README  
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This is a simple readme file for the Python scripts accompanying  
Matheson & Malhotra 2025, Icarus,  
"On the Forced Plane of the Hilda Asteroids".

I am not a software engineer or a computer scientist, so my code is very simple and mostly undocumented. I aim to be able to read the code myself, and that is all. If you want to reuse my code to try to reproduce or extend the results presented in the paper, here are some guidelines for doing so.

You'll need to run Python 3 with a few packages, namely REBOUND, CIRCLE-FIT, and ASTROQUERY.

The files a001\_read\_nesvorny\_elements.py through a019\_demo\_vmf.py are meant to be run in sequential order. You should be able to run them in sequential order in a Python environment or Python IDE with few to no changes. I use Spyder 6 to run Python scripts. This GitHub repository does not contain most of the output files, because csv files of orbital elements or other calculations take up a lot of space and are easily reproduced by running the Python scripts.

The naming convention for the files in this GitHub repository is as follows:

* “a###” is a prefix to keep things straight sequentially and to keep outputs from each script straight.
* “b###” is a prefix for output files produced a a script with the prefix “a###”.
* The string “2e6yr\_2e2yr\_0.2yr\_jd2460796.5” refers to data products and calculations downstream from a WHFAST integration of the planets and Hilda asteroids in REBOUND lasting 2x106 years with an output cadence of 2x102 years, a step size of 0.2 years, and a starting date of JD 2460796.5 (May 1, 2025 at 00:00:00 UTC). The string “2e6yr\_5yr\_0.1yr\_jd2460796.5” is similarly interpreted. In the rest of this readme, I will abbreviate “2e6yr\_2e2yr\_0.2yr\_jd2460796.5” as “tyrsstr” for time, years, string. I will abbreviate “2e6yr\_5yr\_0.1yr\_jd2460796.5” as “tyrsstr\_hires”.
* Most scripts in this repository have the following block of code:  
  jd = 2460796.5 # May 1, 2025 00:00:00  
  time\_yrs = int(2e6)  
  tstep\_yrs = int(2e2)  
  dt\_yrs = 0.2  
  tyrs\_str = '2e6yr'  
  tstepyrs\_str = '2e2yr'  
  dtyrs\_str = '0.2yr'  
  If you want to rerun these scripts with different integration times, output cadences, and time steps, you will need to make the appropriate changes to this block of code everywhere it appears. Those changes will be reflected in the “tyrsstr” in the “b###” output filenames.

List of file types in this folder: CSV, DOCX, PY, plaintext (.list\_###\_WO\_INTERLOPERS, .dat\_WITH\_PROPER\_ELMTS).

All orbital elements in all files in this folder are given as heliocentric elements in the J2000 ecliptic coordinate frame.

“VN25” in this readme is the recent paper “Orbital and Absolute Magnitude Distribution of Hilda Population”, by Vokrouhlicky + Nesvorny + et al, *AJ* 169:242, 2025 May, https://doi.org/10.3847/1538-3881/adbe7b.

List of files in this GitHub repository:

* a000\_a\_README.docx
* a000\_nesvorny\_153\_Hilda\_family.list\_090\_WO\_INTERLOPERS
* a000\_nesvorny\_1212\_Francette\_family.list\_030\_WO\_INTERLOPERS
* a000\_nesvorny\_1345\_Potomac\_family.list\_140\_WO\_INTERLOPERS
* a000\_nesvorny\_1911\_Schubart\_family.list\_060\_WO\_INTERLOPERS
* a000\_nesvorny\_2483\_Guinevere\_family.list\_040\_WO\_INTERLOPERS
* a000\_nesvorny\_astorb\_astdys\_wise\_akari\_sloan.dat\_WITH\_PROPER\_ELMTS
* a001\_read\_nesvorny\_elements.py
* a002\_estimate\_completion\_limit.py
* a003\_integrate\_planets.py
* a004\_integrate\_real\_objects.py
* a005\_integrate\_clones.py
* a006\_label\_asteroids.py
* a007\_statistics\_vmf.py
* a008\_statistics\_cf.py
* a009\_laplaceplanevec\_t0.py
* a010\_a\_laplaceplane.py
* a010\_b\_laplaceplane\_clones.py
* a011\_qpaeiplots.py
* a012\_f\_meanpoleconfidenceoverlaps\_fourpanels\_allvmf.py
* a013\_deltadegplots\_vmfobj\_cfclones.py
* a014\_10plots\_q\_xcc\_vmfobj\_cfclones.py
* a015\_compare\_laplace\_planes.py
* a016\_table\_numbers.py
* a019\_demo\_vmf.py
* b001\_astorb\_horizons.csv
* b005\_(Hilda/Potomac/Schubart/Ismene)\_aau0\_clones.csv
* b006\_astorb\_labels.csv
* b007\_(B/BFG/BPHS/BPHSFG/H/P/S)\_ statistics\_vmf\_(tyrsstr).csv
* b008\_(Hilda/Ismene/Potomac/Schubart)\_clones\_statistics\_cf\_(tyrsstr).csv
* b011\_aei\_all\_(tyrsstr).png
* b011\_qp\_all\_(tyrsstr).png
* b012\_meanpoleconfidenceoverlaps\_twopanels\_(tyrsstr).png
* b013\_deltadegplots\_vmfobj\_cfclones.png
* b014\_10plots\_q\_xcc\_vmfobj\_cfclones.png
* b019\_demo\_vmf\_histograms.png
* figure1.png
* figure2a.png
* figure2b.png
* figure3.png
* figure4.png
* figure5.png
* main\_icarus\_clean\_20251020M.tex
* refs\_for\_icarus.bib
* Response-October2025\_submitted\_20251020M.tex
* ICARUS-D-25-00191\_R1.pdf

a000\_nesvorny\_153\_Hilda\_family.list\_090\_WO\_INTERLOPERS

* This and the other files prefixed **a000\_nesvorny** are the lists of Hilda asteroids assigned to different collisional families by VN25. Although they do not have a .txt filename, these files are saved as plaintext that can be opened by any text editor or IDE.

a001\_read\_nesvorny\_elements.py

* Takes the names of objects in the **a000\_nesvorny** files and retrieves heliocentric orbital elements from JPL Horizons via Astroquery.
* The orbital elements are saved in **b001\_astorb\_horizons.csv**.

a002\_estimate\_completionlimit.py

* Takes the orbital elements in **b001\_astorb\_horizons.csv** and estimates the observational completeness limit for the Hilda asteroids.
* Does not save results to file.

a003\_integrate\_planets.py

* Saves the heliocentric orbital elements of the four outer planets over a specified integration time. It also saves the time points and calculates the invariable plane of the solar system over time, which remains pretty much constant as it should.
* The orbital elements and invariable plane are saved in **b003\_planets\_(aau/e/ideg/Mdeg/nodedeg/perideg/xinvar/yinvar)\_(tyrsstr).csv.** The output times are saved in **b002\_tyrsvec\_(tyrsstr).csv**.

a004\_integrate\_real\_objects.py

* Integrates each asteroid's orbit over the same specified integration time.
* The results are saved in **b004\_astorb\_(aau/e/ideg/Mdeg/nodedeg/perideg)\_(tyrrsstr).csv.**

a005\_integrate\_clones.py

* Integrates clones of each chosen representative asteroid (Potomac, Hilda, Schubart, and Ismene) over the same time. It saves their initial semimajor axes and it saves their heliocentric orbital elements over time.
* The orbital elements are saved in **b005\_(Hilda/Potomac/Schubart/Ismene)\_(aau/e/ideg/Mdeg/nodeg/perideg)\_clones\_(tyrsstr).csv**.
* The initial semimajor axes are saved in **b005\_(Hilda/Potomac/Schubart/Ismene)\_aau0\_clones.csv.**

a006\_label\_asteroids.py

* Labels asteroids according to their collisional family.
* The result is saved as **b006\_astorb\_labels.csv**.

a007\_statistics\_vmf.py

* Saves von Mises-Fisher statistics for different sets of asteroids according to the abbreviations below:
  + B = Background Hildas
  + P = Potomac family
  + H = Hilda family
  + S = Schubart family
  + F = Francette family
  + G = Guinevere family
  + BFG = Backgrounds + Francettes + Guineveres
  + BPHS = Backgrounds + Potomacs + Hildas + Schubarts
  + BPHSFG = Backgrounds + Potomacs + Hildas + Schubarts + Francettes + Guineveres
* The results are saved as **b007\_(B/P/H/S/BFG/BPHS/BPHSFG)\_statistics\_vmf\_(tyrsstr).csv.**

a008\_statistics\_cf.py

* Saves circle-fit statistics for the Potomac clones, Hilda clones, Schubart clones, and Ismene clones.
* The results are saved as **b008\_(Hilda/Ismene/Potomac/Schubart)\_clones\_statistics\_cf\_(tyrsstr).csv.**

a009\_laplaceplanevec\_t0.py

* Saves the Laplace plane for a range of semimajor axes at time zero for the integrations.
* The result is saved as **b009\_laplaceplane\_t0\_(tyrsstr).csv.**

a010\_a\_laplaceplane.py

* Saves the instantaneous Laplace plane over time for the mean semimajor axes of the different sets of asteroids according to the abbreviations described for **a007\_statistics\_vmf**.
* The results are saved as **b010\_laplaceplane\_(B/P/H/S/BFG/BPHS/BPHSFG) \_(tyrsstr).csv.**

a010\_b\_laplaceplane\_clones.py

* Saves the instantaneous Laplace plane over time for the seed asteroid for each group of clones.
* The results are saved as **b010\_laplaceplane\_(Hilda/Ismene/Potomac/Schubart)\_clones\_(tyrsstr).csv.**

a011\_qpaeiplots.py

* Saves plots in the (q,p) plane and as subplots of (a,e), (e,i), and (a,i) for each subset of the Hilda group according to the usual abbreviations. You may comment and uncomment different sections of the code depending on what you want to plot.
* Some of the code will make plots that distinguish between librating, maybe, and circulating objects in case you want to see the distribution of those.
* The plots are saved as **b011\_(aei/qp)\_(B/P/H/S/BFG/BPHS/BPHSFG) \_(tyrsstr).png.**
* Figure 1 and Figure 2 of the paper are **b011\_aei\_all\_2e6yr\_2e2yr\_0.2yr\_jd2460796.5.png** and **b011\_qp\_all\_2e6yr\_2e2yr\_0.2yr\_jd2460796.5.png.**

a012\_f\_meanpoleconfidenceoverlaps\_fourpanels\_allvmf.py

* Produces Figure 3 in the paper, which plots the mean planes of the different subsets of objects in the (q,p) plane and their vMF confidence regions. You can change which subsets you want to plot.
* Saves the figure as **b012\_meanpoleconfidenceoverlaps\_twopanels\_(tyrsstr).png.**

a013\_deltadegplots\_vmfobj\_cfclones.py

* Produces Figure 5 in the paper. This is the distance in degrees between the mean planes of the various groups of asteroids, compared to the Laplace plane, the Jupiter plane, and the invariable plane.
* The figure is saved as **b013\_deltadegplots\_vmfobj\_cfclones.png**.

a014\_10plots\_q\_xcc\_vmfobj\_cfclones.py

* Produces Figure 4 in the paper. This is the difference in *q* between the mean planes of the various groups of asteroids, compared to the Laplace plane, and the 95% confidence bounds in the location of the mean plane.
* The figure is saved as **b014\_10plots\_q\_xcc\_vmfobj\_cfclones.png**.

a015\_compare\_laplace\_planes.py

* This is run in the Python IDE to produce a number for the maximum distance between the instantaneous Laplace planes calculated at various relevant semimajor axes.
* It does not save any results to a file.

a016\_table\_numbers.py

* This is run in the Python IDE to produce Table 1 in the paper.
* It does not save any results to a file.

a019\_demo\_vmf.py

* Draws bootstrap samples to show that the vMF distribution adequately describes the mean plane sampling distribution for the Hilda asteroids.
* Saves figure to **b019\_demo\_vmf\_histograms.png.**
* This is Figure 1 in the paper.

b001\_astorb\_horizons.csv

* JPL Horizons initial conditions for the Hilda asteroids at the chosen epoch.

b005\_(Hilda/Potomac/Schubart/Ismene)\_aau0\_clones.csv

* Initial semimajor axes for the clones of the chosen asteroids.

b006\_astorb\_labels.csv

* Labels for each Hilda asteroid according to their collisional families.

b007\_(B/BFG/BPHS/BPHSFG/H/P/S)\_statistics\_vmf\_(tyrsstr).csv

* vMF mean plane statistics for different sets of asteroids.

b008\_(Hilda/Ismene/Potomac/Schubart)\_clones\_statistics\_cf\_(tyrsstr).csv

* Circle-fit mean plane statistics for various sets of asteroid clones.

b011\_aei\_all\_(tyrsstr).png

* Figure 2a in the paper.

b011\_qp\_all\_(tyrsstr).png

* Figure 2b in the paper.

b012\_meanpoleconfidenceoverlaps\_twopanels\_(tyrsstr).png

* Figure 3 in the paper.

b013\_deltadegplots\_vmfobj\_cfclones.png

* Figure 5 in the paper.

b014\_10plots\_q\_xcc\_vmfobj\_cfclones.png

* Figure 4 in the paper.

b019\_demo\_vmf\_histograms.png

* Figure 1 in the paper.

figure1.png

figure2a.png

figure2b.png

figure3.png

figure4.png

figure5.png

main\_icarus\_clean\_20251020M.tex

* Latex manuscript for submitted paper.

refs\_for\_icarus.bib

* Bibtex file for submitted paper.

Response-October2025\_submitted\_20251020M.tex

* Response to reviewers for submitted paper.

ICARUS-D-25-00191\_R1.pdf

* Manuscript of submitted paper.