10], we found that 195 $H < 15$ asteroids enter the TR. These so-called "active" bodies can be compared with N_{MC} from the table above. (Note: Since we have not yet discovered all $H < 18$ MC objects, we concentrate on the set with $H < 15$). Using the power-law H distribution determined in the NEA region (i.e., $N(< H) \sim 10^{0.41H}$), we estimate that $N_{MC}\,(H < 18)\ /\ N_{MC}\,(H < 15)$ is ~ 16. Therefore, we predict that the number of $H < 15$ bodies in the MC region is $2200/16 = 138$, roughly 1.5 times lower than the observed number (195).

Discussion. We consider it a success to be within a factor of 2 of reality (i.e., we assume we are not severely biased for objects with $H < 15$, which may or may not be true.). To explain the difference between our predictions and observations, we suggest the following scenarios:

(i) It is possible that our procedure underestimated α_{MC}. To fix this within the context of our model, the MC contribution to the NEAs should be increased significantly, such that over half of all NEAs come from the MC region. This solution, however, provides a poor fit with the observed Spacewatch NEAs (i.e., we predict far too many Amor asteroids).

(ii) Our α_{IS} values are determined by fitting our model results to the Spacewatch NEAs, two-thirds of which have $18 < H < 22$. Hence, our α_{IS} values may be more characteristic of km and sub-km NEAs than multi-km NEAs. If we had sufficient data to fit the large NEAs alone, it is plausible that we would get a different combination of α_{IS} values, with the contribution from the MCs increasing by a factor of 2.

Scenario (ii), which we favor, implies that the contribution from the MC region should increase for large NEAs. We can think of several reasons why this may be true:

(ii.a) If the Yarkovsky effect is the dominant means by which asteroids enter the IS, α_{IS} must vary with size. Numerical simulations show that small objects in the inner main belt, with the fast drift rates, jump over the tiny resonances feeding the MC regions to enter the powerful 3:1 or ν_6 resonances [11]. Conversely, the largest NEAs like Eros are hardly affected by the Yarkovsky effect, such that their most likely source would be the numerous tiny resonances feeding the MC region [5].

(ii.b) The median dynamical lifetime of asteroids in the 3:1 and ν_6 resonances is ~ 2 Myr [12], whereas the timescale to inject multiple 5 km asteroids into these regions via family-forming events is much longer (100-1000 Myr) [2]. For this reason, it is doubtful that the 3:1 and ν_6 resonances are more than a sporadic source of large NEAs.

(ii.c) So far, we have assumed that that size-distribution slope of the NEAs is a good fit to all multi-km NEAs. The main belt size distribution in the $D > 1$ km range, however, is wavy, with local maxima at different sizes [13]. Recent results suggest that one such peak occurs near $D \sim 5$ km. If true, we would expect the wave to extend into the MC region, possibly explaining the observed "overabundance" of $H < 15$ MC asteroids in a self-consistent manner.

References. [1] Bottke et al. (2000) *Science*, submitted; [2] Farinella, P., et al. (1993) *Icarus* 101, 174. [3] Farinella, P., et al. (1998) *Icarus* 132, 378; [4] Migliorini, F., et al. (1998) *Science*, 281, 2022. [5] Morbidelli, A. and D. Nesvorný (1999) *Icarus* 139, 295. [6] Wisdom, J. and M. Holman. (1991) *Astron. J.* 102, 1528 ; Levison, H. F., and M. J. Duncan (1994) *Icarus* 108, 18. [7] Morbidelli, A. and B. Gladman (1998) *Meteor. Plan. Sci.* 33, 999. [8] Jedicke, R. and T. S. Metcalfe (1998) *Icarus* 131, 245. [9] Morrison, D. (Ed.) (1992) *The Spaceguard Survey* (NASA, Washington, D. C.). [10] http://asteroid.lowell.edu [11] Bottke et al. (2000) *Icarus*, in press. [12] Gladman, B. J., et al. (1997) *Science* 277, 197. [13] Durda, D. D. (1998) *Icarus* 135, 431.