Newton

a New Solar System Dynamics Tool

Marc A. Murison

Astronomical Applications Department
U.S. Naval Observatory
Washington, DC

October 14, 1998

Overview

- Motivation
- Design consequences
- GUI features
- Research features
- Live demonstration

Motivation

- AA's Dynamical Astronomy Division: recent activity
  - Development of Newcomb
    - High-precision, high-accuracy solar system ephemeris program
    - USNO replacement for PEP and JPL's DE programs, both of which are products of the 1960s
  - Optimization of ephemeris storage
  - Determination of asteroid masses
    - Half of the world's existing mass determinations
  - Asteroid ephemerides
    - Astronomical Almanac
    - Research

Motivation (continued)

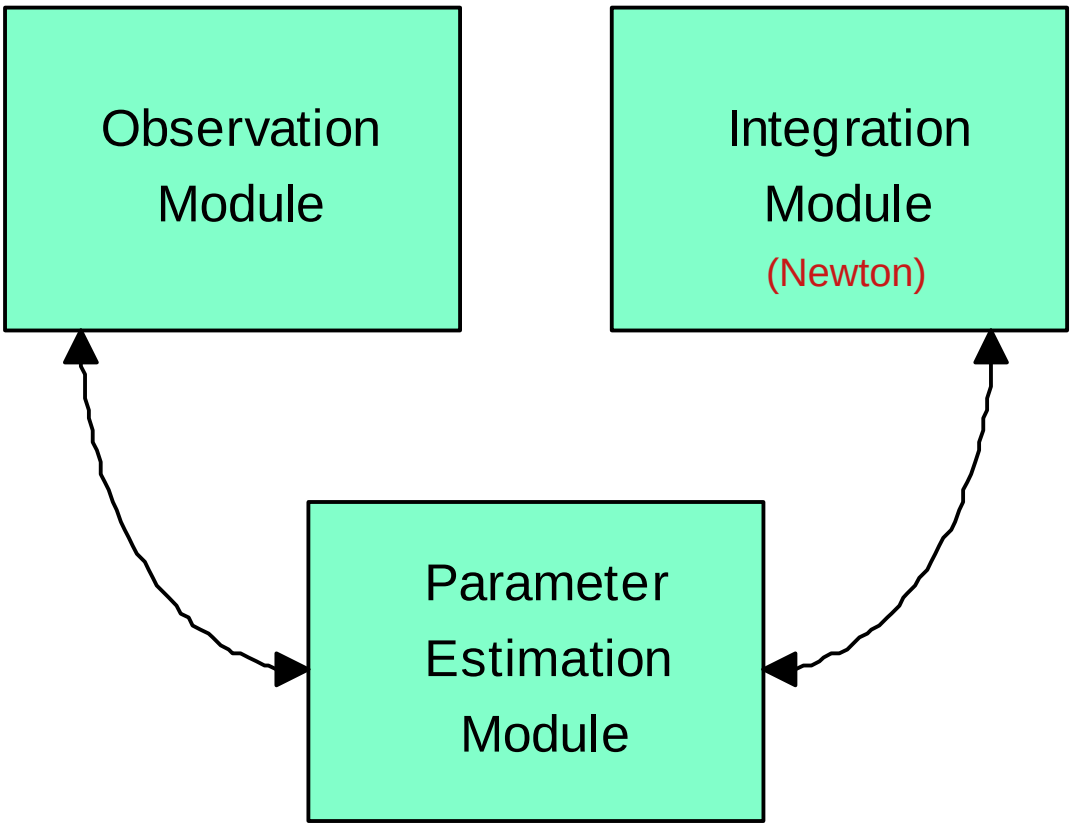
- Chaotic dynamics of minor planets
  - Inner solar system asteroids
  - Outer asteroid belt
  - Trans-Neptunian objects
  - Resonances, resonances, everywhere resonances!
- Dynamics of FAME precession
- Upgrade of NOVAS astrometry package for ICRS compatibility
  - Radio and optical astrometric reduction and analysis algorithms give the same results to less than 1 microarcsecond

- Notice that all but two of these require a **solar system integrator**

Motivation (continued)

- Ephemeris program integration module
  - High accuracy
  - High reliability
  - Fast

Newcomb Primary Modules



Motivation (continued)

- Solar system dynamics research tool
  - Testing and verification for ephemeris program usage
  - **Interactive** exploration of dynamical effects
  - **Flexible** — modify existing tools & features, with minimal impact
  - **Extensible** — add new tools & features without changing underlying program structure
    - Reuse of code

Design Consequences

- Object-oriented design
  - Flexible
  - Extensible
  - Minimize maintenance burden
  - Major advantage over existing programs
    - PEP and DE (ephemeris)
    - SWIFT, Mercury (solar system)
- C++ programming language
  - Required technical complexity
  - Likely to be around the next 10-20 years or more
  - Excellent design/debug environments are available

Design Consequences (continued)

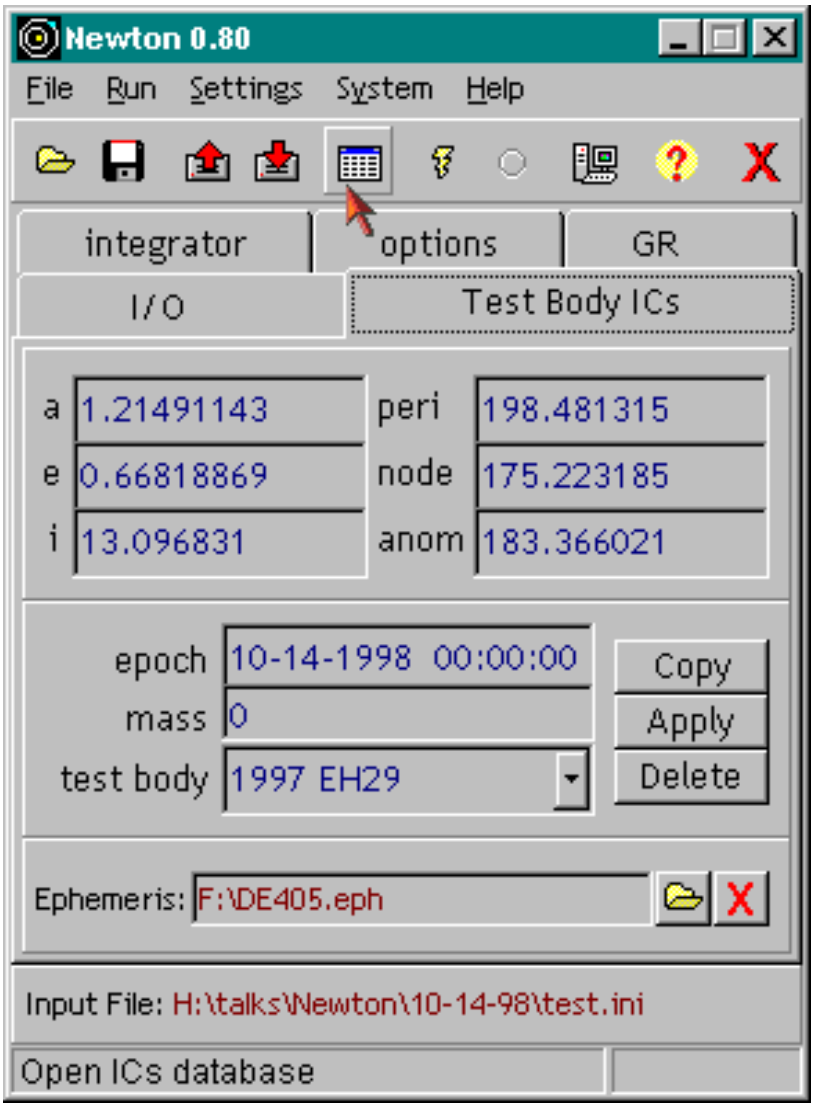
- RAD (Rapid Application Development)
  - Want a sophisticated GUI but do **NOT** want to do GUI programming
    - 3rd party solutions found to be inadequate
  - Component programming
    - drag 'n' drop interface elements
    - A component can be any self-contained entity, from a simple button or edit field to, for example, a text editor, an xy plot or a frequency analysis package
  - RAD really shines when it comes to interface design
  - No need to reinvent GUI wheels
  - Extensible & flexible

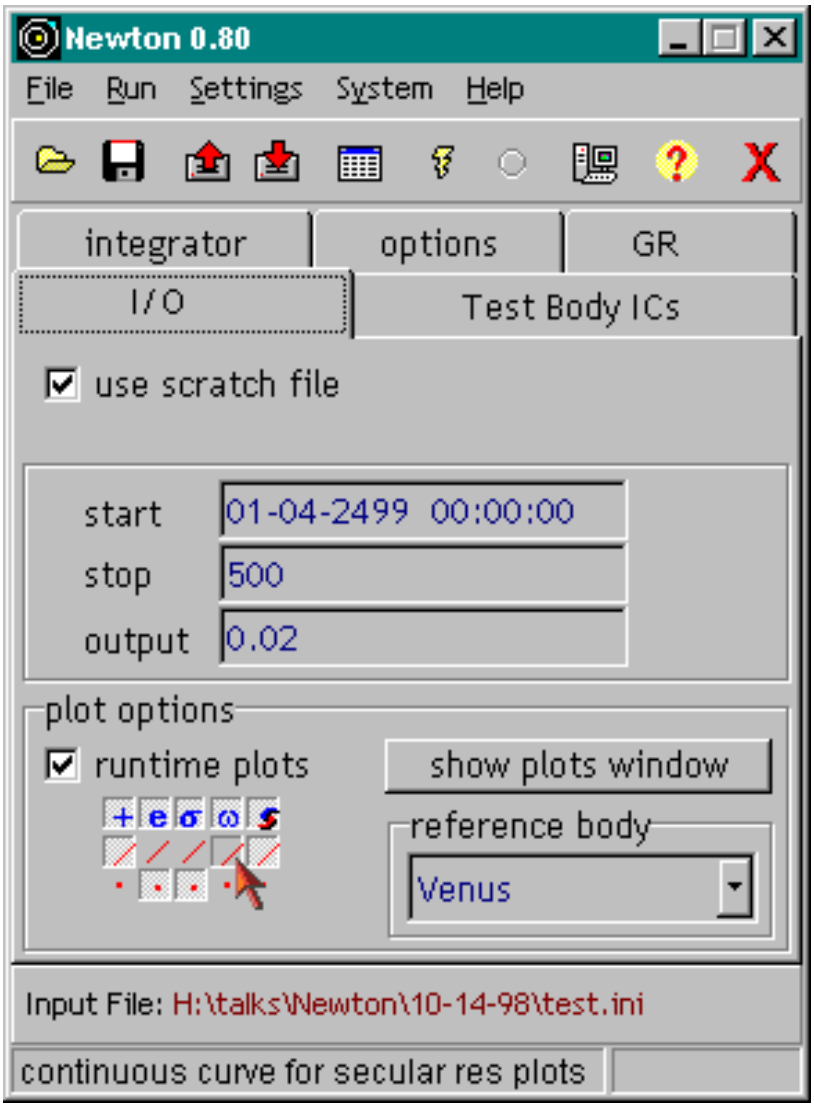
GUI Features of Newton

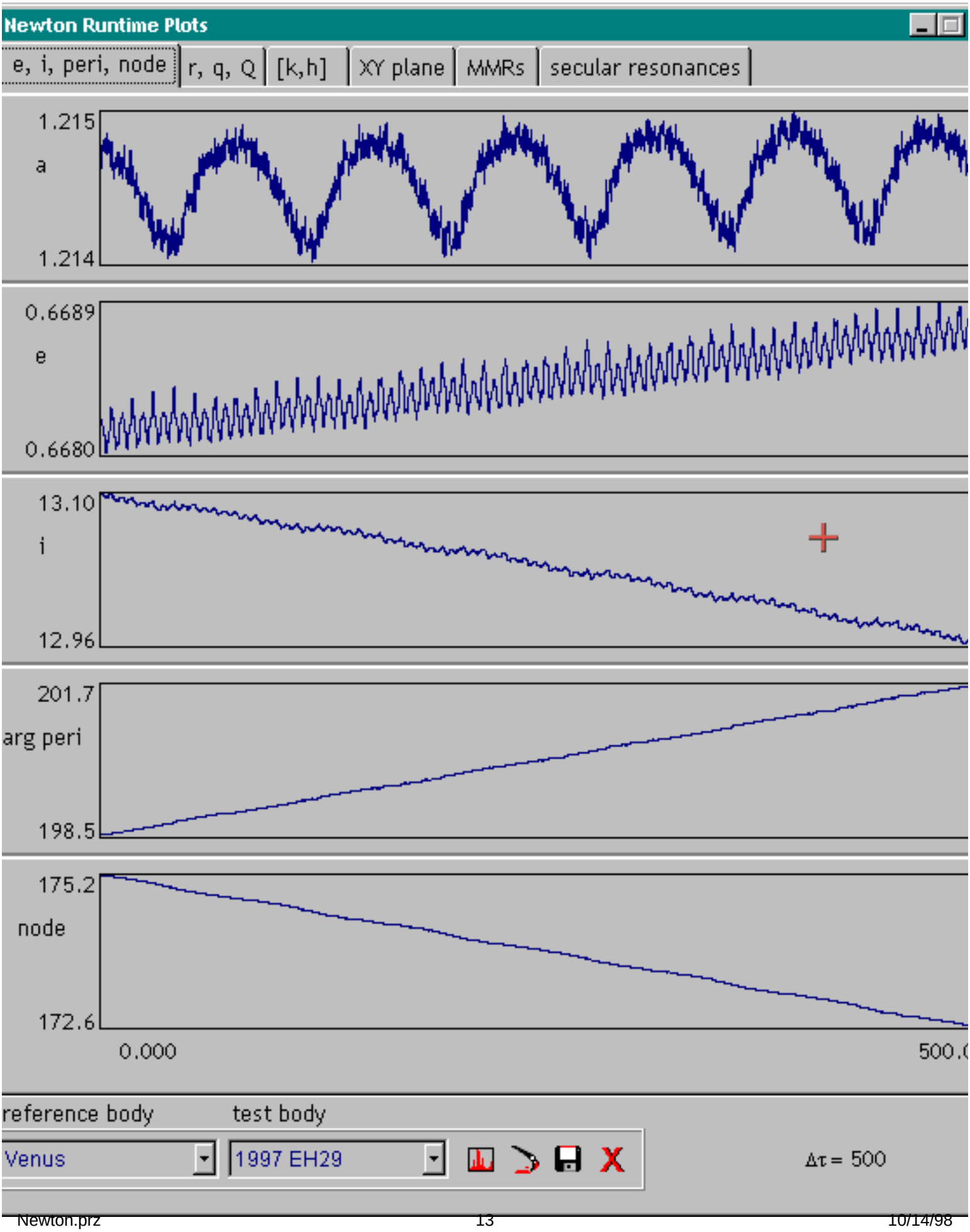
- Full assortment of standard Windows 95/98 widgets
  - Menus, buttons, drop-down lists, spinners, toolbars, dialog pages, right-click "popup" menus, etc.
  - All are implemented as components
- HTML browser (a drop-in component) for online help
- Locally designed components
  - xy plots
    - Automatic rescaling
    - Popup coordinates
    - zoom
    - Auto-wrapping at 0/360 degrees
  - Frequency analysis
  - Orbital elements

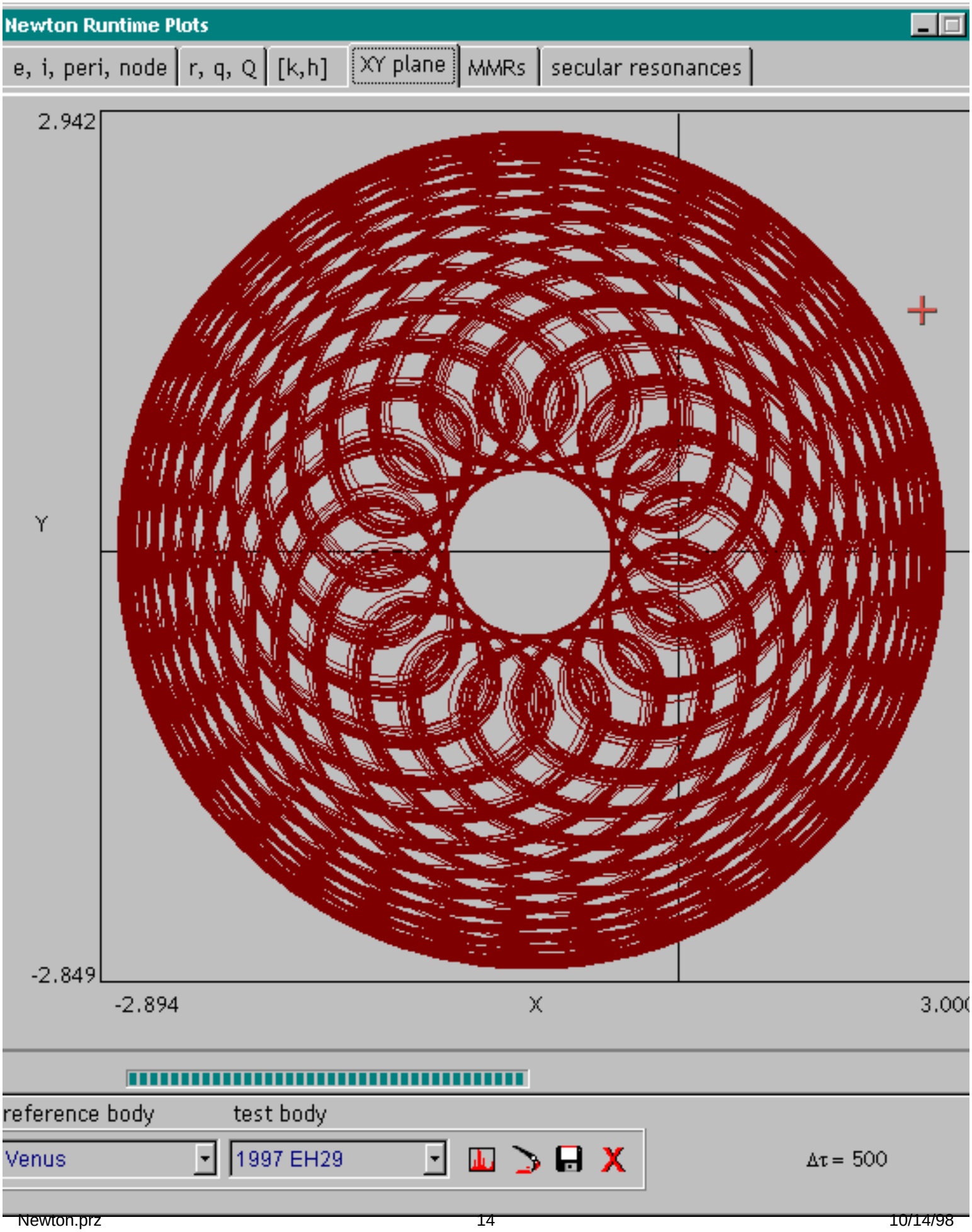
GUI Features of Newton (continued)

- Plotting
  - Progresses during integrations
  - Post integration (re)analysis
  - On-the-fly switching of test bodies and reference bodies
  - Individual plot type on/off switches
  - Zoom in on interesting features
- Data output
  - Entire integrations (all integrated bodies) to binary files
  - Individual test body data to ASCII files (for reading by spreadsheets and graphics packages)
- Test body list editing


Newton 0.80
File
Run
Settings
System
Help
integrator
options
GR
I/O
Test Body ICs
a
1.21491143
peri
198.481315
e
0.66818869
node
175.223185
i
13.096831
anom
183.366021
epoch
10-14-1998 00:00:00
mass
0
test body
1997 EH29
Copy
Apply
Delete
Ephemeris:
F:\DE405.eph
Input File: H:\talks\Newton\10-14-98\test.ini
Open ICs database


Newton 0.80
File
Run
Settings
System
Help
integrator
options
GR
I/O
Test Body ICs
use scratch file
start
01-04-2499 00:00:00
stop
500
output
0.02
plot options
runtime plots
show plots window
reference body
Venus
Input File: H:\talks\Newton\10-14-98\test.ini
continuous curve for secular res plots


Newton Runtime Plots
e, i, peri, node
r, q, Q
[k,h]
XY plane
MMRs
secular resonances
1.215
a
1.214
0.6689
e
0.6680
13.10
i
12.96
201.7
arg peri
198.5
175.2
node
172.6
0.000
500.0
reference body
test body
Venus
1997 EH29
Δτ = 500


Newton Runtime Plots
e, i, peri, node
r, q, Q
[k,h]
XY plane
MMRs
secular resonances
2.942
Y
-2.849
-2.894
X
3.000
reference body
test body
Venus
1997 EH29
Δτ = 500

Research Features

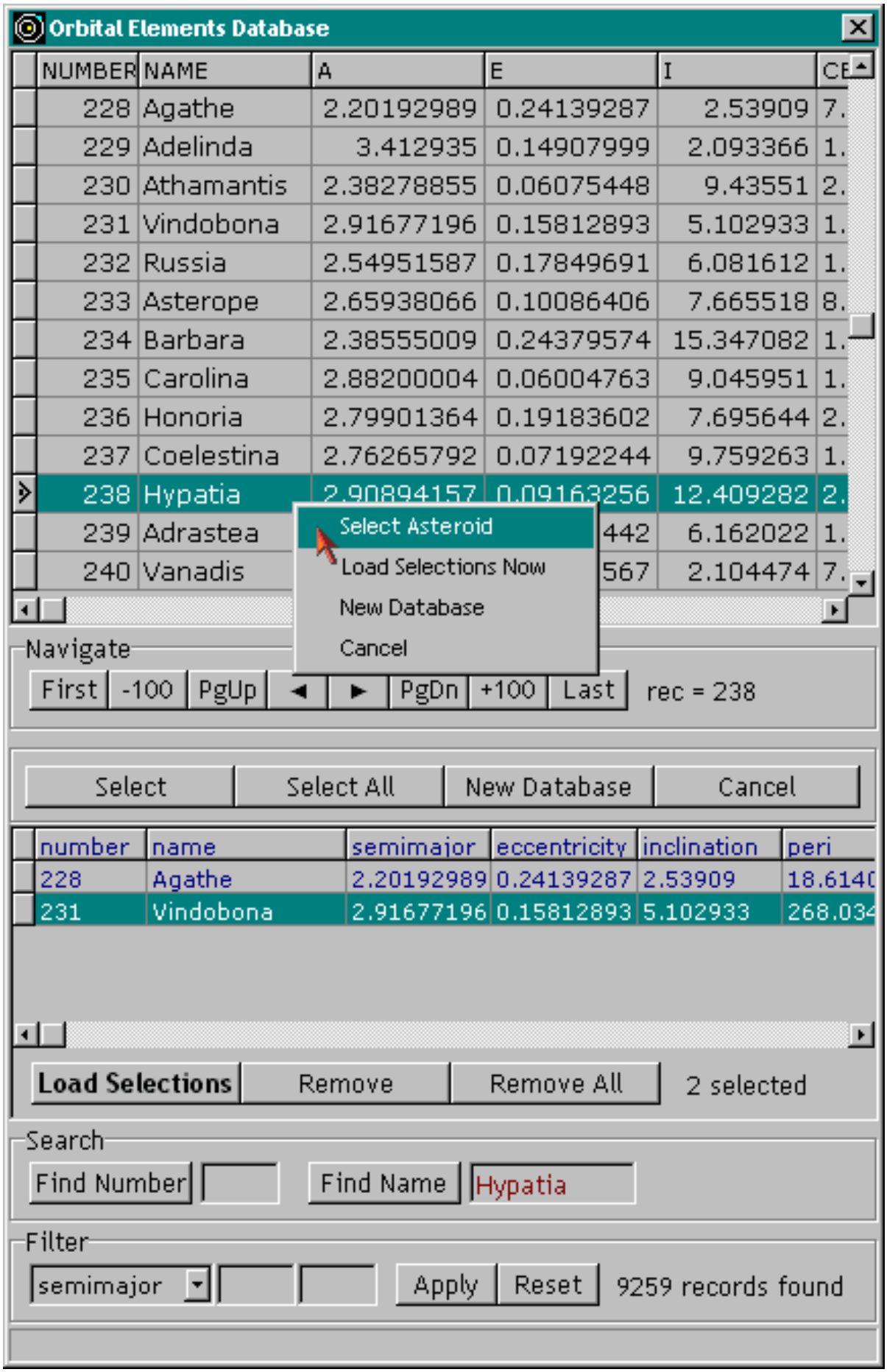
- Solar system model:
  - Newtonian gravity
  - GR (coming soon)
    - Test bodies and/or planets
  - All major planets
    - Any combination may be turned on or off
    - Earth/Moon treated as separate or combined
  - Natural satellites (coming soon)
  - Ephemeris file for planet ICs (e.g., DE405)
  - Unlimitied number of test bodies
  - Test bodies can have mass and interact with planets
    - Asteroid belt is largest source of uncertainty in the ephemeris of Mars!
    - The "innie-outie" problem

Research Features (continued)

- Numerical integration methods
  - Bulirsch-Stoer
    - Optimized
  - Runga-Kutta
  - Everhart's RADAU (coming soon)
  - Symplectic (coming soon)
  - Anything else you care to add — a testbed for numerical methods

Research Features (continued)

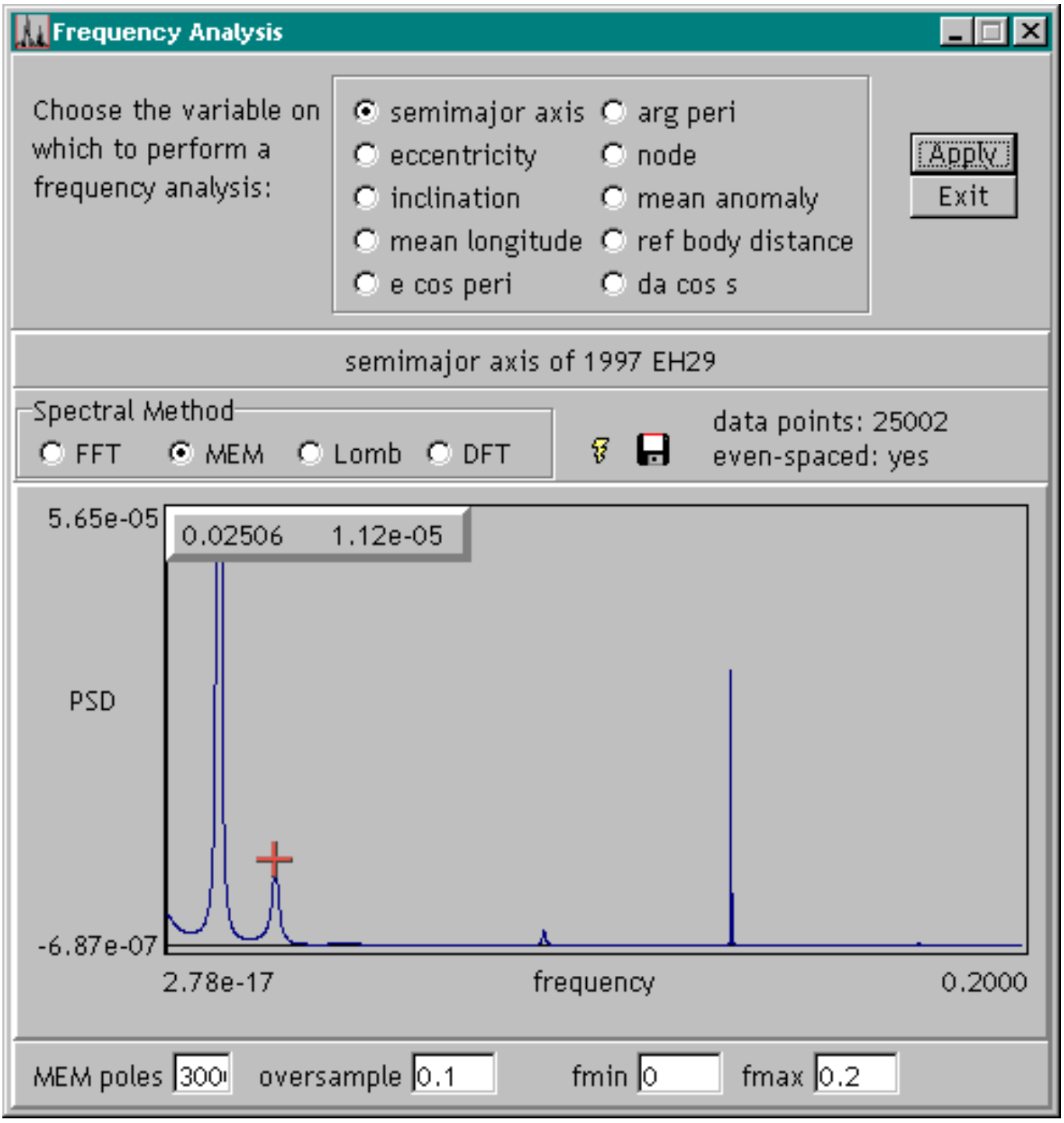
- Asteroids database
  - Initial conditions
  - Any dbase IV (or paradox, or ...) file containing orbital elements for some epoch
    - e.g., Ted Bowell's list available on the web
  - Searching
    - Number, name
  - Filtering
    - Semimajor axis
    - Eccentricity
    - Inclination
    - Diameter
    - Color
    - Observing arc
    - Number of observations
    - H magnitude


Orbital Elements Database
NUMBER NAME A E I
228 Agathe 2.20192989 0.24139287 2.53909
229 Adelinda 3.412935 0.14907999 2.093366
230 Athamantis 2.38278855 0.06075448 9.43551
231 Vindobona 2.91677196 0.15812893 5.102933
232 Russia 2.54951587 0.17849691 6.081612
233 Asterope 2.65938066 0.10086406 7.665518
234 Barbara 2.38555009 0.24379574 15.347082
235 Carolina 2.88200004 0.06004763 9.045951
236 Honoria 2.79901364 0.19183602 7.695644
237 Coelestina 2.76265792 0.07192244 9.759263
238 Hypatia 12.409282
239 Adrastea 6.162022
240 Vanadis 2.104474
Select Asteroid
Load Selections Now
New Database
Cancel
Navigate
First -100 PgUp ◄ ► PgDn +100 Last
rec = 238
Select Select All New Database Cancel
number name semimajor eccentricity inclination peri
228 Agathe 2.20192989 0.24139287 2.53909
231 Vindobona 2.91677196 0.15812893 5.102933
Load Selections Remove Remove All 2 selected
Search
Find Number Find Name Hypatia
Filter
semimajor Apply Reset 9259 records found

Research Features (continued)

- Diagnostics of chaotic motion:
  - Frequency analysis
    - FFT
    - Maximum Entropy Method
    - Lomb periodogram
    - DFT
  - Maximum Lyapunov exponent calculation (determined by integration of the trajectory phase space tangent vector) (coming soon)
  - Calculation of the trajectory curvature tensor (coming soon)
    - Components of the Riemann curvature tensor (see, e.g., Gurzadyan and Savvidy 1986 and Kandrup 1990)

- Gurzadyan, V.G., and Savvidy, G.K. (1986). "Collective Relaxation of Stellar Systems", *Astron. Astrophys*. **160**, 203.
- Kandrup, H.E. (1990). "Divergence of Nearby Trajectories for the Gravitational N-Body Problem", *Ap. J.* **364**, 420.

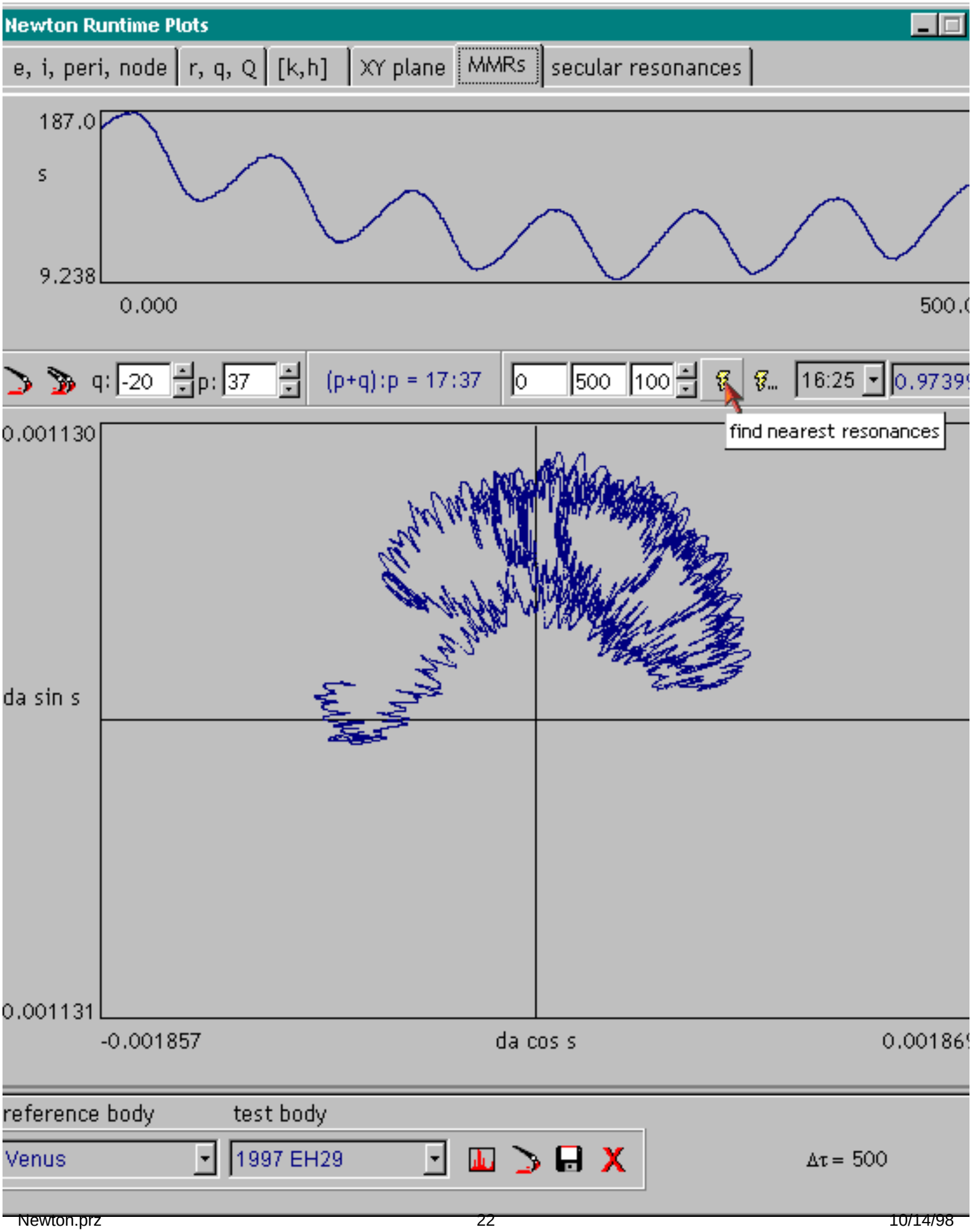

Frequency Analysis
Choose the variable on which to perform a frequency analysis:
semimajor axis
arg peri
eccentricity
node
inclination
mean anomaly
mean longitude
ref body distance
e cos peri
da cos s
Apply
Exit
semimajor axis of 1997 EH29
Spectral Method
FFT
MEM
Lomb
DFT
data points: 25002
even-spaced: yes
5.65e-05
0.02506
1.12e-05
PSD
-6.87e-07
2.78e-17
frequency
0.2000
MEM poles
300
oversample
0.1
fmin
0
fmax
0.2

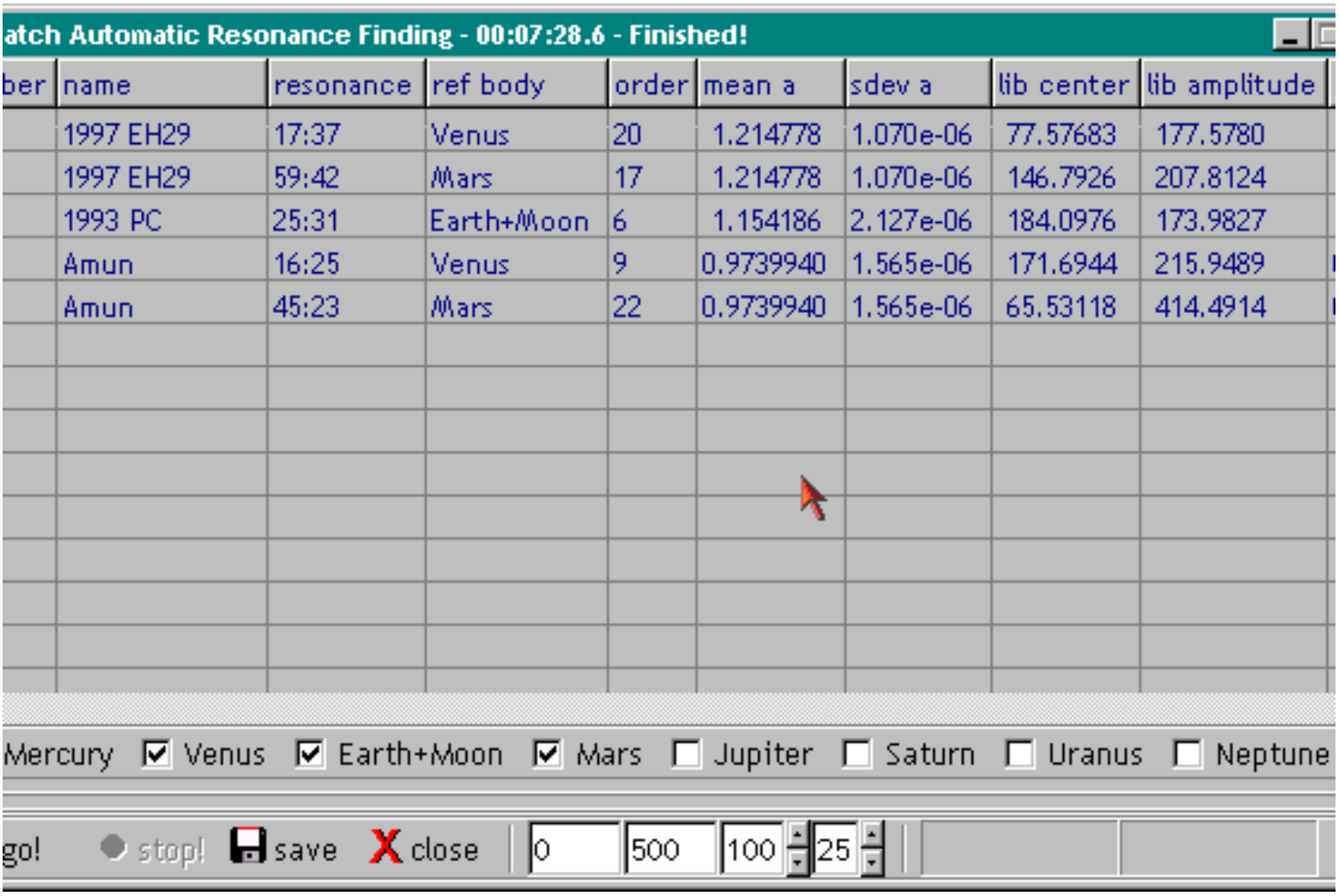
Research Features (continued)

- Resonance diagnostics:
  - Mean-motion critical angle

$$\sigma = (p+q)\cdot L_{ref} - p\cdot L - q\cdot(\omega+\Omega)$$

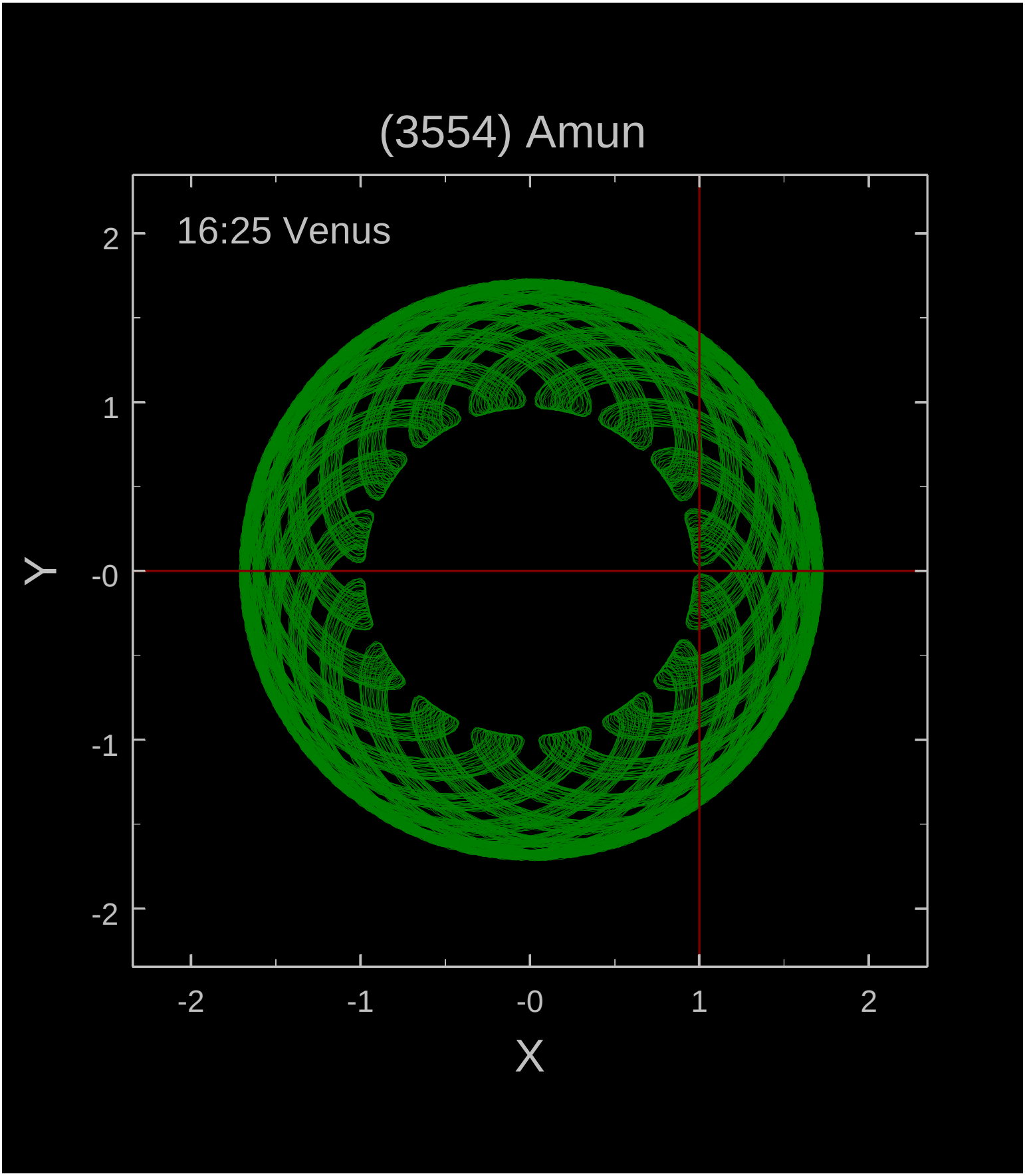
  - Automatic determination of mean-motion resonances!
    - Uses new algorithm — complete and very fast
    - Subject of another talk...
  - Secular resonance critical angles (ω-ω_{ref}, Ω-Ω_{ref}, Kozai resonance)
    - Until now, no tools existed for exploring secular resonances due to the inner planets
      - Theory much too complicated (large, multiple-source perturbations)
      - GUIs geared for interactive use not the norm in astronomy
    - Hence, nobody has looked for secular resonances in the inner solar system due to the inner planets

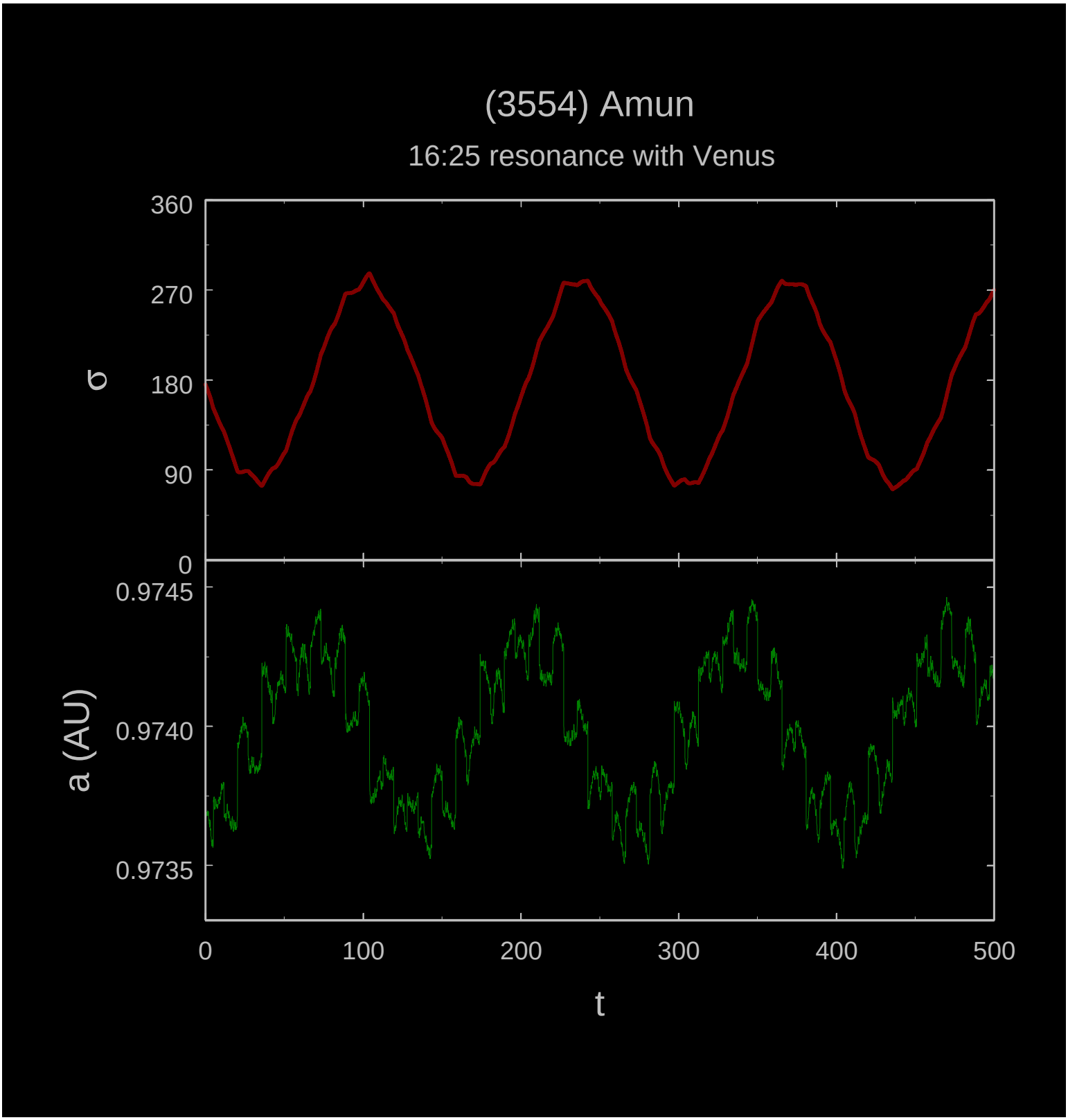

Newton Runtime Plots
e, i, peri, node
r, q, Q
[k,h]
XY plane
MMRs
secular resonances
187.0
s
9.238
0.000
500.0
q: -20
p: 37
(p+q):p = 17:37
0
500
100
16:25
0.97399
find nearest resonances
0.001130
da sin s
0.001131
-0.001857
da cos s
0.001869
reference body
test body
Venus
1997 EH29
Δτ = 500

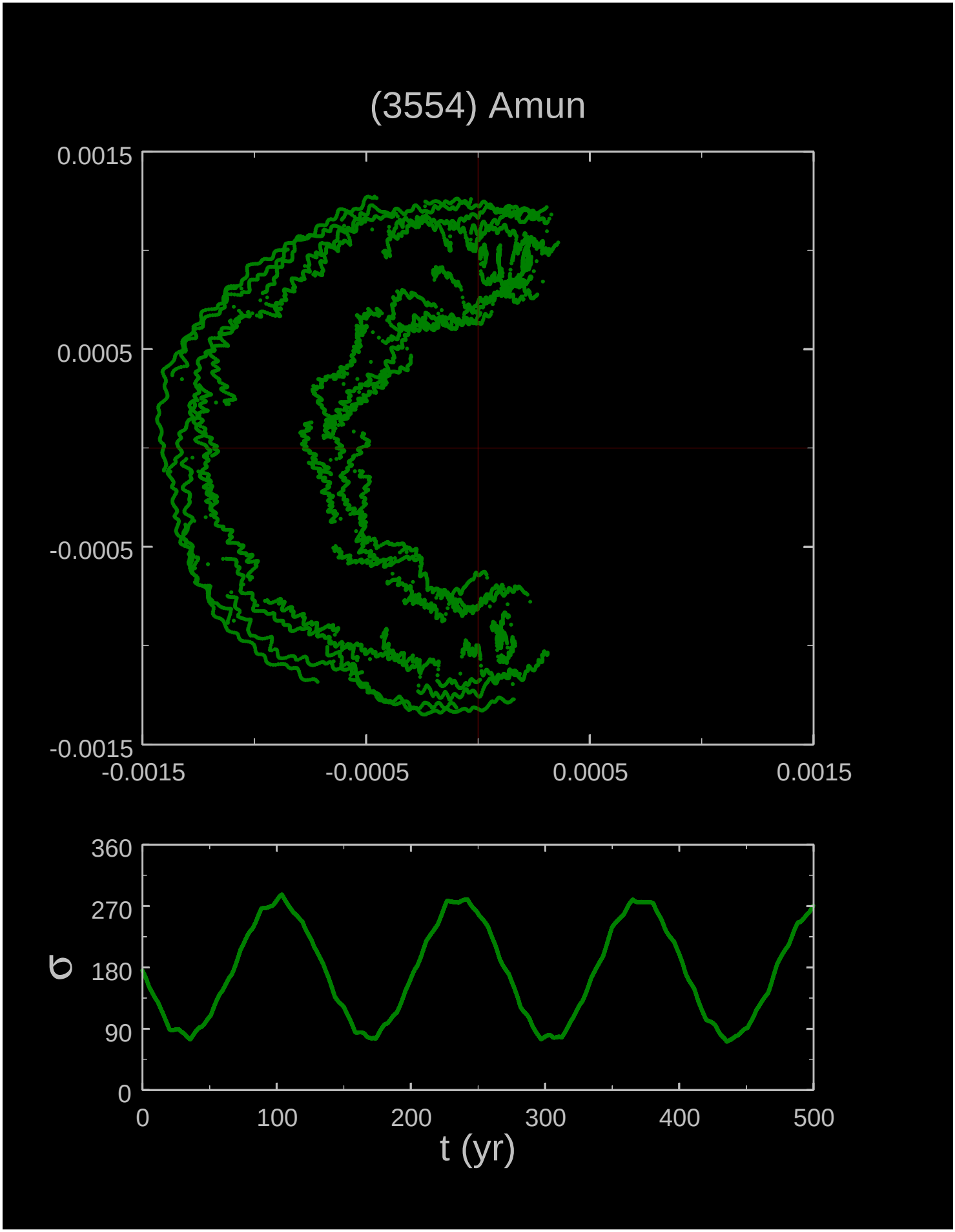

atch Automatic Resonance Finding - 00:07:28.6 - Finished!
ber
name
resonance
ref body
order
mean a
sdev a
lib center
lib amplitude
1997 EH29 17:37 Venus 20 1.214778 1.070e-06 77.57683 177.5780
1997 EH29 59:42 Mars 17 1.214778 1.070e-06 146.7926 207.8124
1993 PC 25:31 Earth+Moon 6 1.154186 2.127e-06 184.0976 173.9827
Amun 16:25 Venus 9 0.9739940 1.565e-06 171.6944 215.9489
Amun 45:23 Mars 22 0.9739940 1.565e-06 65.53118 414.4914
Mercury
Venus
Earth+Moon
Mars
Jupiter
Saturn
Uranus
Neptune
go!
stop!
save
close
0
500
100
25

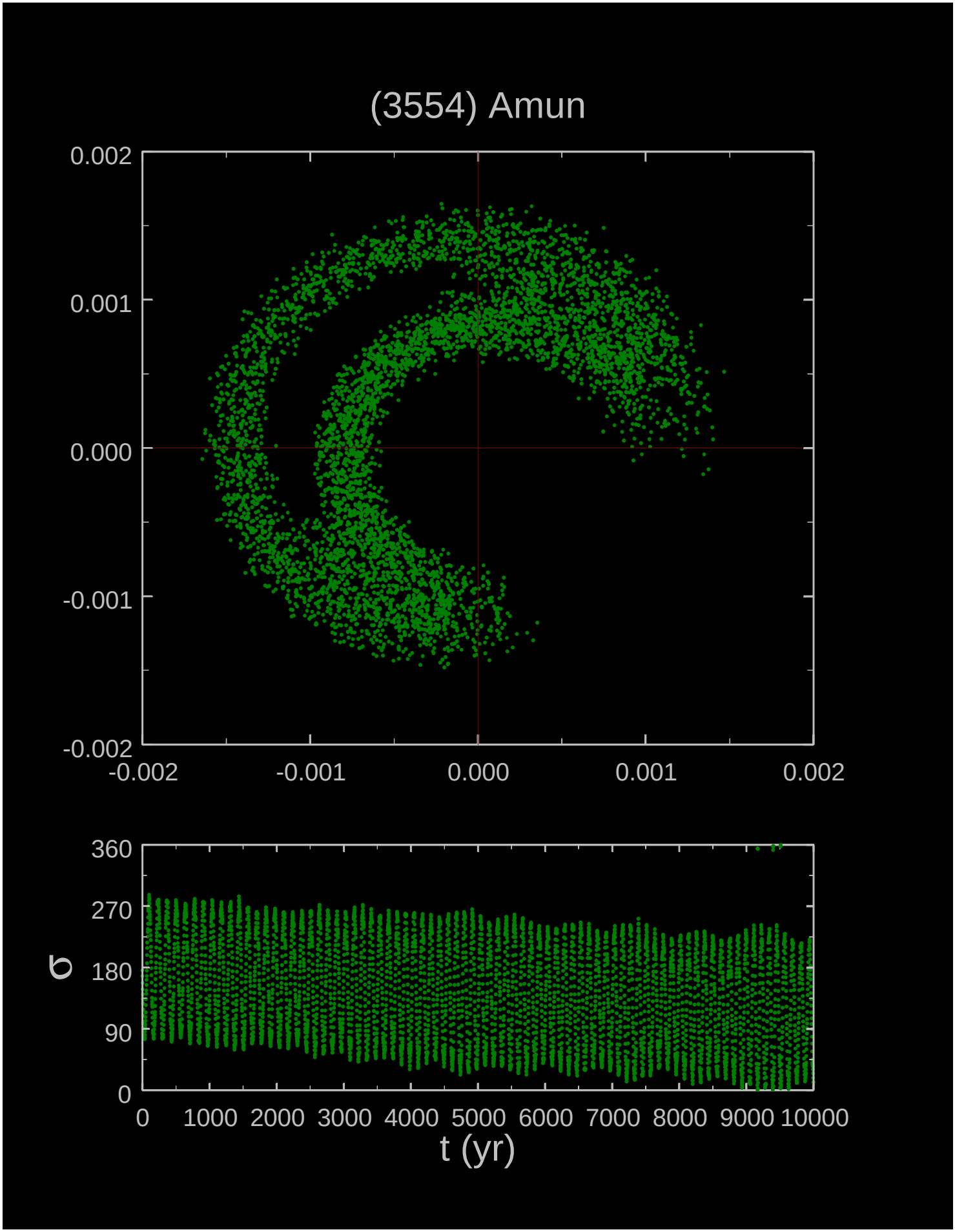
Current Research Projects Using Newton

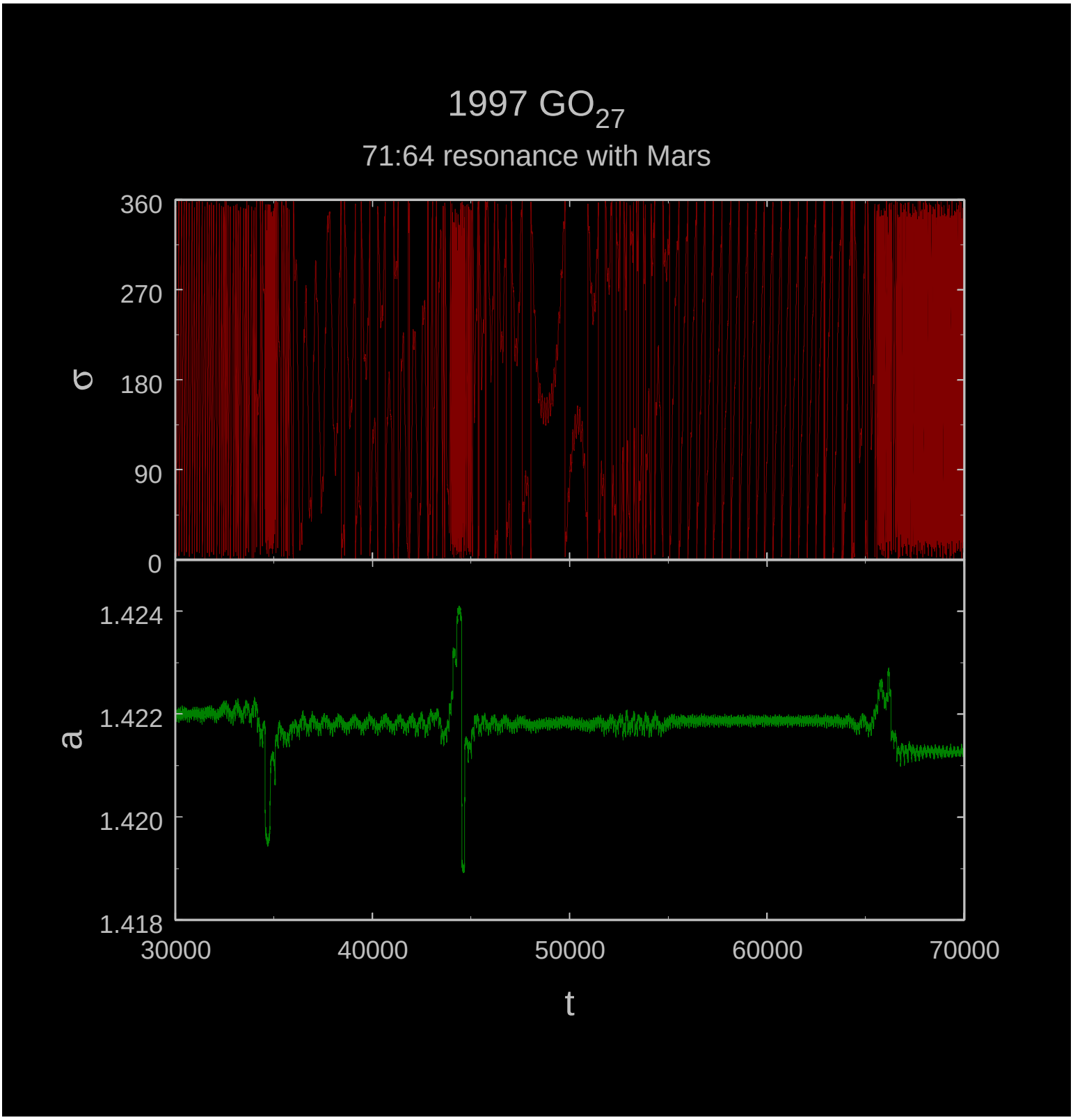
- These serve as an arduous testing ground for the ephemeris program integration module
- Dynamical survey of inner solar system asteroids
  - Identification of all mean-motion resonances
  - Some resonances are of very high order
  - Resonance statistics as a function of time
  - Double resonances
  - Secular resonances in the inner solar system
- Trans-Neptunian Objects
  - Pluto and company
  - Pile-ups at major MMRs

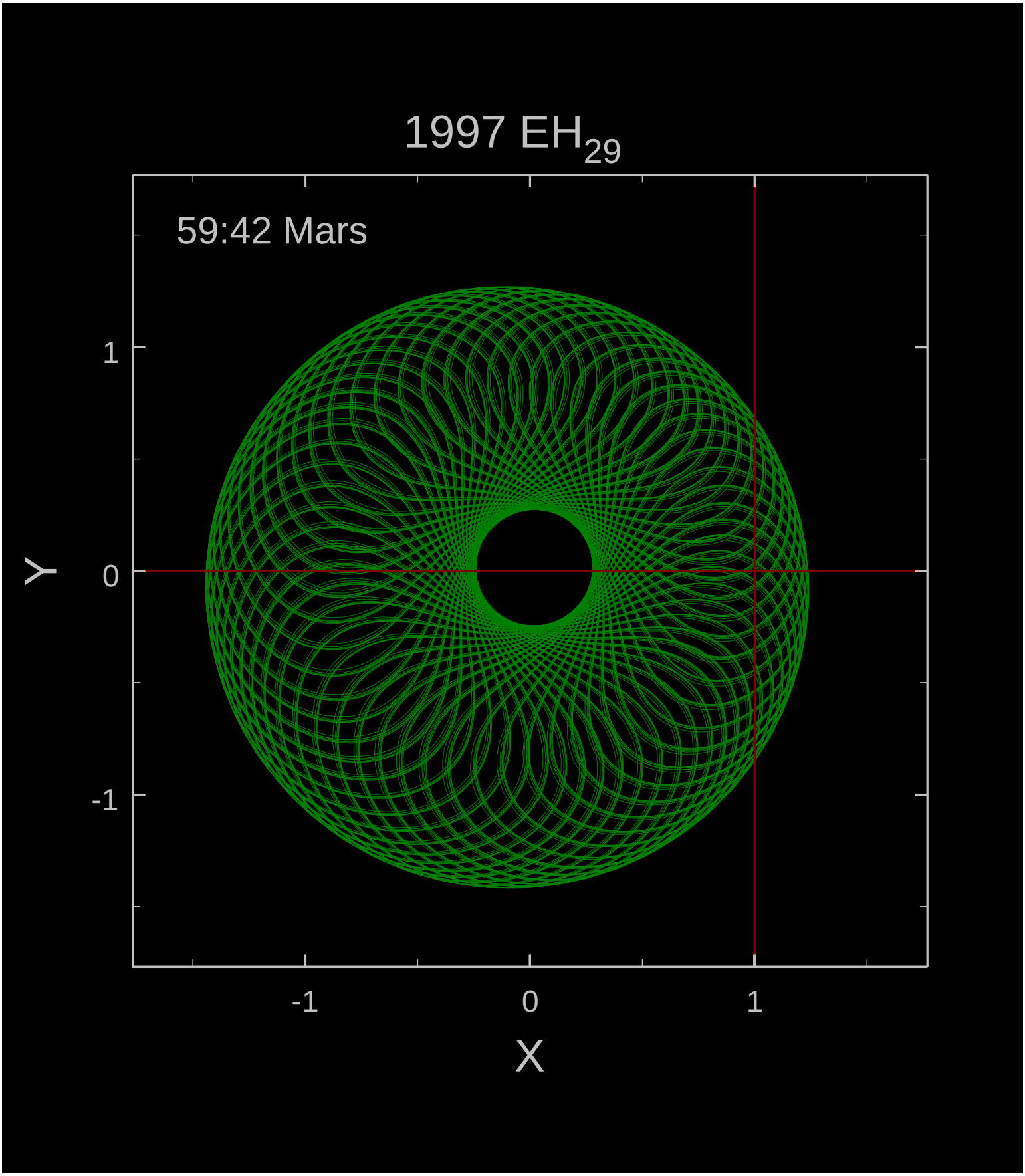

(3554) Amun
16:25 Venus
2
1
-0
-1
-2
Y
-2
-1
-0
1
2
X

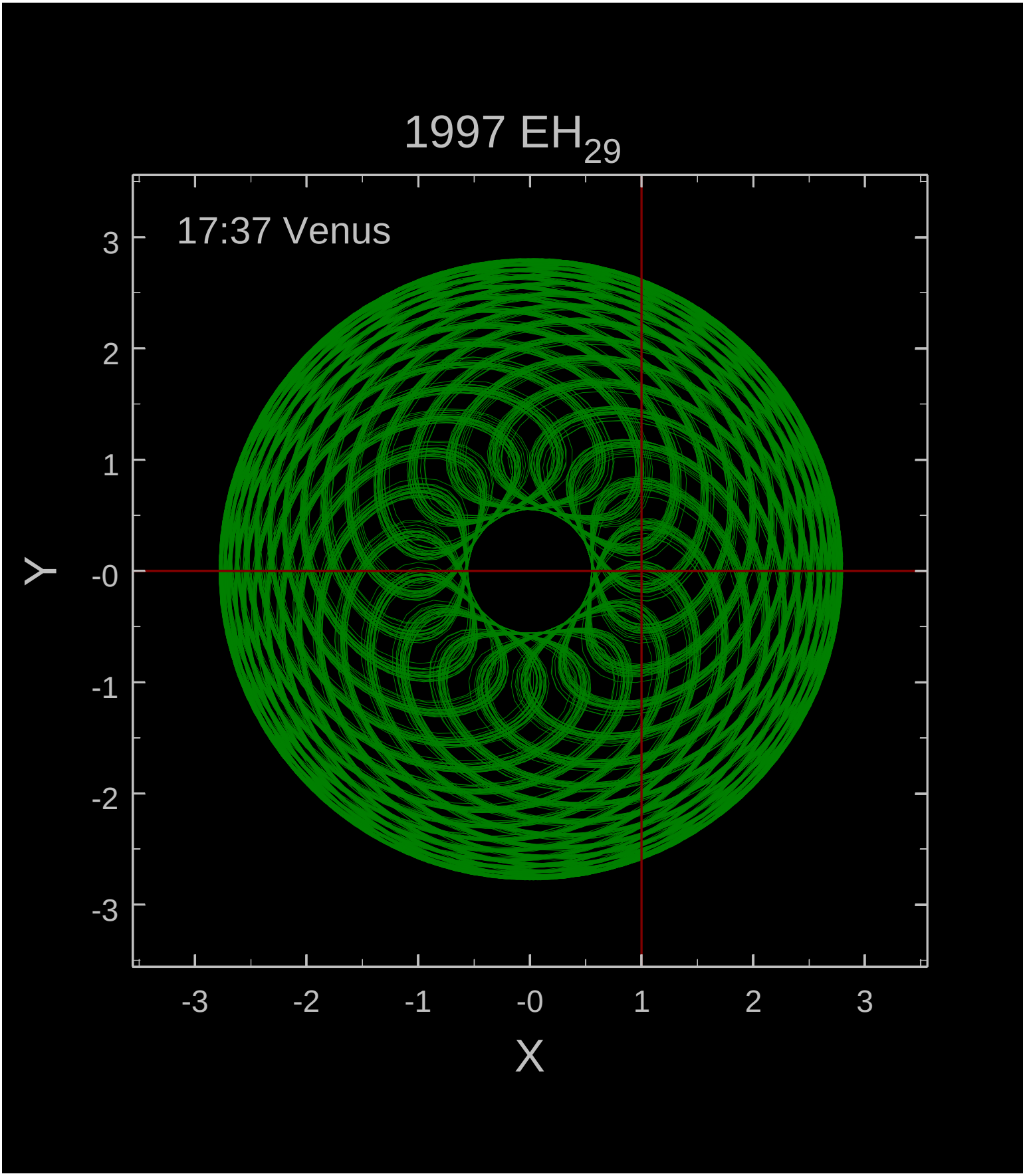

(3554) Amun
16:25 resonance with Venus
360
270
180
90
0
σ
0.9745
0.9740
0.9735
a (AU)
0
100
200
300
400
500
t

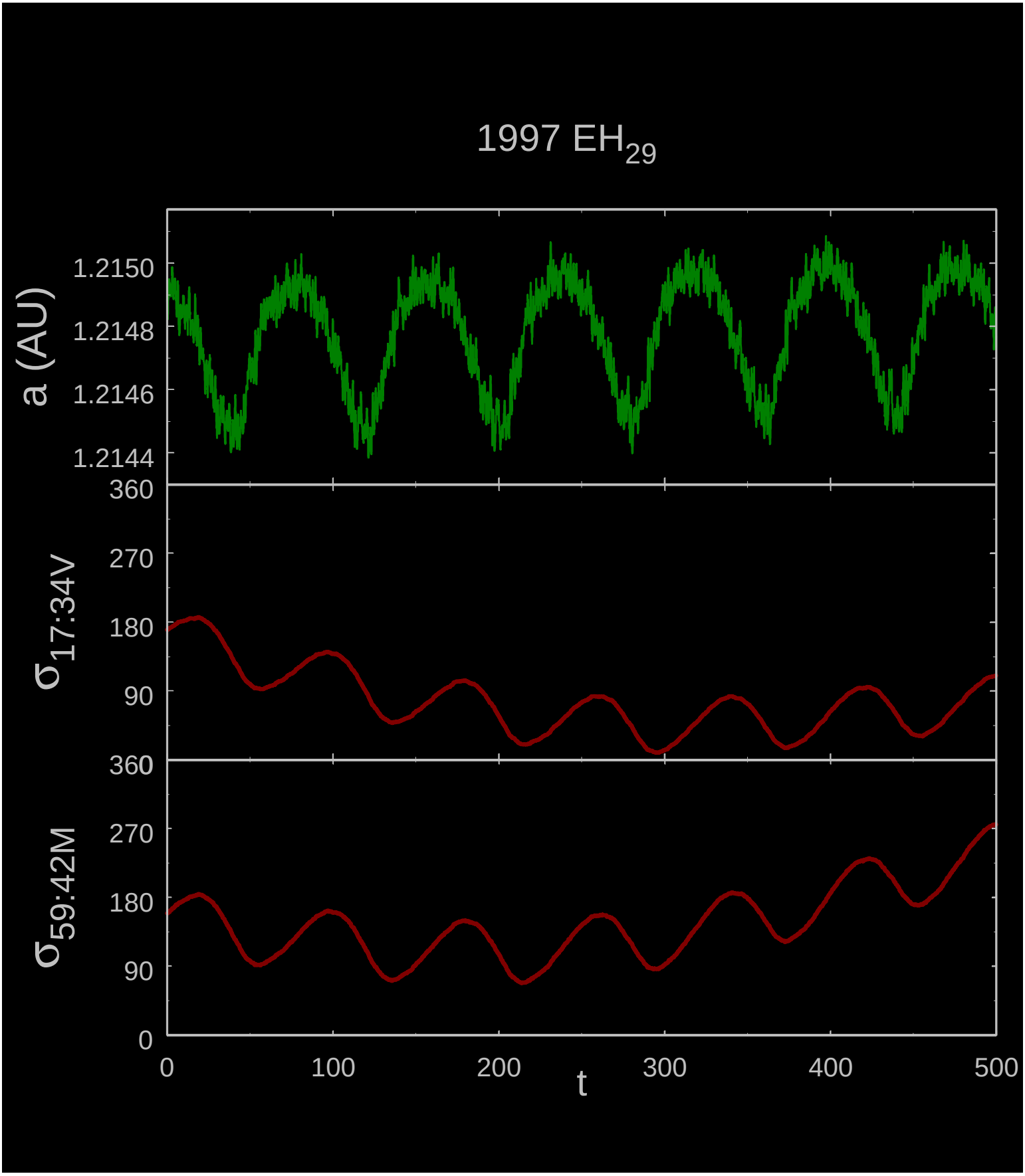

(3554) Amun
0.0015
0.0005
-0.0005
-0.0015
-0.0015
-0.0005
0.0005
0.0015
360
270
180
90
0
b
0
100
200
300
400
500
t (yr)

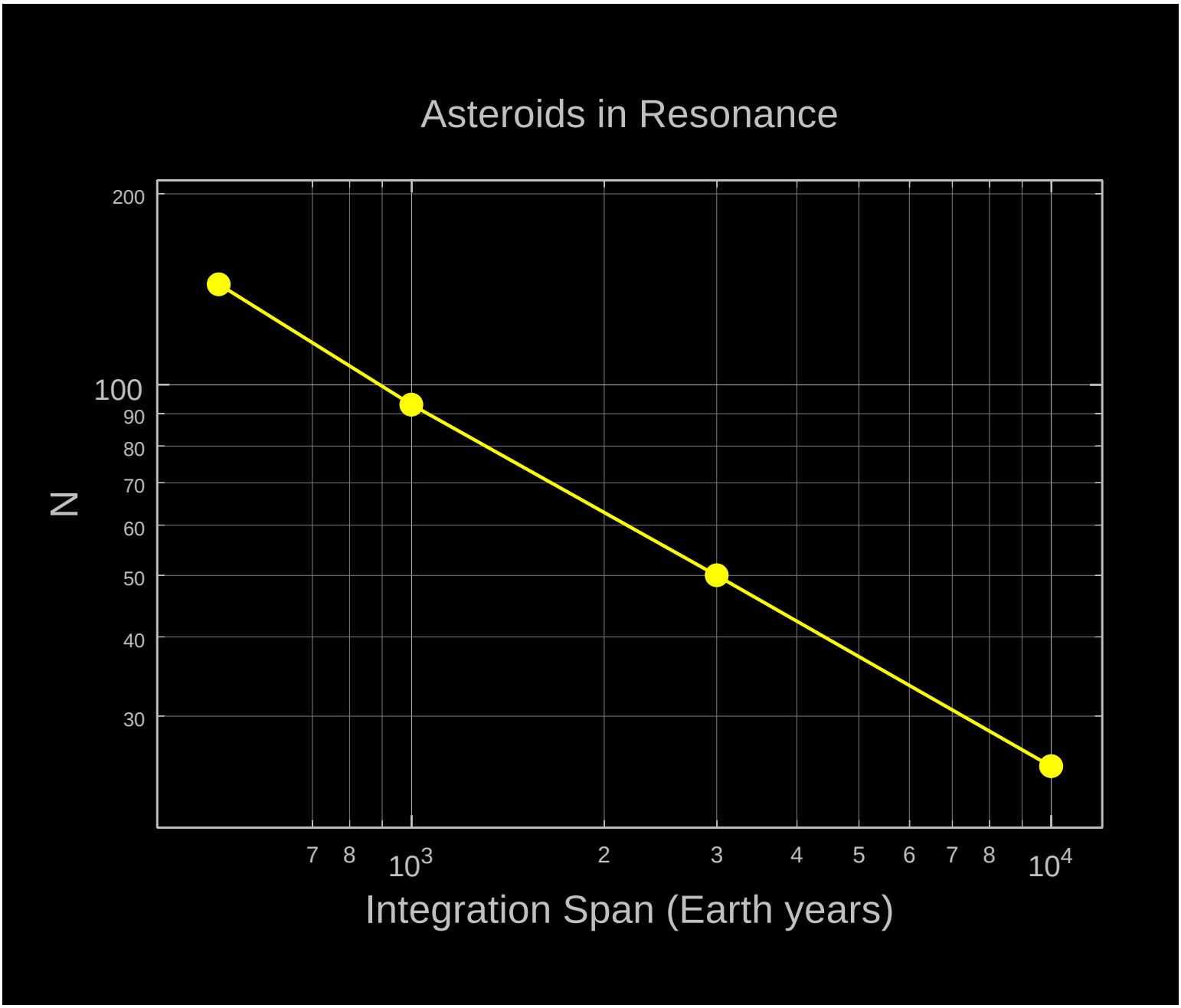

(3554) Amun
0.002
0.001
0.000
-0.001
-0.002
-0.002
-0.001
0.000
0.001
0.002
360
270
180
90
0
b
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
t (yr)

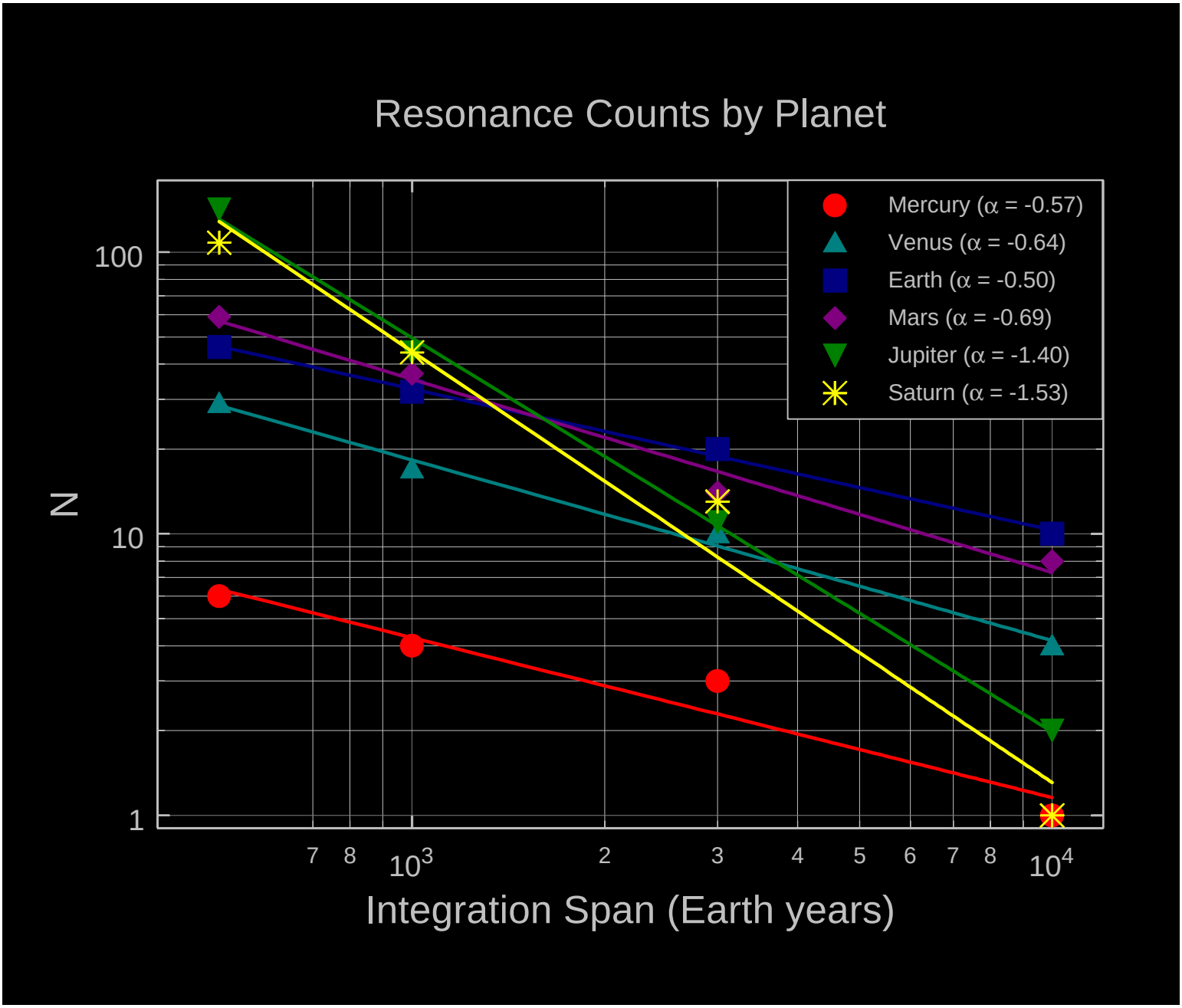

1997 GO27
71:64 resonance with Mars
360
270
180
90
0
ω
1.424
1.422
1.420
1.418
a
30000
40000
50000
60000
70000
t

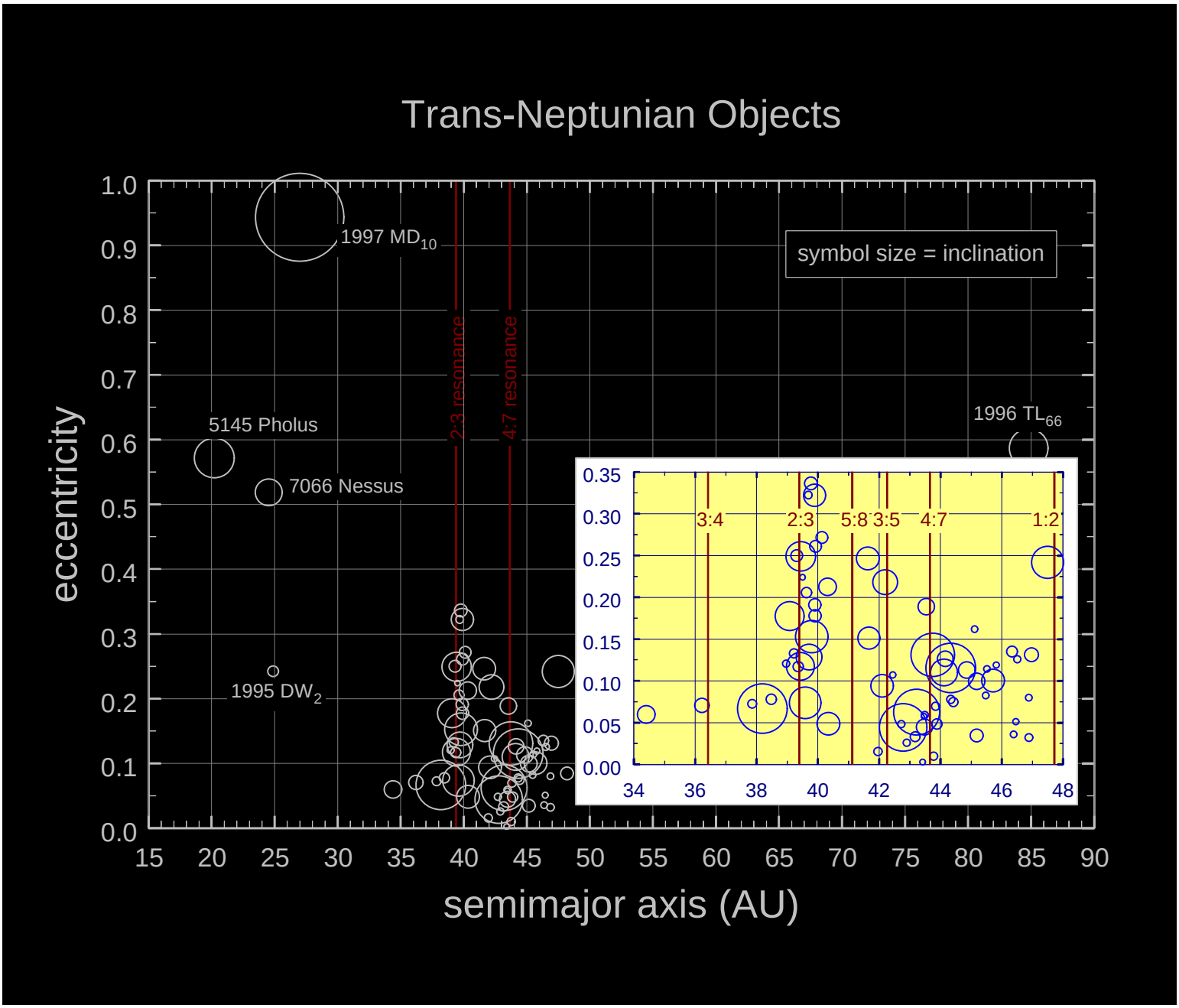

1997 EH29
59:42 Mars
1
0
-1
Y
-1
0
1
X

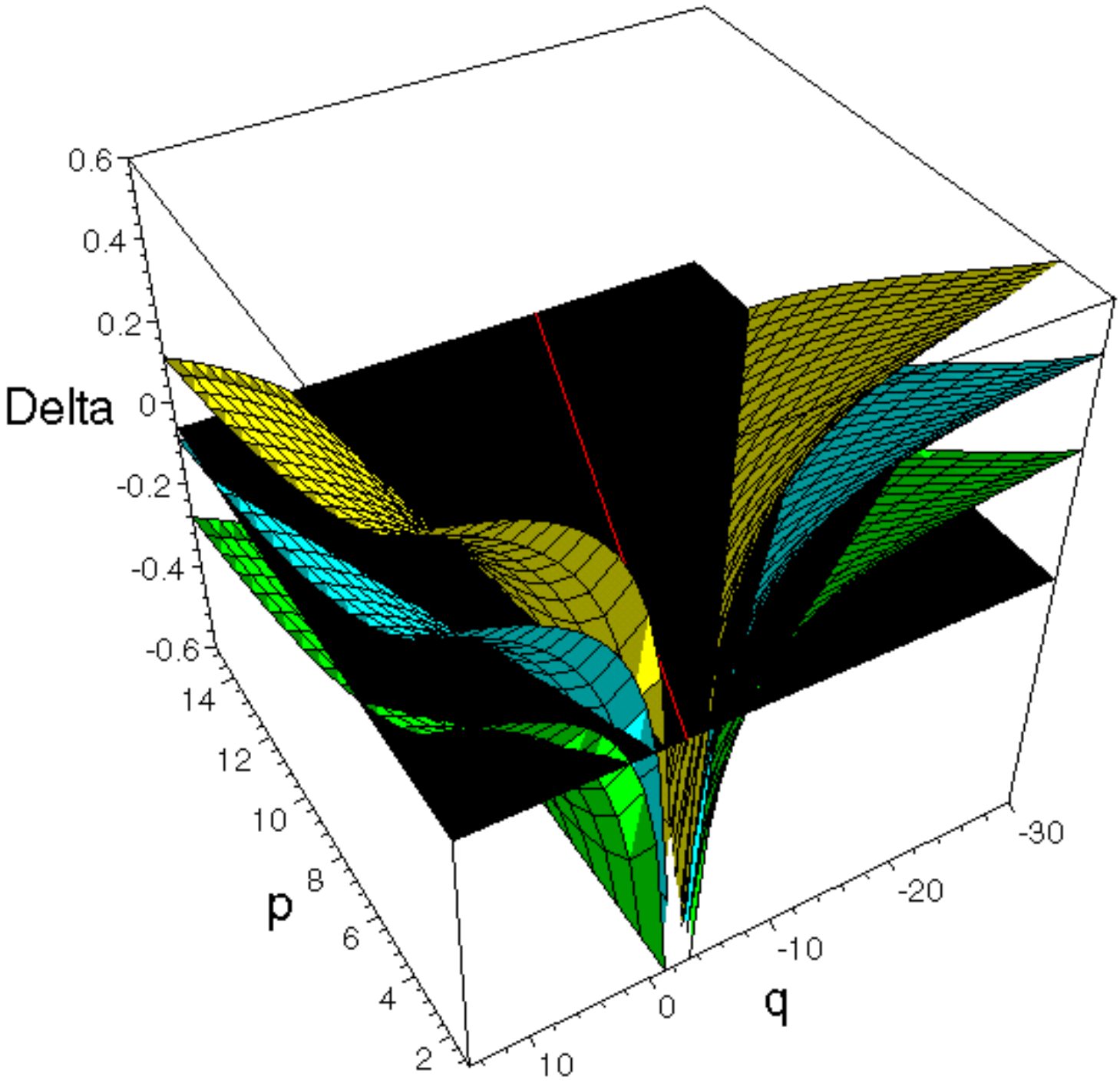

1997 EH29
17:37 Venus
3
2
1
-0
-1
-2
-3
Y
-3
-2
-1
-0
1
2
3
X


1997 EH29
a (AU)
1.2150
1.2148
1.2146
1.2144
σ17:34V
360
270
180
90
σ59:42M
360
270
180
90
0
0
100
200
300
400
500
t


Asteroids in Resonance
200
100
90
80
70
60
50
40
30
N
7
8
10^3
2
3
4
5
6
7
8
10^4
Integration Span (Earth years)


Resonance Counts by Planet
Mercury (α = -0.57)
Venus (α = -0.64)
Earth (α = -0.50)
Mars (α = -0.69)
Jupiter (α = -1.40)
Saturn (α = -1.53)
N
100
10
1
7 8 10^3 2 3 4 5 6 7 8 10^4
Integration Span (Earth years)


Trans-Neptunian Objects
eccentricity
semimajor axis (AU)
1997 MD10
5145 Pholus
7066 Nessus
1995 DW2
1996 TL66
2:3 resonance
4:7 resonance
symbol size = inclination
3:4
2:3
5:8
3:5
4:7
1:2


Delta
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
p
14
12
10
8
6
4
2
q
10
0
-10
-20
-30

Summary

- Newton is a new, multipurpose solar system dynamics exploration tool
- Integration Module of the new USNO ephemeris program currently in development
  - Complete gravitational model of the solar system
- Fully modern design and implementation
  - Object-oriented design
    - Extensible
    - Flexible
    - Low maintenance burden
  - RAD programming
    - Interactive, intuitive GUI
    - Easy to use
    - Easy to modify and add new capabilities
  - C++ for speed, longevity, high-level numerics
- Excellent resonance detection & diagnostic tool
- Already proving to be a useful solar system dynamics research tool