Trans-Neptunian Objects

A Brief Review

Marc A. Murison

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

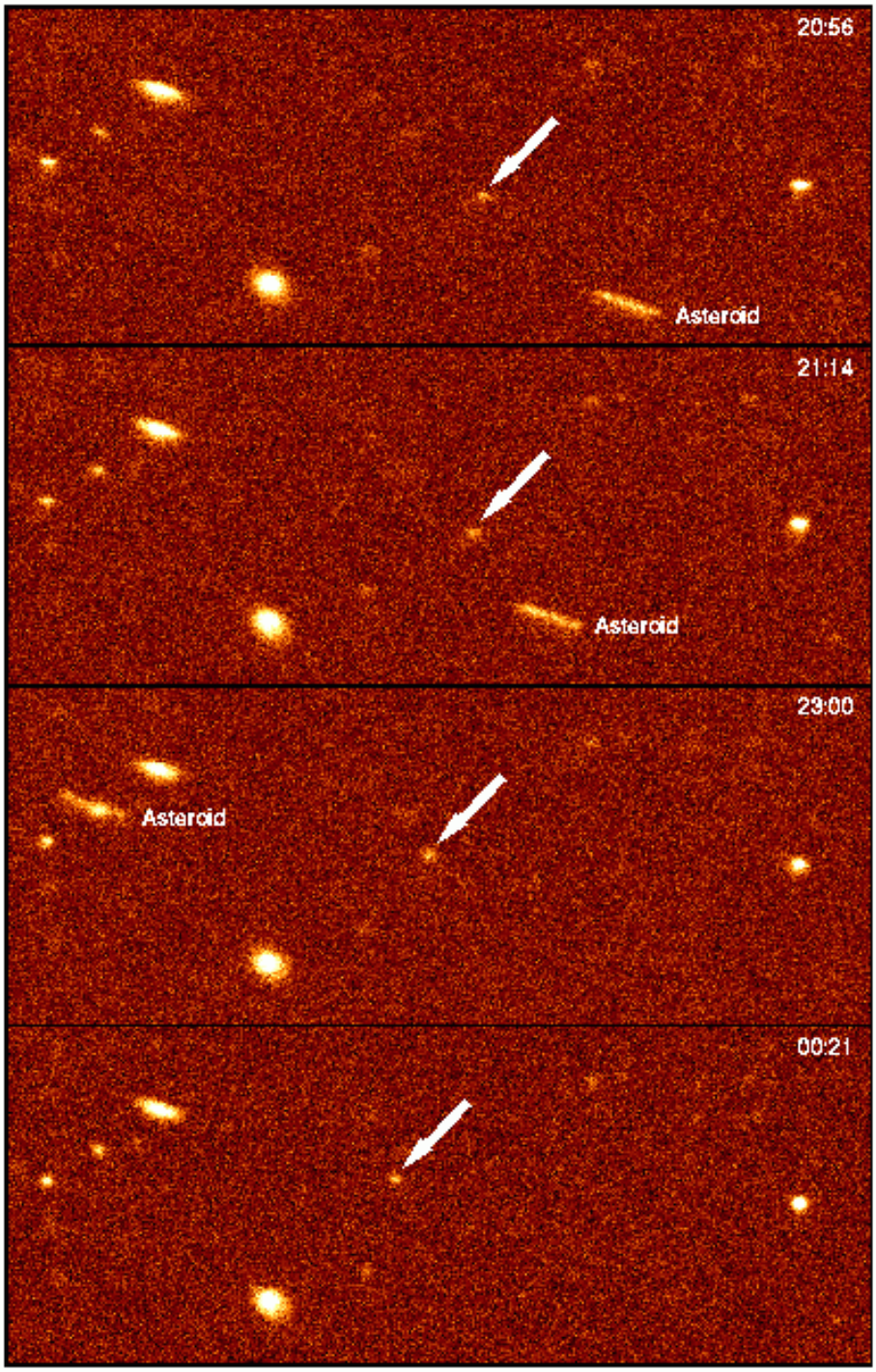
http://aa.usno.navy.mil/murison/

November 18, 1998

Overview

- Introduction
  - Discovery
  - Location in the solar system
  - Observational (in)accuracies
- TNO Surface Characteristics
  - Broadband visual and IR photometry
  - Visual spectra
  - Broadband colors
    - Two populations!
    - Dynamical associations? None!?
- Dynamical Structure of the Outer Solar System
  - Orbital Element Distributions
  - Resonance Sweeping
  - Illustrative Examples from 100,000 yr Integrations
    - Mean-motion resonances
    - The peculiar (for now) orbit of 1996 TL_{66}
  - 10 Myr integrations: secular resonances
- The Centaurs

Discovery Images of 1992 QB_1



Trans-Neptunian Objects: Introduction

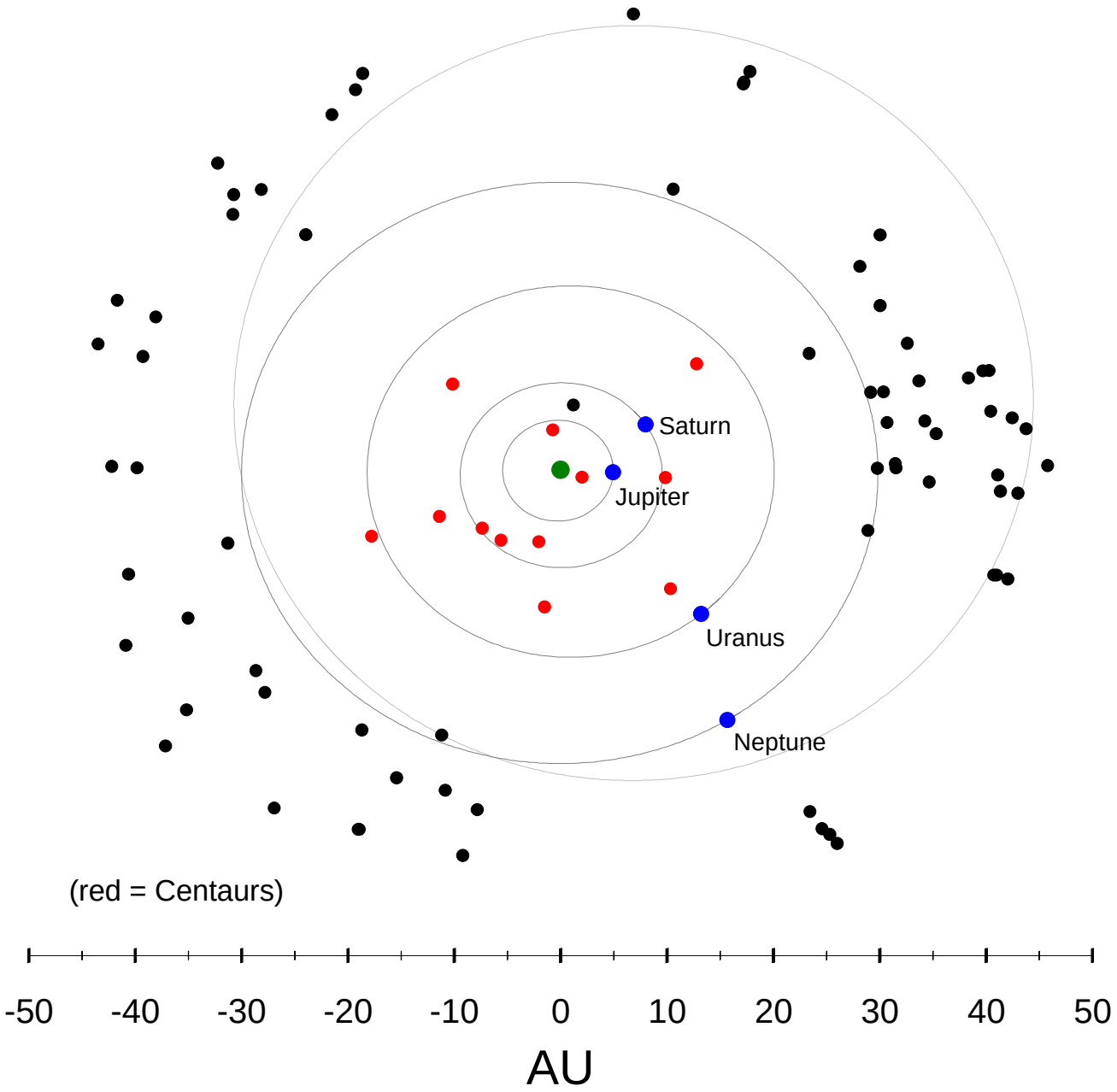
- Often referred to as "Kuiper Belt Objects", or, more accurately, as "Edgeworth-Kuiper Belt Objects".
- From $a > a_{Neptune}$ (30 AU) to roughly $a < 50$ AU
  - Objects are dynamically stable beyond ~50 AU (Malhotra 1996 AJ, Levison & Duncan 1993 AJ, Holman & Wisdom 1993 AJ)
- Potentially large population of objects, but hard to find
  - ~10 per sq. deg. at R~25 (Luu et al., 1998 ApJ Lett.)
  - Sensitivity of the 10m Kecks: >80 km at <50 AU
  - Perhaps >70,000 with D > 100 km
  - In numbers and mass: approximately two orders of magnitude larger than the asteroid belt! (Malhotra 1997)
  - Currently: only 82 known (including Pluto and 12 Centaurs)

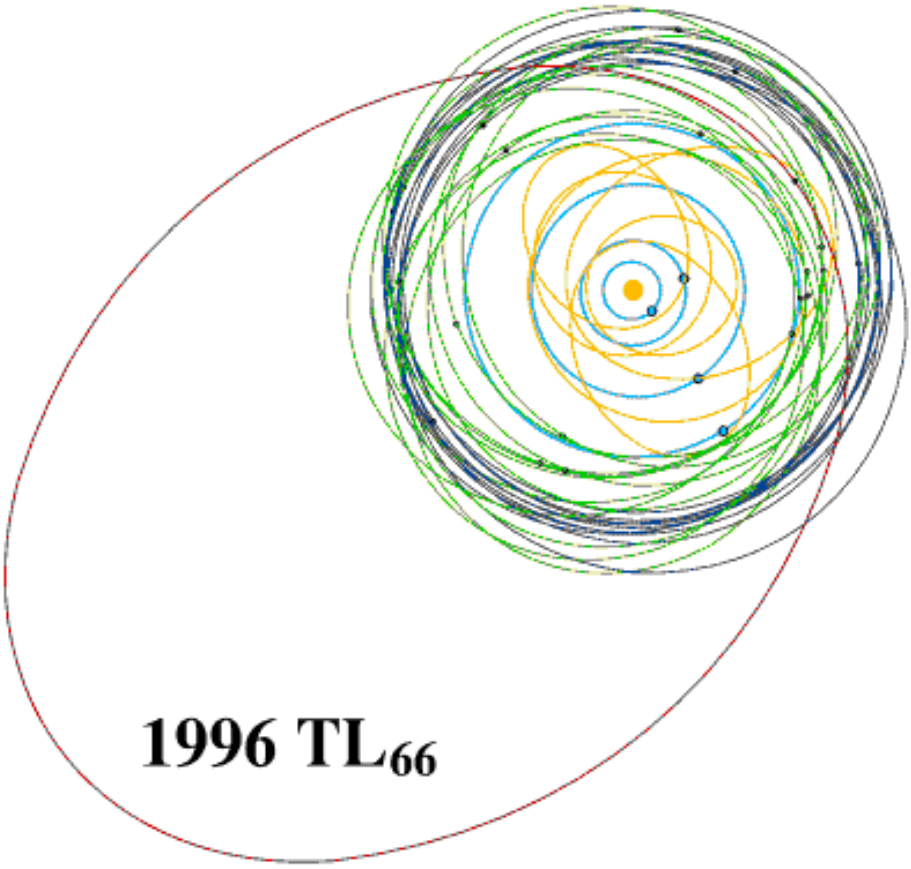
Trans-Neptunian Objects: Introduction

- Represent primitive objects from early accretional phases of the solar system
  - Most primitive and least disturbed material in the SS
  - Why?
    - Long- and intermediate-period comets originated in the giant-planet region
    - Short-period comets originated in the Edgeworth-Kuiper belt
- Kuiper Belt serves as reservoir of short-period comets (SPCs).
  - Also known as Jupiter family comets
  - Albedos typically ~0.04
- Centaurs:
  - TNOs caught in transition to becoming SPCs.
  - 12 found so far, with semimajor axes ranging from 5.8 to 27.0 AU.
- Colors
  - Spectra range from nearly flat to very red
  - Broadband: **two distinct populations!**

The Outer Solar System

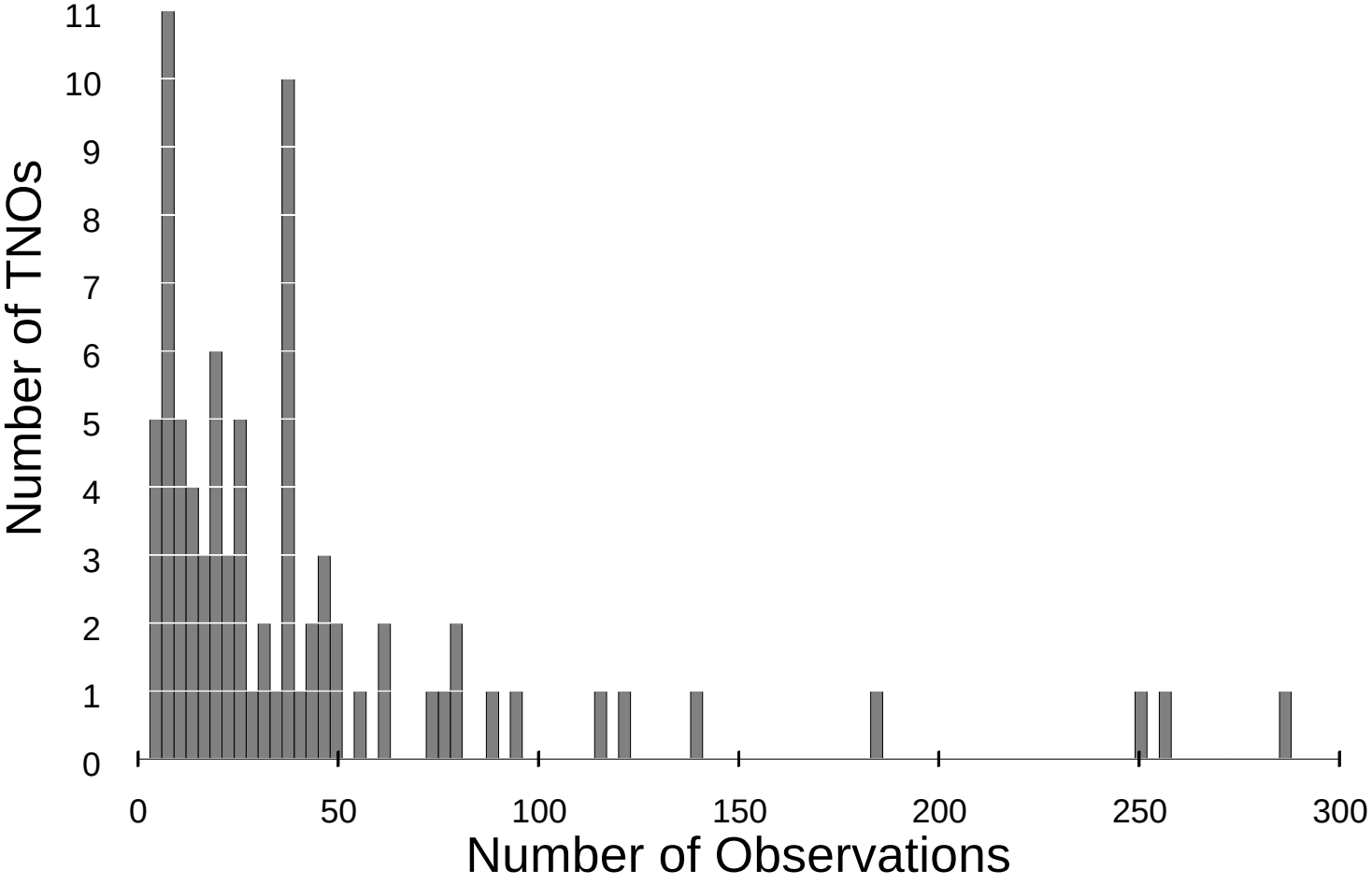
October 14, 1998

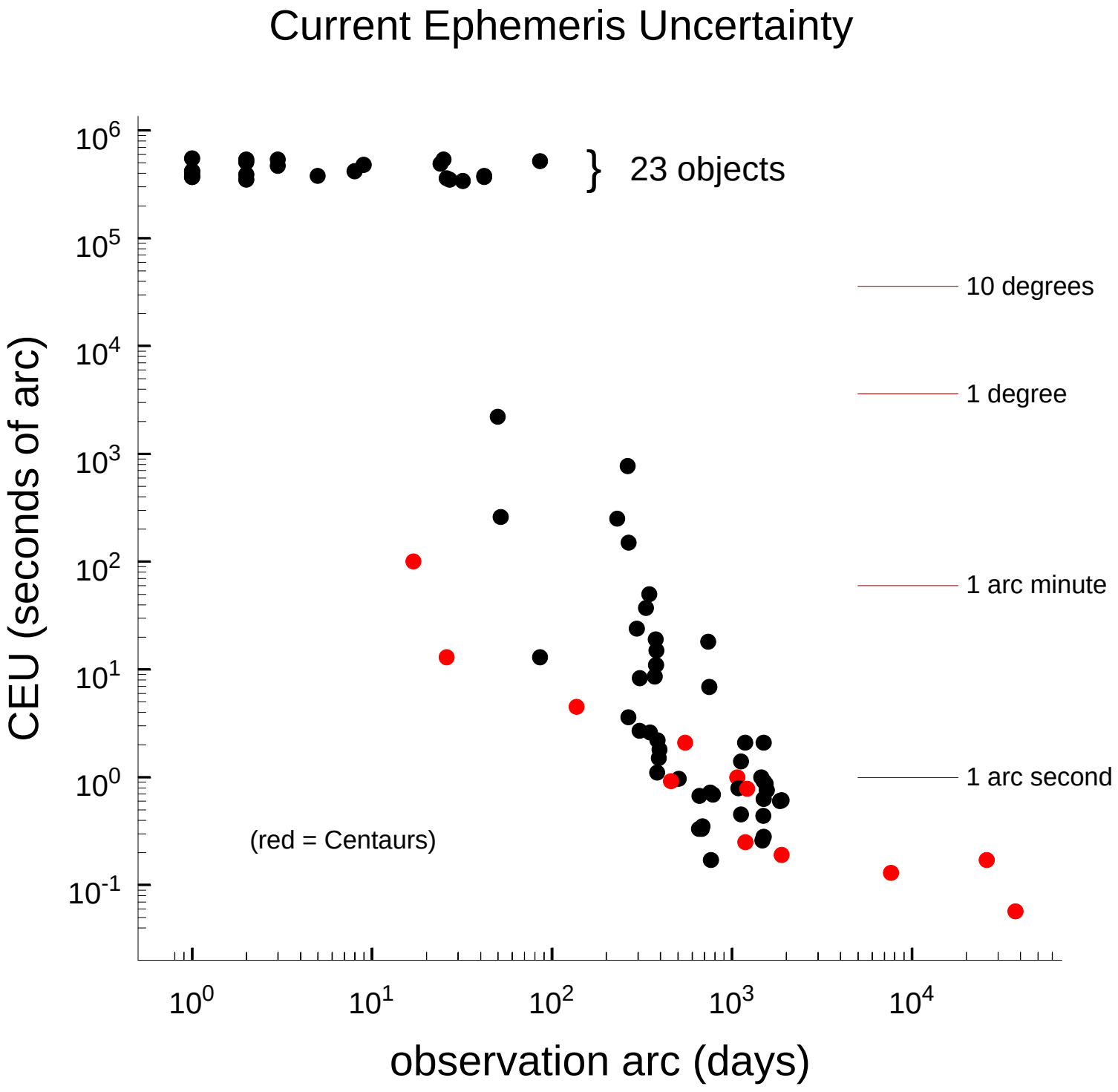




Minor Planet Center

Plot prepared on 1997 June 5


Number of TNOs
0
1
2
3
4
5
6
7
8
9
10
11
0
50
100
150
200
250
300
Number of Observations

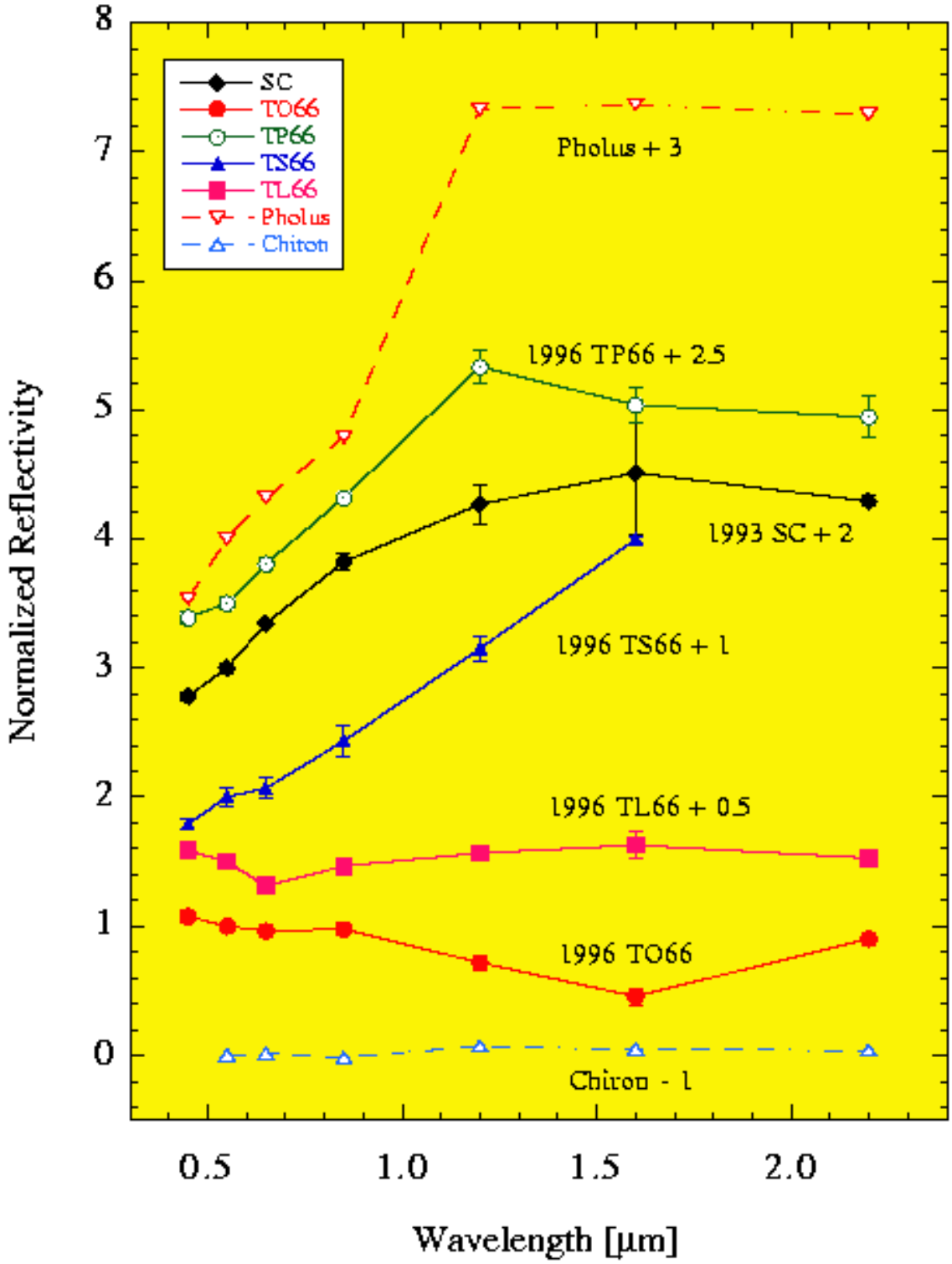

Current Ephemeris Uncertainty
CEU (seconds of arc)
observation arc (days)
23 objects
10 degrees
1 degree
1 arc minute
1 arc second
(red = Centaurs)
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^0
10^1
10^2
10^3
10^4

Surface Properties

Colors and Spectra

- Wide range of surface compositions
  - Jewitt & Luu (1998 AJ)
  - Broadband visible & IR (0.4-2.2 μm)
- Extremely red objects
  - Implies surfaces rich in complex organic molecules (Tegler & Romanishin, 1997 Icarus)
- Observed variety currently unexplainable
  - Protoplanetary formation
  - Dynamical evolution

Broadband Visible and IR



Jewitt and Luu (1998). Astron. J. Fig 1

TNO Spectra

- Range from flat to very red

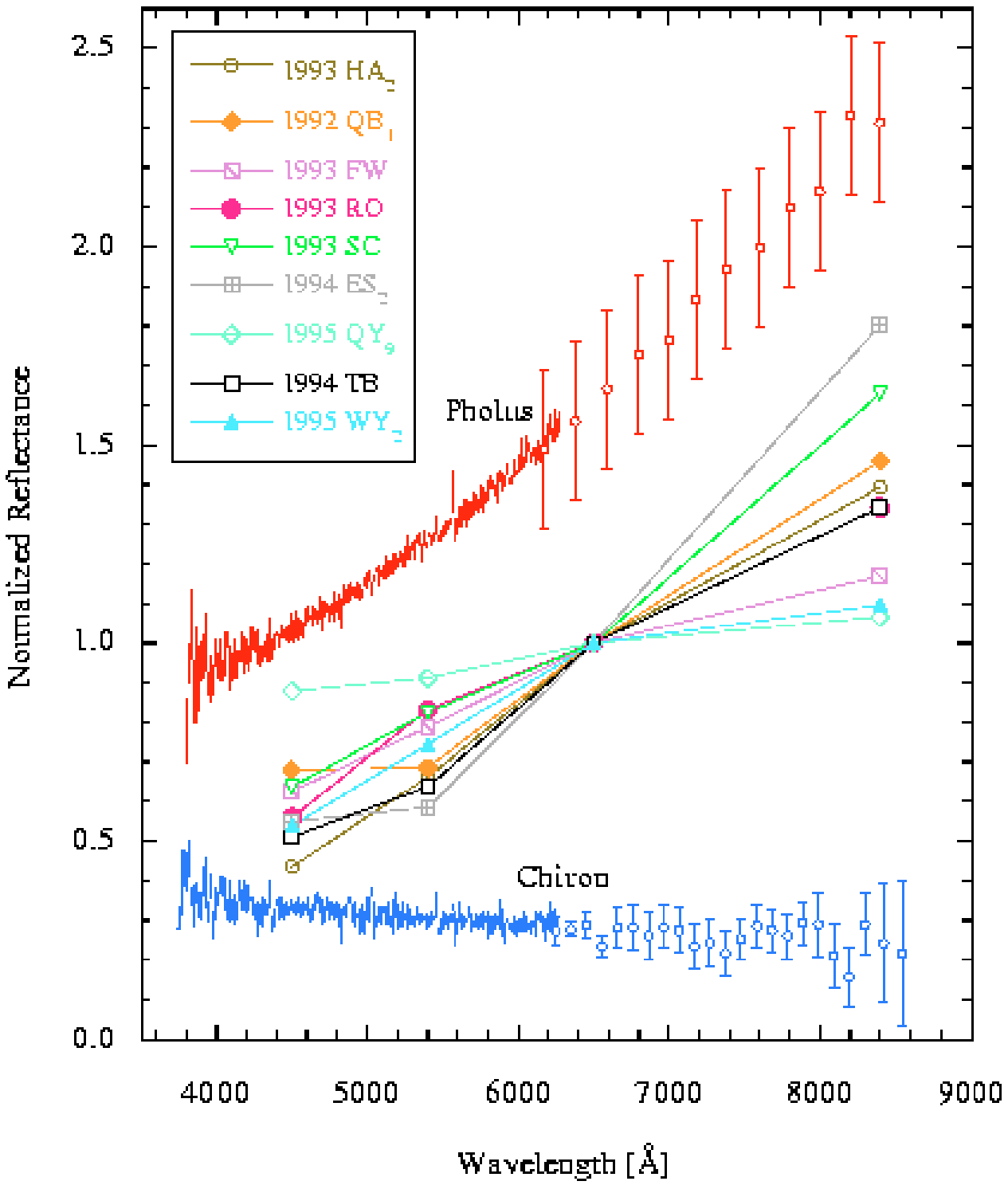
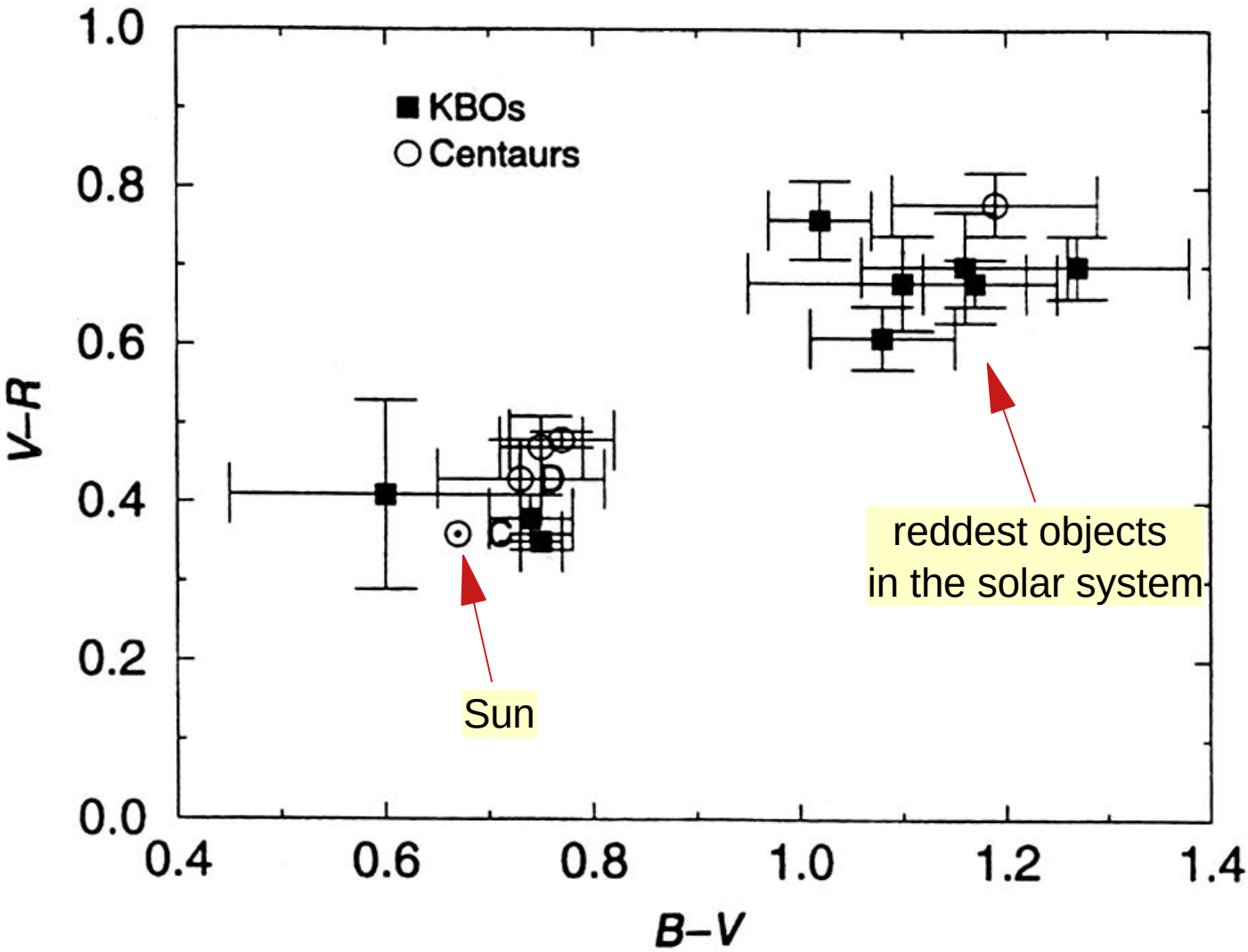


Fig 3: Luu & Jewitt, AJ Nov 1996

Color Distribution is Bimodal

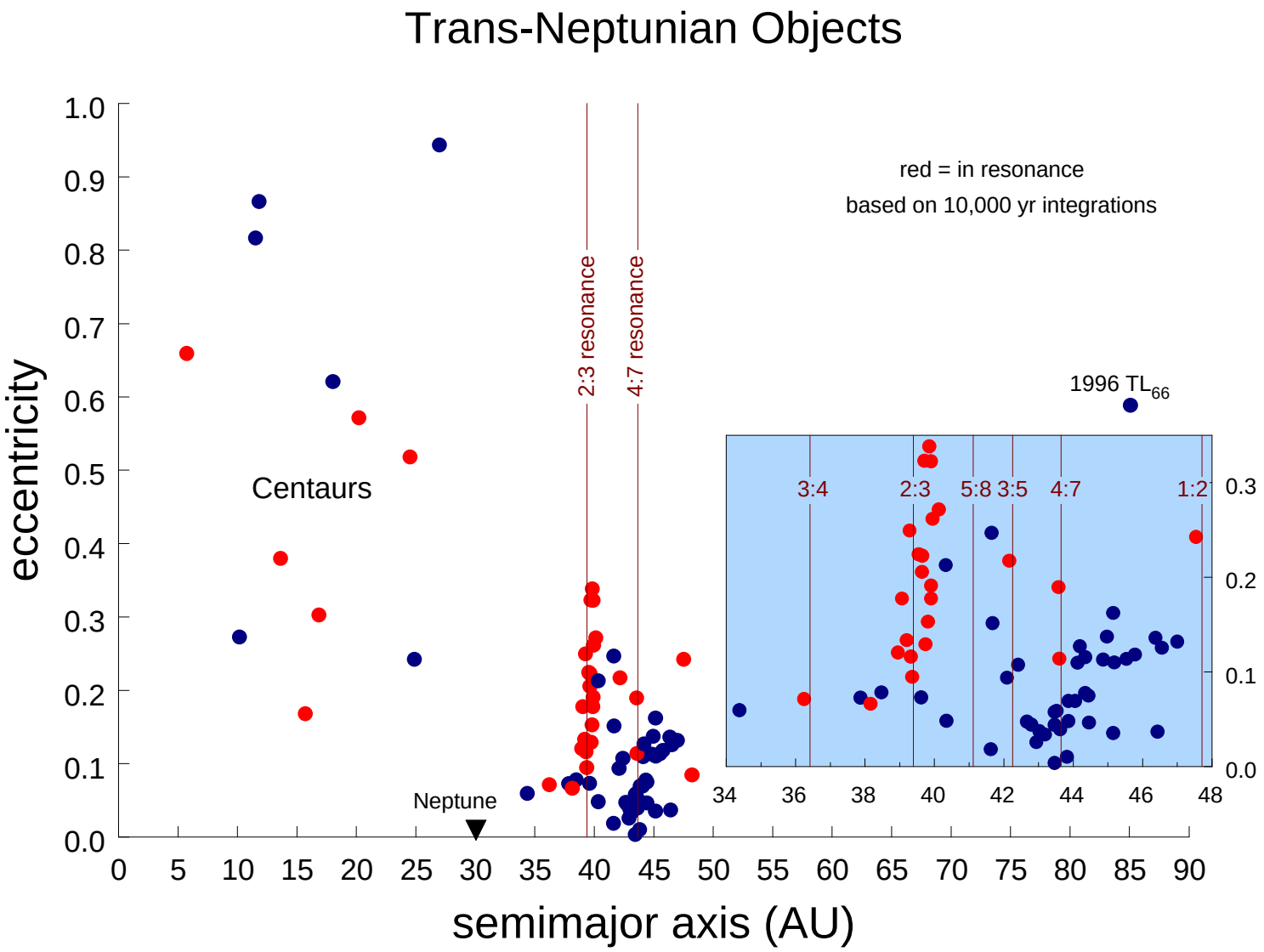
- Tegler & Romanishin, *Nature* **392**, 49 (March 5, 1998)
- 2-year survey
- Centaurs indistinguishable from TNOs
- 13 objects plotted:



Dynamics

Orbital Element Distributions

- Inner edge defined by orbit of Neptune (30 AU)
- Pile-up at the resonances: resonance sweeping (Malhotra) — more on this later
- Large inclinations could have been excited by resonance sweeping (Malhotra 1997)
- Large eccentricities could have been excited by Neptune-scattered planetesimals (Morbidelli & Valsecchi, 1997 Icarus)
- 2:3 is not a permanent trap (Morbidelli, 1997 Icarus)
  - The resonance has a complex dynamical structure
  - Small-eccentricity orbits are pumped up in inclination by secular resonances
  - Large libration amplitude orbits are strongly chaotic
  - Regular orbits exist only at small libration amplitude and moderate eccentricity
  - Moderate libration amplitude is characterized by slow diffusion (~10^9 yr)
    - Source of SPCs


Trans-Neptunian Objects
red = in resonance
based on 10,000 yr integrations
2:3 resonance
4:7 resonance
Centaurs
Neptune
1996 TL66
3:4
2:3
5:8
3:5
4:7
1:2
eccentricity
semimajor axis (AU)

Resonance Sweeping and Capture (Malhotra)

- Why are TNOs collected at major mean-motion resonances?
- Suppose a mass M scatters a planetesimal m, ejecting it from the system. Then angular momentum conservation requires

$$-\frac{da}{a} \propto \frac{m}{M}$$

- A single planet would, on average, suffer zero net change in orbital radius.
- But the four Jovian planets act together to evolve differently (numerical simulations of Fernandez & Ip, 1984): Jupiter shrinks slightly in radius, while Saturn, Uranus, and Neptune increase significantly in radius.
  - Planetesimals get handed down, planet to planet, until they reach Jupiter, which is very efficient at scattering them outward.
  - Rescattered (by Neptune) objects have a bias towards larger angular momentum, stolen from Jupiter.
  - Therefore, Neptune (and Uranus and Saturn) gains angular momentum.

Resonance Sweeping and Capture (Malhotra)

- Hence, low-order mean-motion resonances exterior to Neptune sweep outward through the primordial objects in the outer solar system, collecting them in the process.
  - Resonance capture is a common phenomenon in the solar system.
- Result (Malhotra 1996 AJ): region interior to ~50 AU would have been sculpted into highly nonuniform distribution, with pile-ups at the major mean-motion resonances

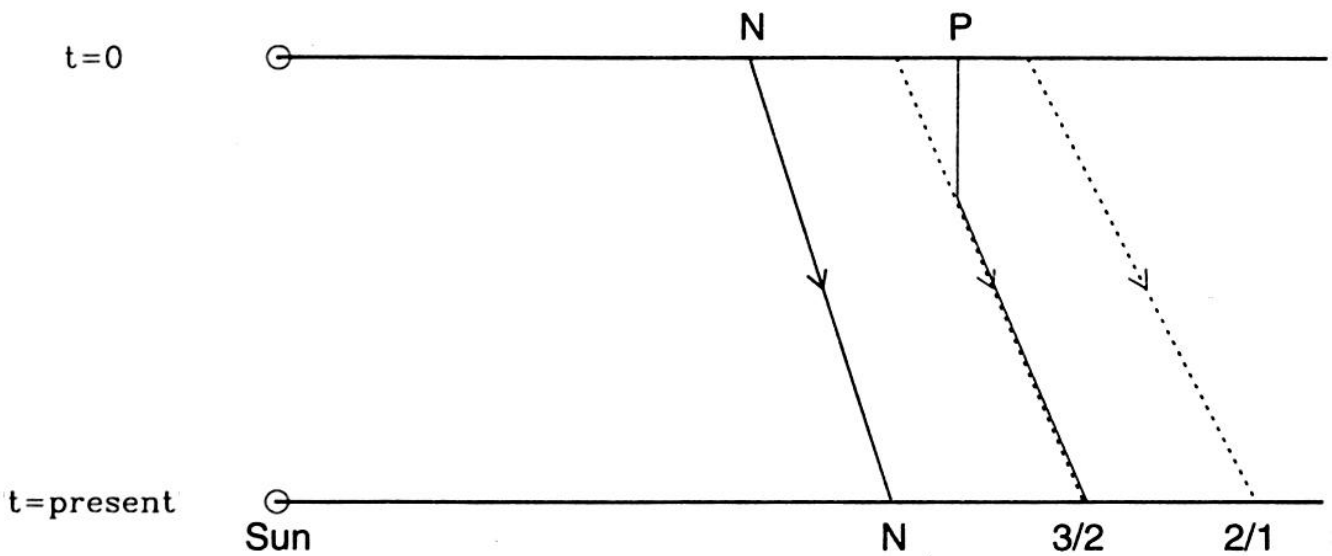
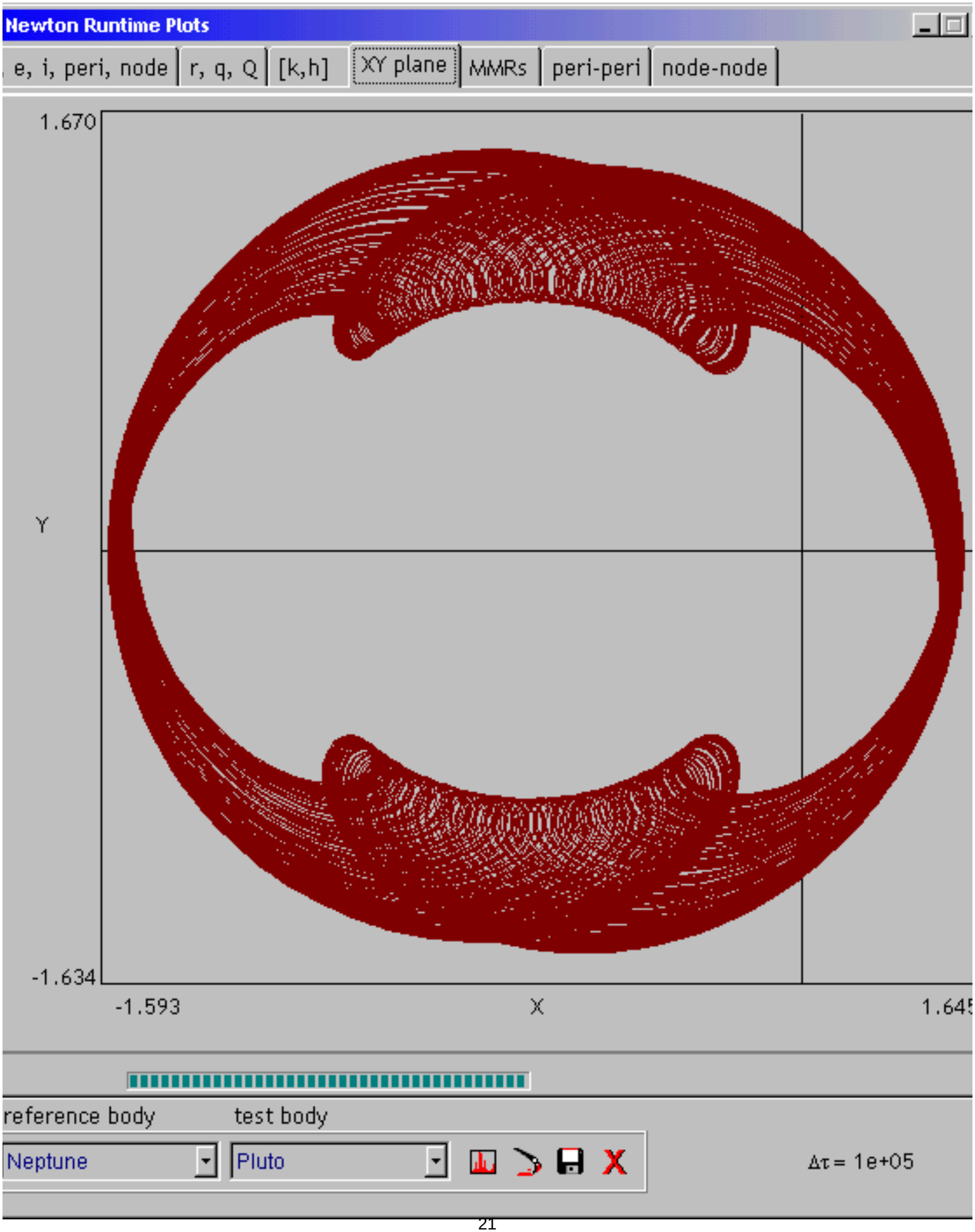
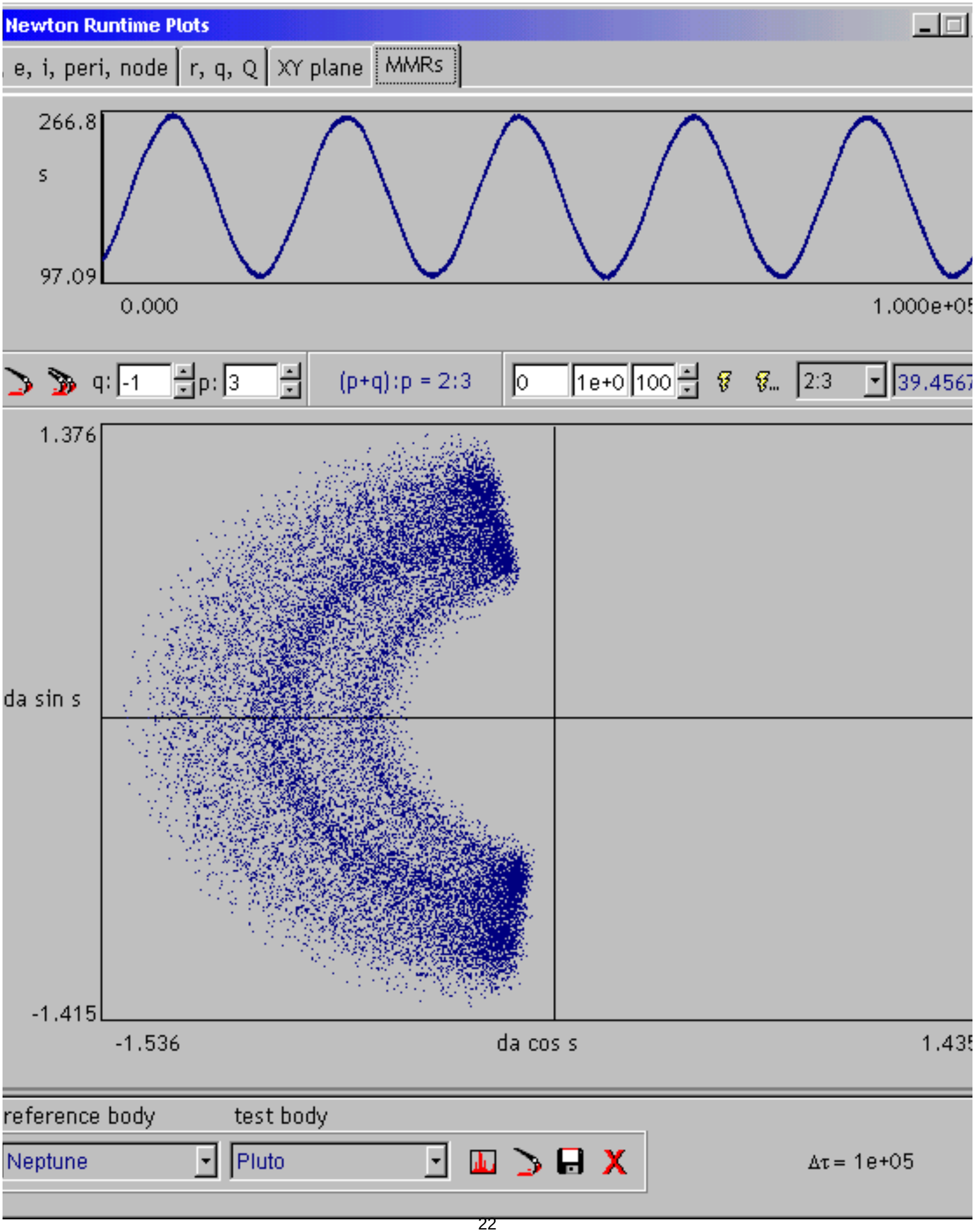


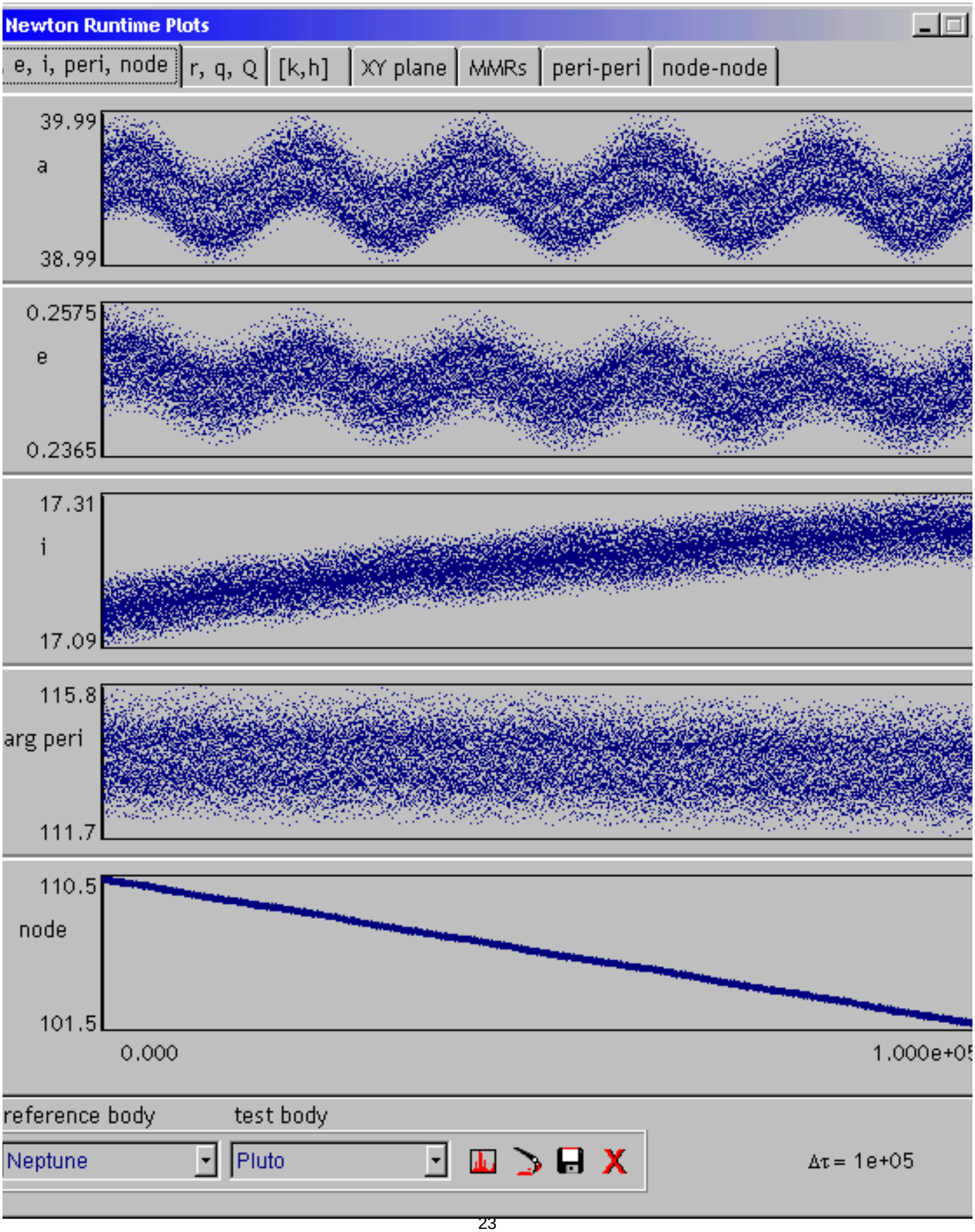
FIG. 1. A schematic diagram to illustrate the outward radial migration of Neptune and its exterior orbital resonances during the late stages of planet formation. The distance from the Sun is along the horizontal direction. Neptune's outward orbital migration is shown along the path marked N–N. For clarity, only two first-order resonances (3:2 and 2:1) are shown (dotted lines). A "Pluto" in an initially circular, nonresonant orbit beyond Neptune could have been captured into the 3:2 resonance and would evolve along the solid line path indicated by P—3/2.

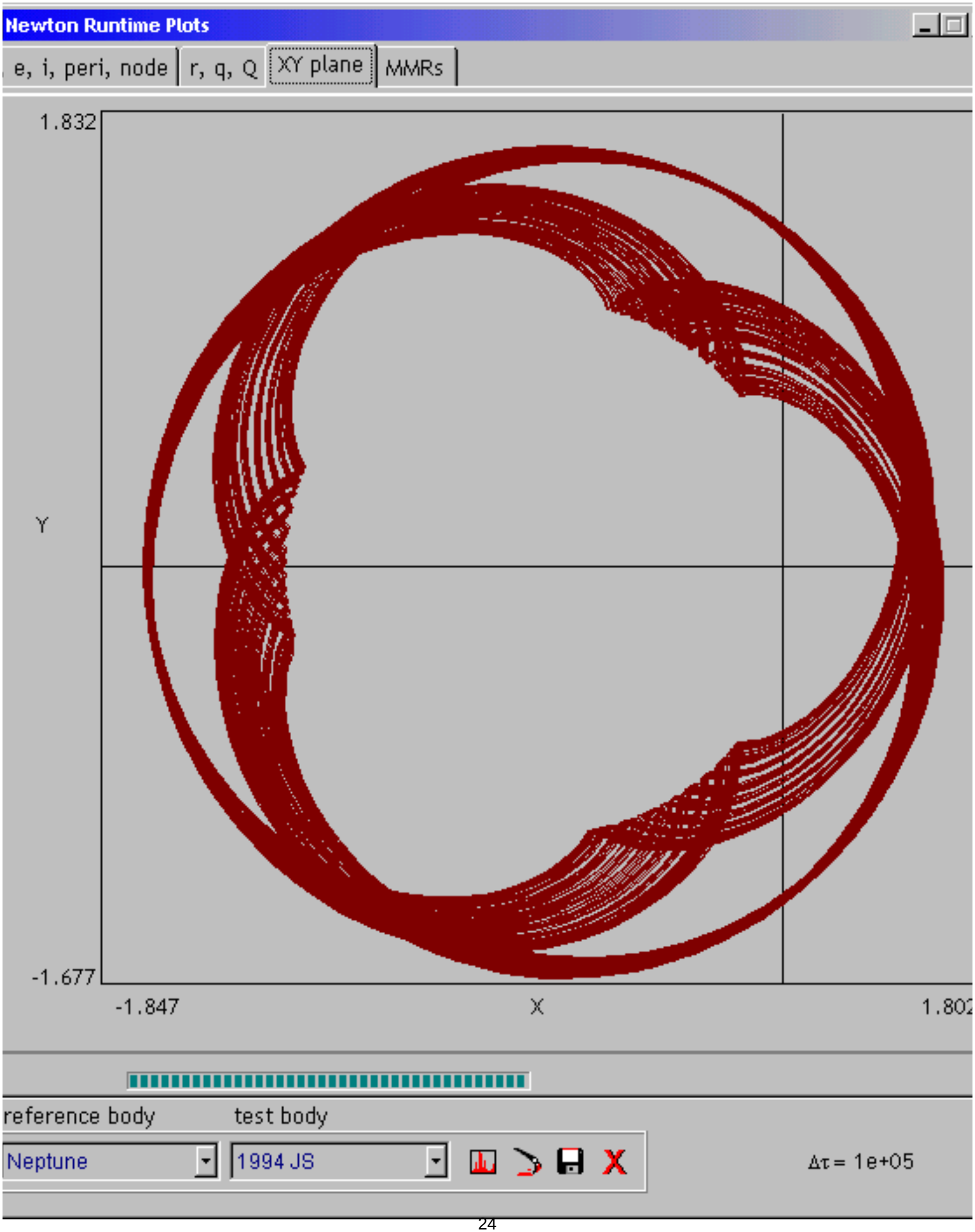
100,000 yr Orbits

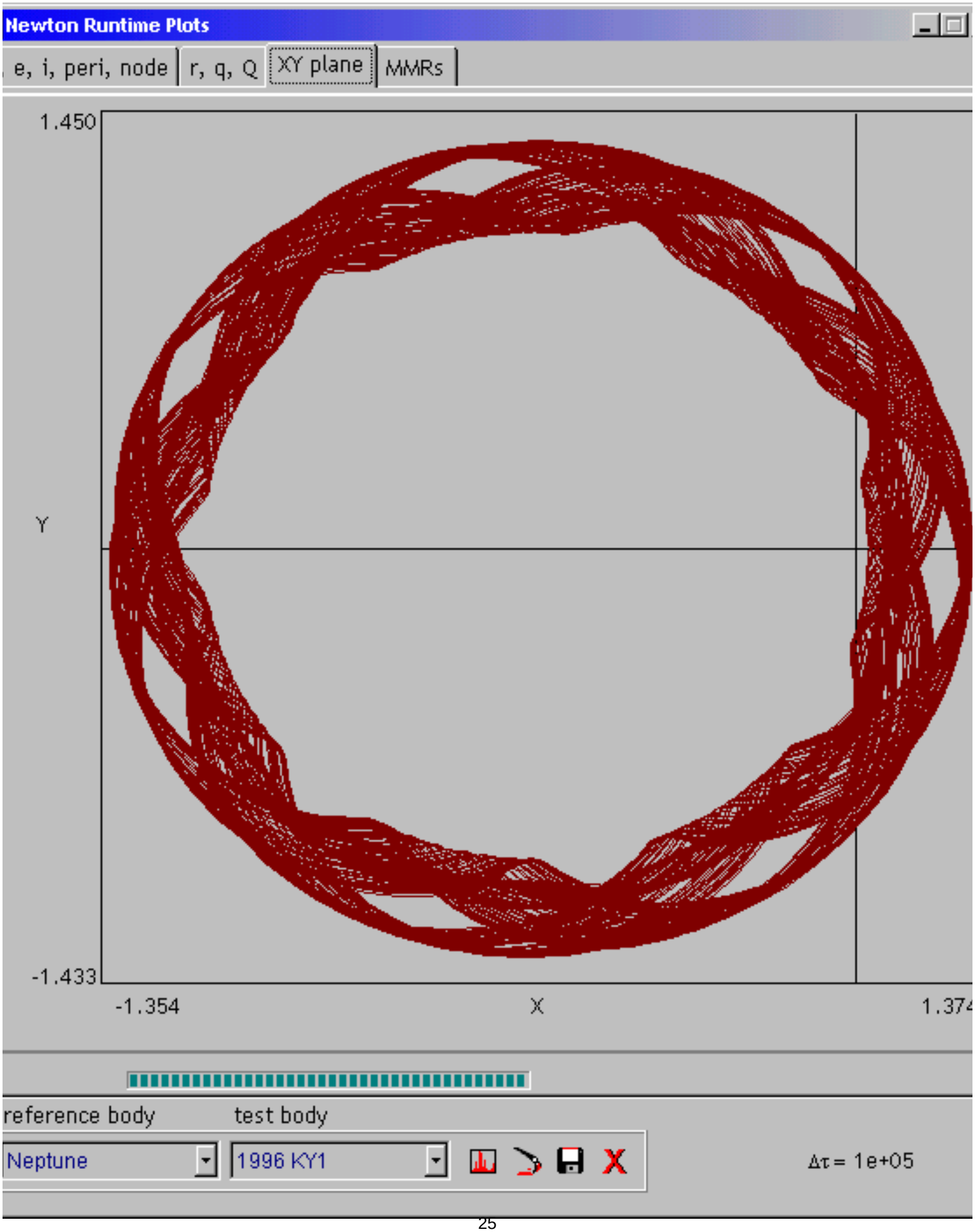
(calculated with Newton)

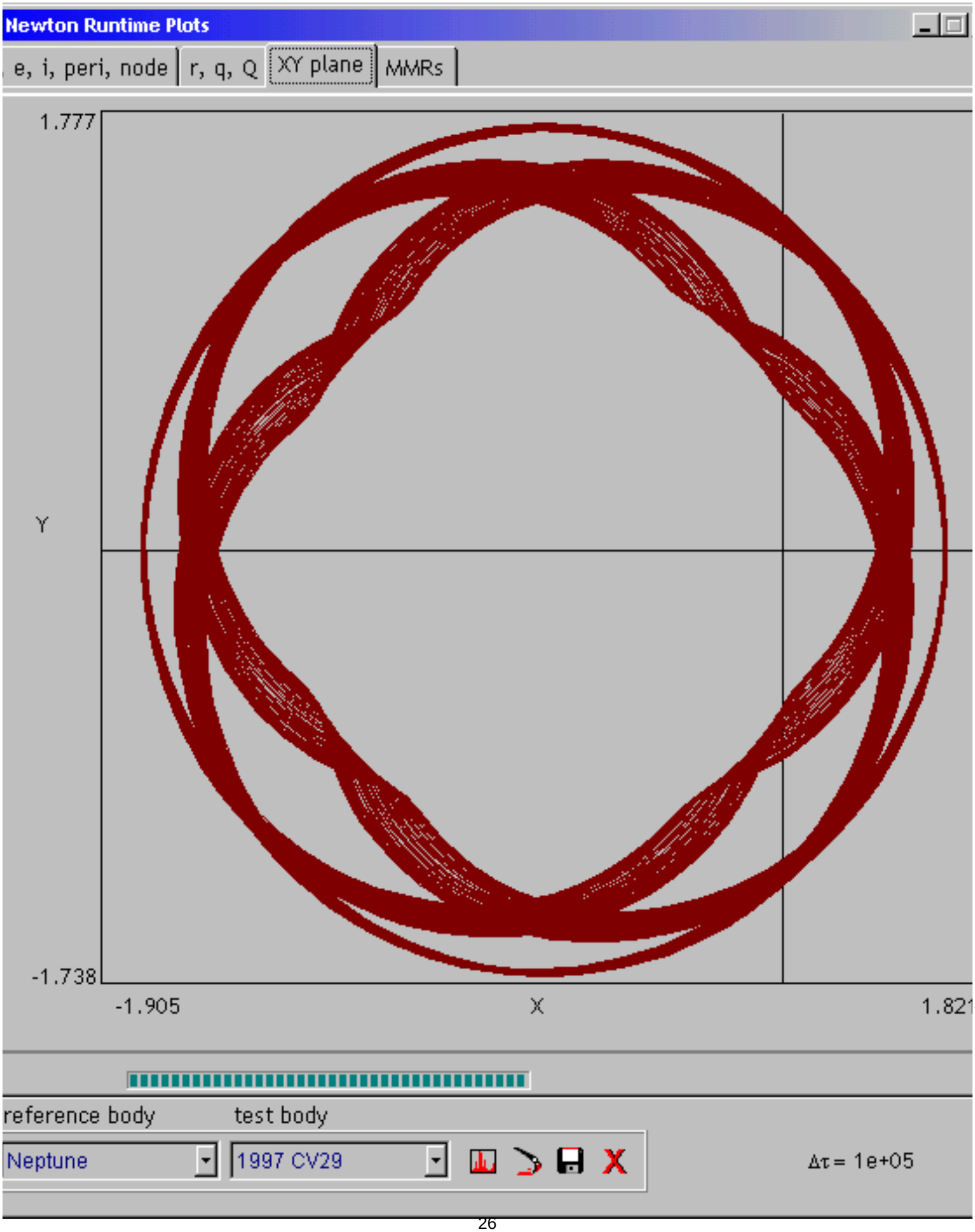

Newton Runtime Plots
e, i, peri, node
r, q, Q
[k,h]
XY plane
MMRs
peri-peri
node-node
1.670
Y
-1.634
-1.593
X
1.645
reference body
test body
Neptune
Pluto
Δτ = 1e+05

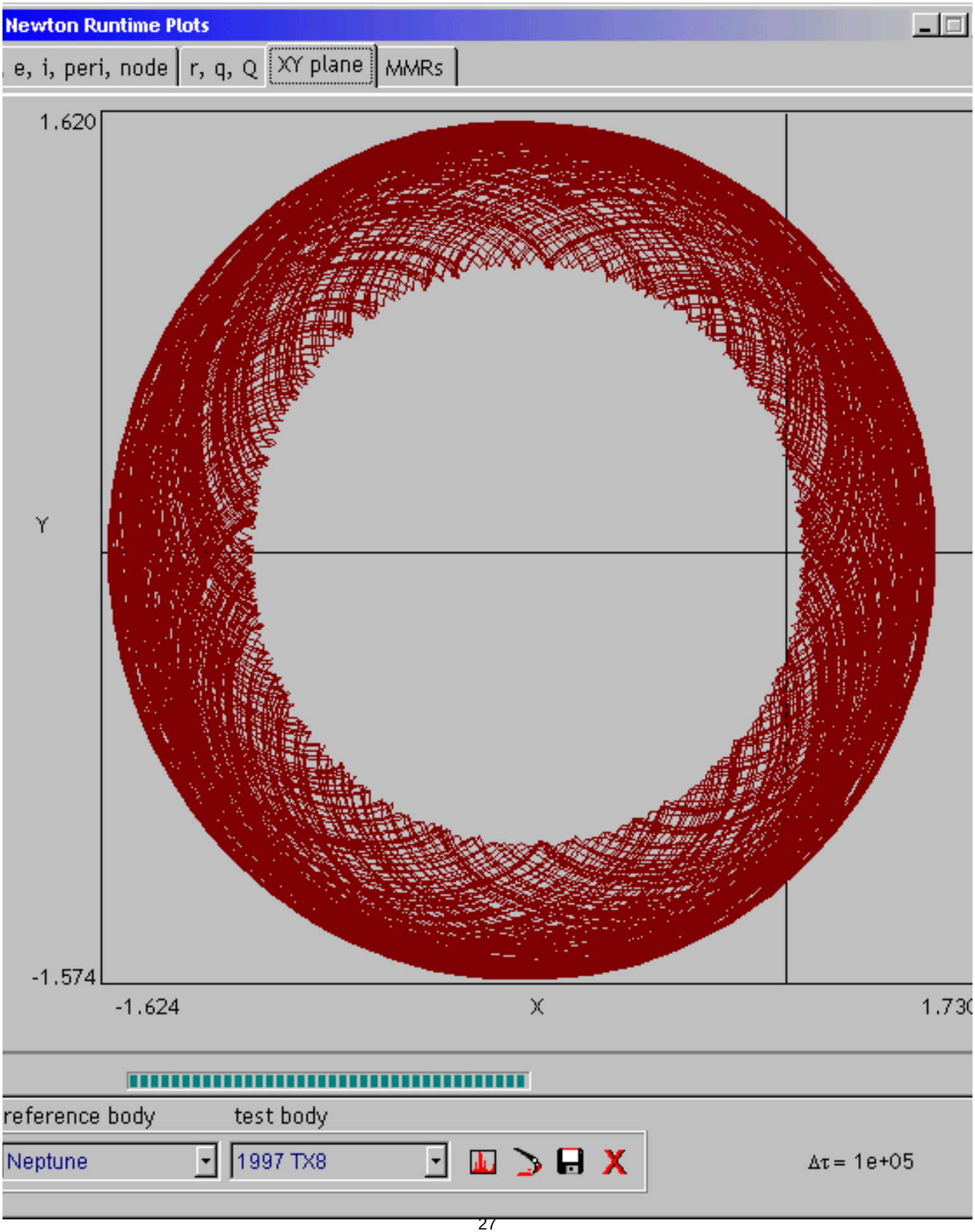

Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
266.8
s
97.09
0.000
1.000e+05
q: -1
p: 3
(p+q):p = 2:3
0
1e+0
100
2:3
39.4567
1.376
da sin s
-1.415
-1.536
da cos s
1.435
reference body
test body
Neptune
Pluto
Δτ = 1e+05

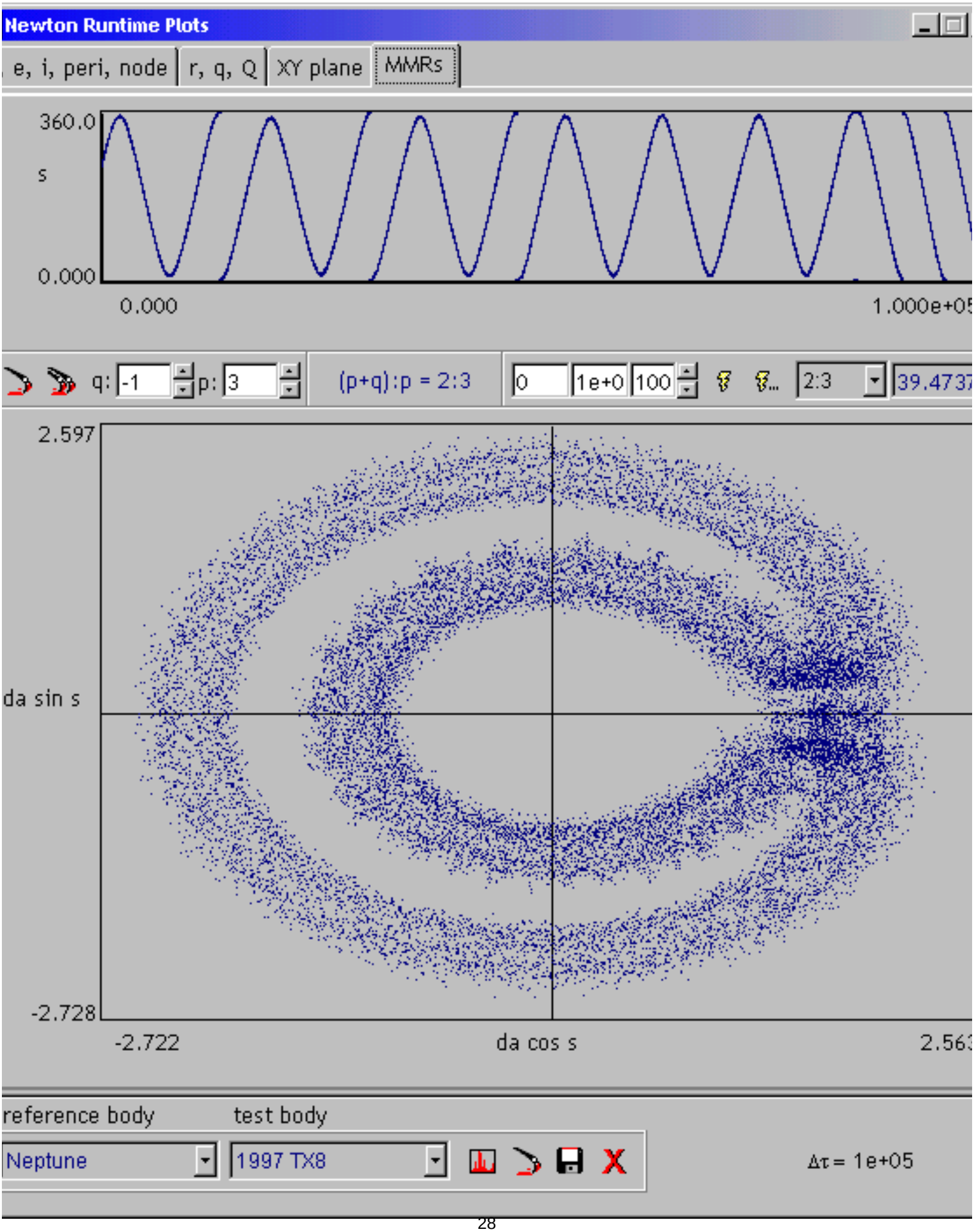

Newton Runtime Plots
e, i, peri, node
r, q, Q
[k,h]
XY plane
MMRs
peri-peri
node-node
39.99
a
38.99
0.2575
e
0.2365
17.31
i
17.09
115.8
arg peri
111.7
110.5
node
101.5
0.000
1.000e+05
reference body
test body
Neptune
Pluto
Δτ = 1e+05

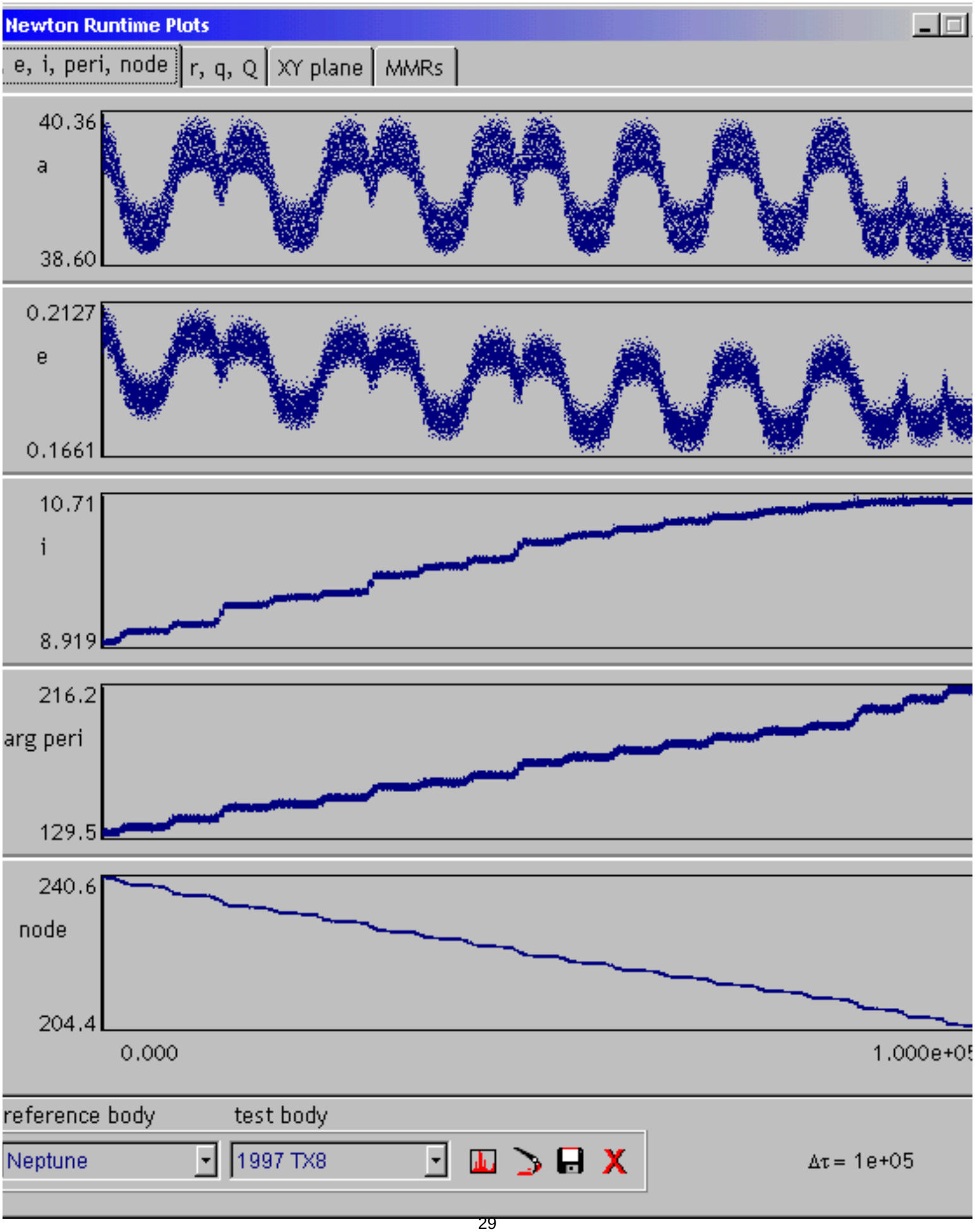

Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
1.832
Y
-1.677
-1.847
X
1.802
reference body
test body
Neptune
1994 JS
Δτ = 1e+05


Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
1.450
Y
-1.433
-1.354
X
1.374
reference body
test body
Neptune
1996 KY1
Δτ = 1e+05


Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
1.777
Y
-1.738
-1.905
X
1.821
reference body
test body
Neptune
1997 CV29
Δτ = 1e+05

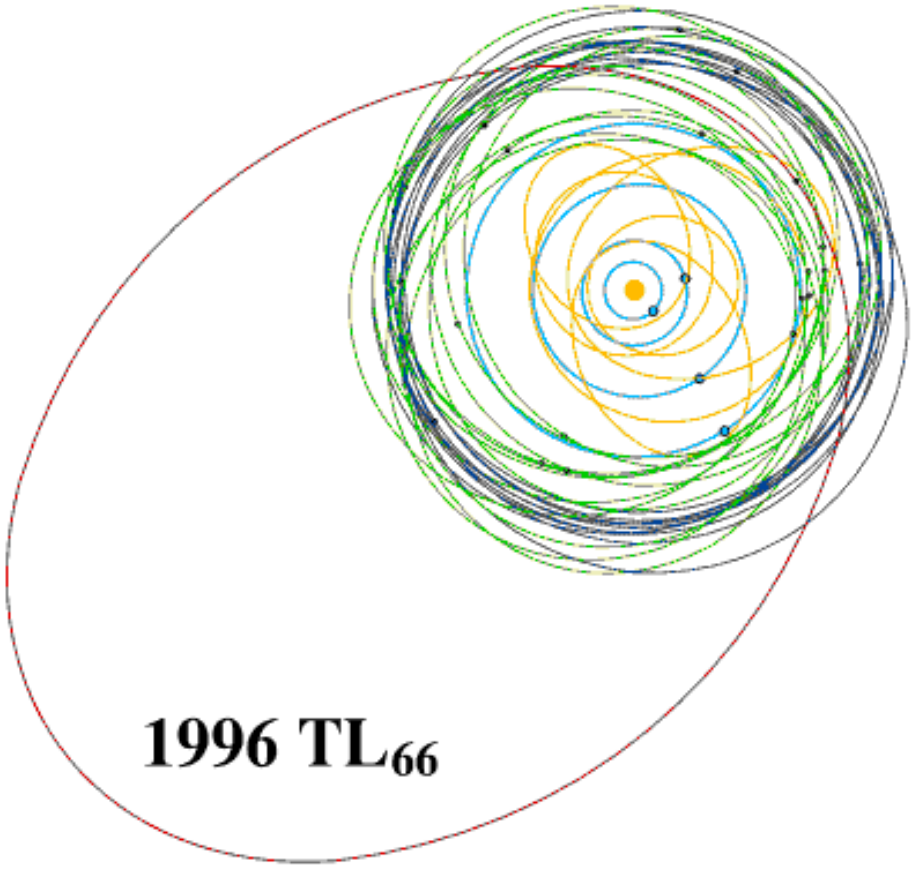

Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
1.620
Y
-1.574
-1.624
X
1.730
reference body
test body
Neptune
1997 TX8
Δτ = 1e+05


Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
360.0
s
0.000
0.000
1.000e+05
q: -1
p: 3
(p+q):p = 2:3
0
1e+0
100
2:3
39.4737
2.597
da sin s
-2.728
-2.722
da cos s
2.563
reference body
test body
Neptune
1997 TX8
Δτ = 1e+05


Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
40.36
a
38.60
0.2127
e
0.1661
10.71
i
8.919
216.2
arg peri
129.5
240.6
node
204.4
0.000
1.000e+05
reference body
test body
Neptune
1997 TX8
Δτ = 1e+05

The Orbit of 1996 TL_{66}

- Bright (R=20.9)
  Large (~500 km)
  Eccentric (e=0.58)
- New class of objects: evidence of scattering by Neptune
- Perhaps ~6400 of these scattered TNOs (Luu et al., 1997)

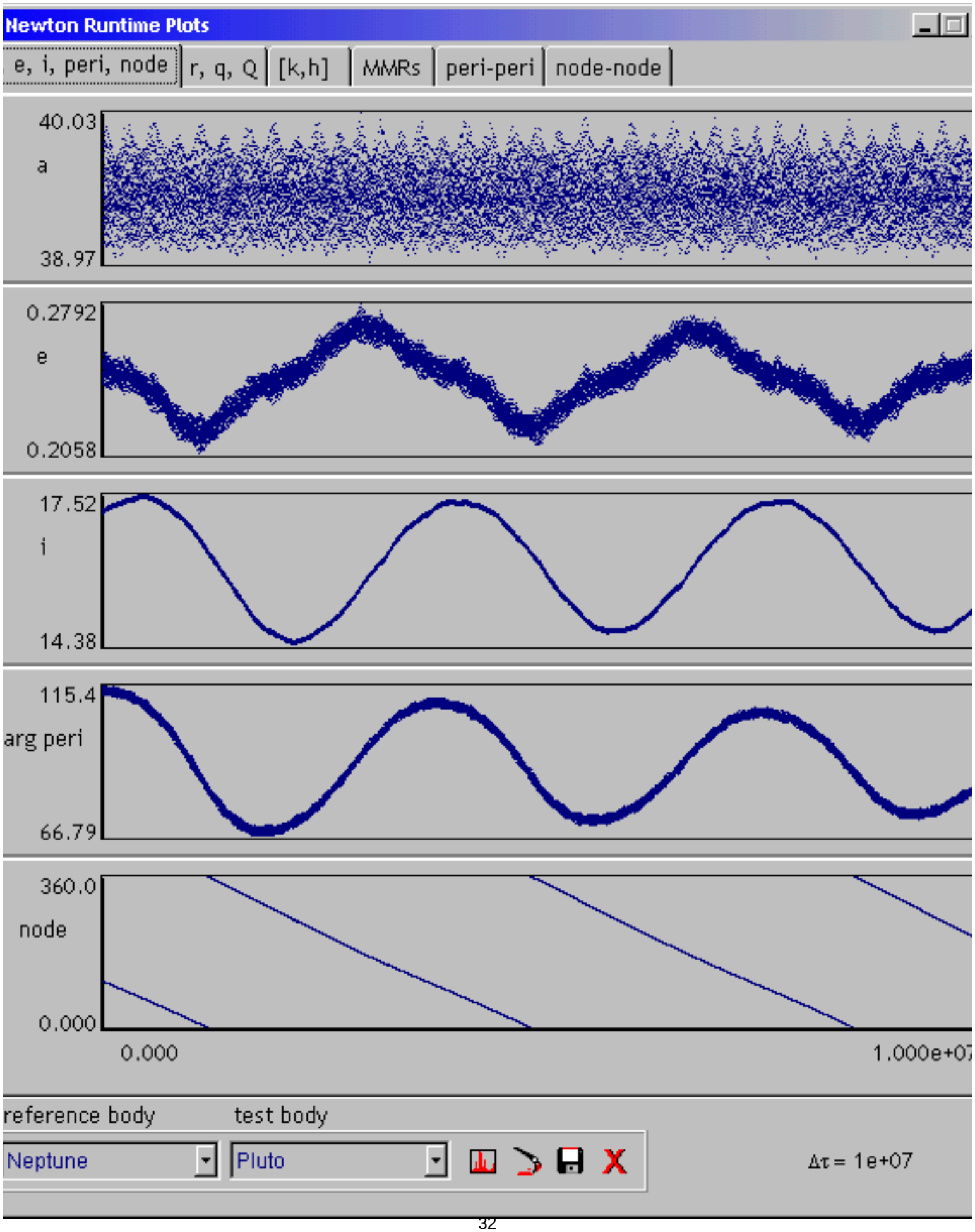


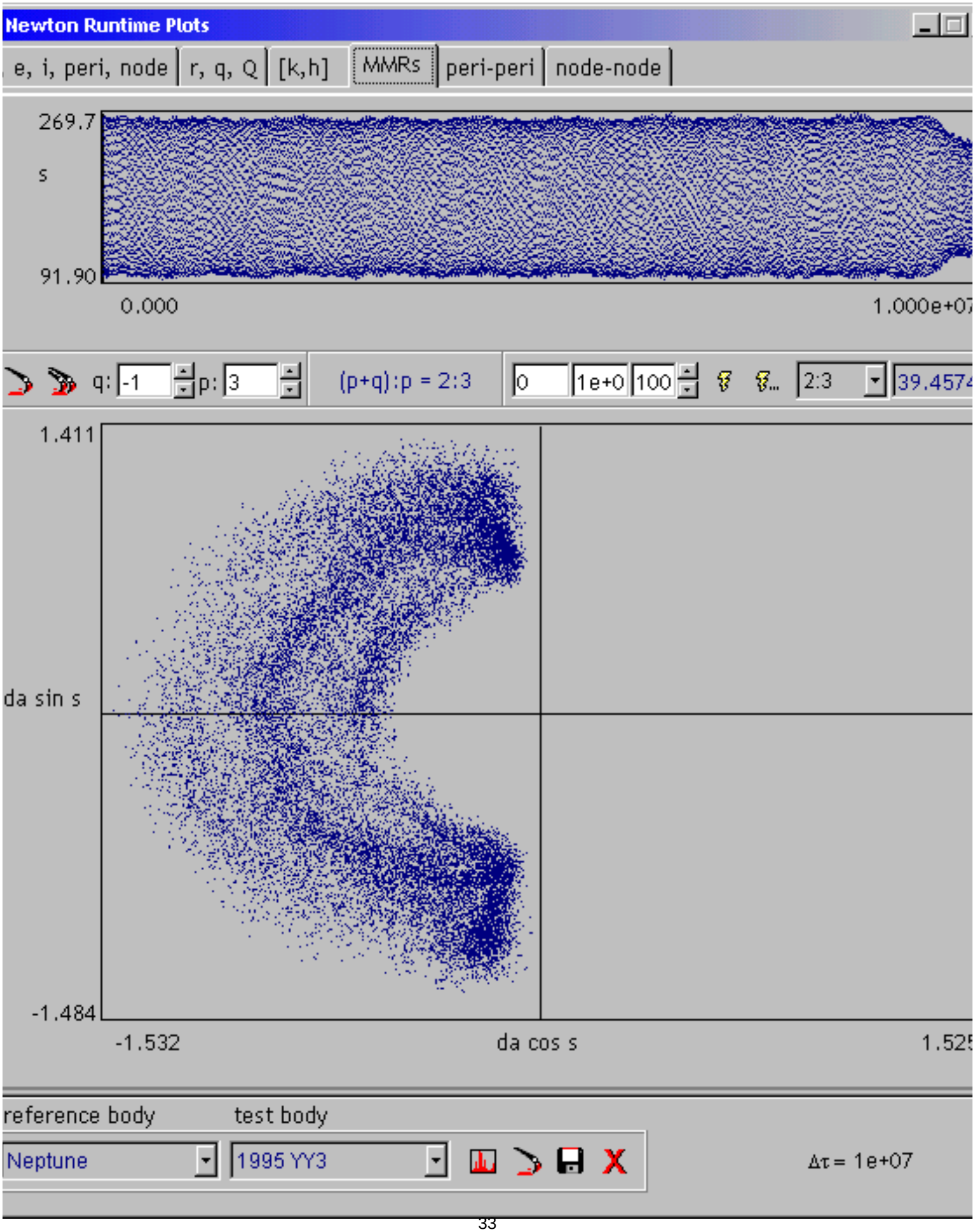
Minor Planet Center

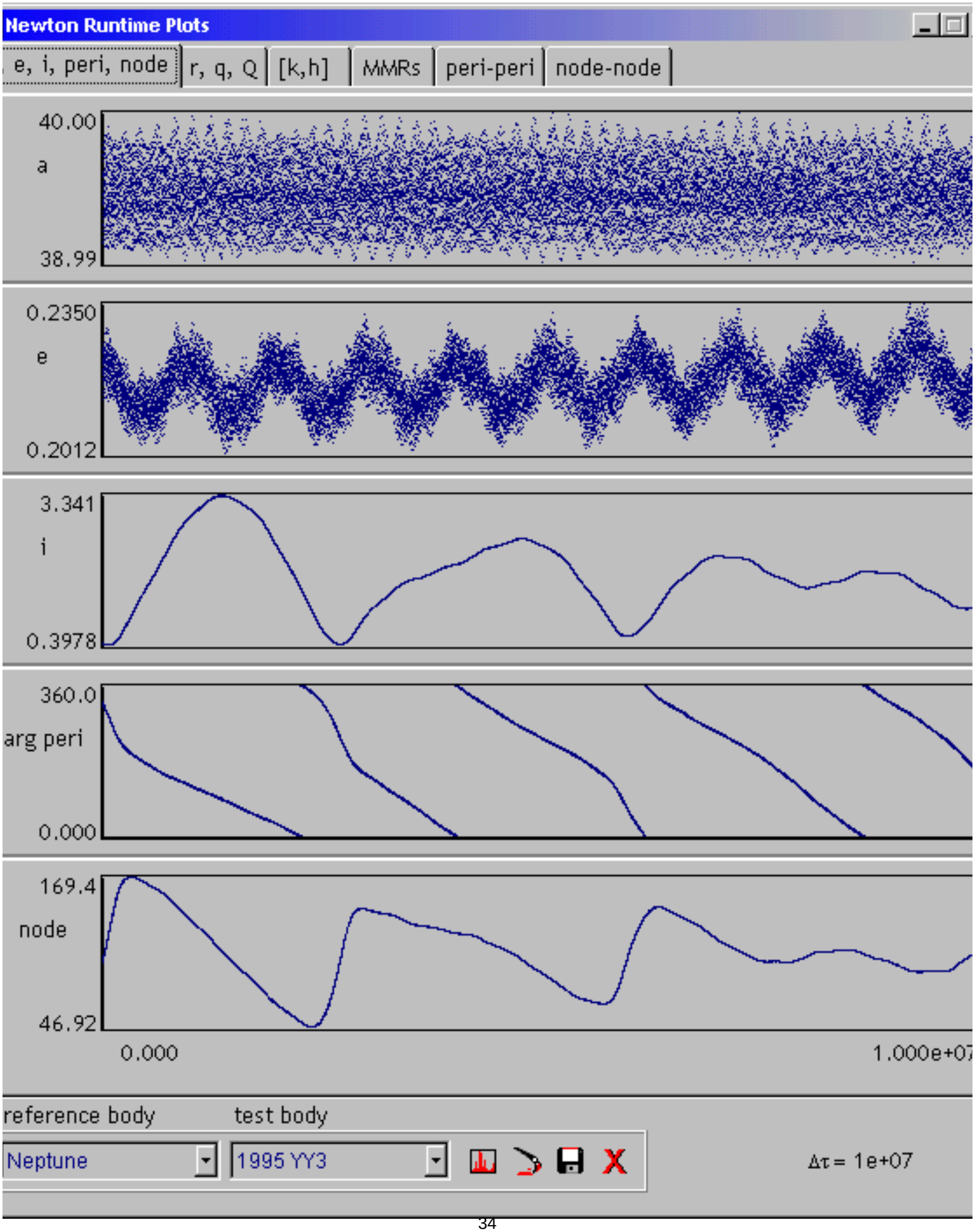
Plot prepared on 1997 June 5

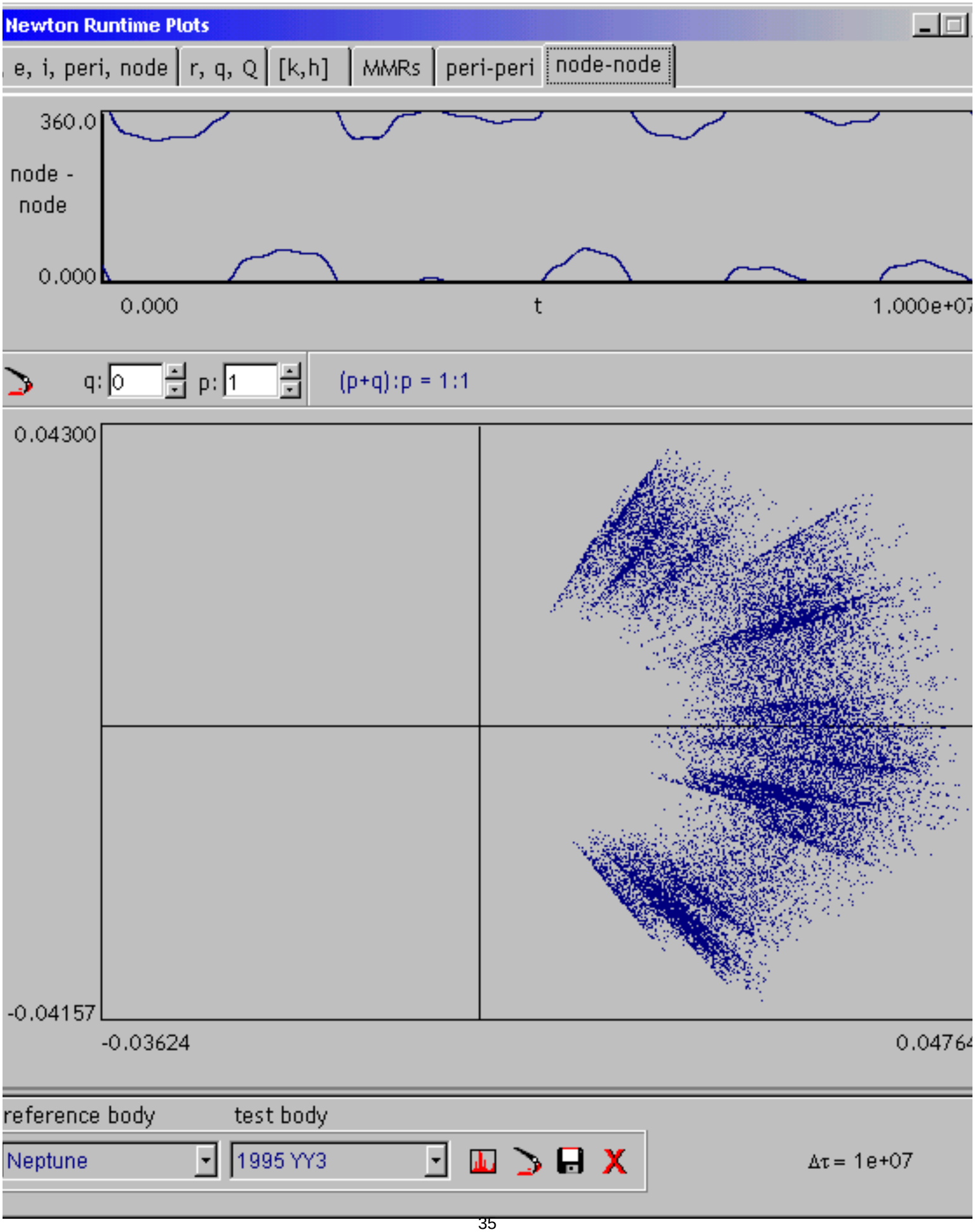
10 Myr Orbits

(calculated with Newton)

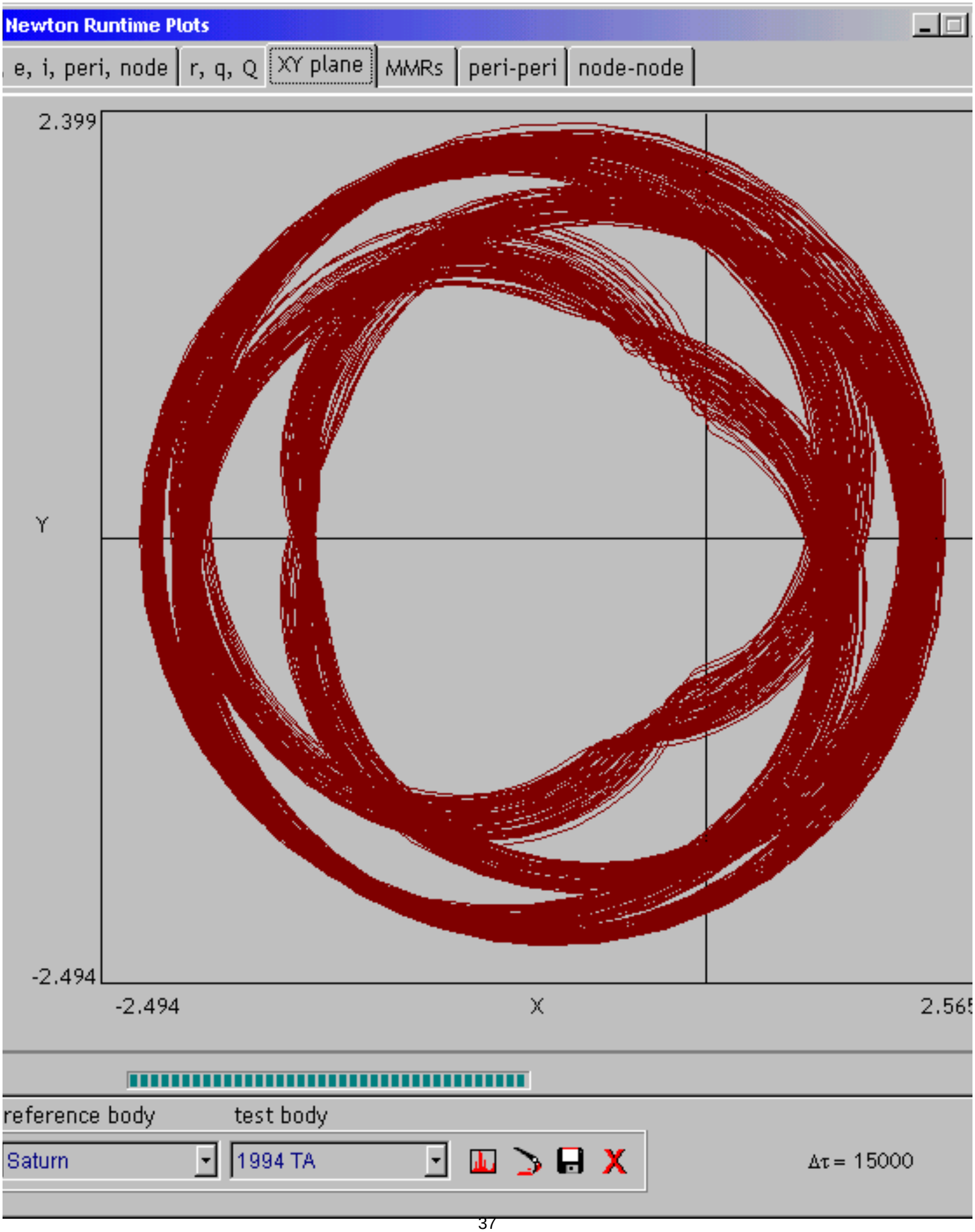

Newton Runtime Plots
e, i, peri, node
r, q, Q
[k,h]
MMRs
peri-peri
node-node
40.03
a
38.97
0.2792
e
0.2058
17.52
i
14.38
115.4
arg peri
66.79
360.0
node
0.000
0.000
1.000e+07
reference body
test body
Neptune
Pluto
Δτ = 1e+07

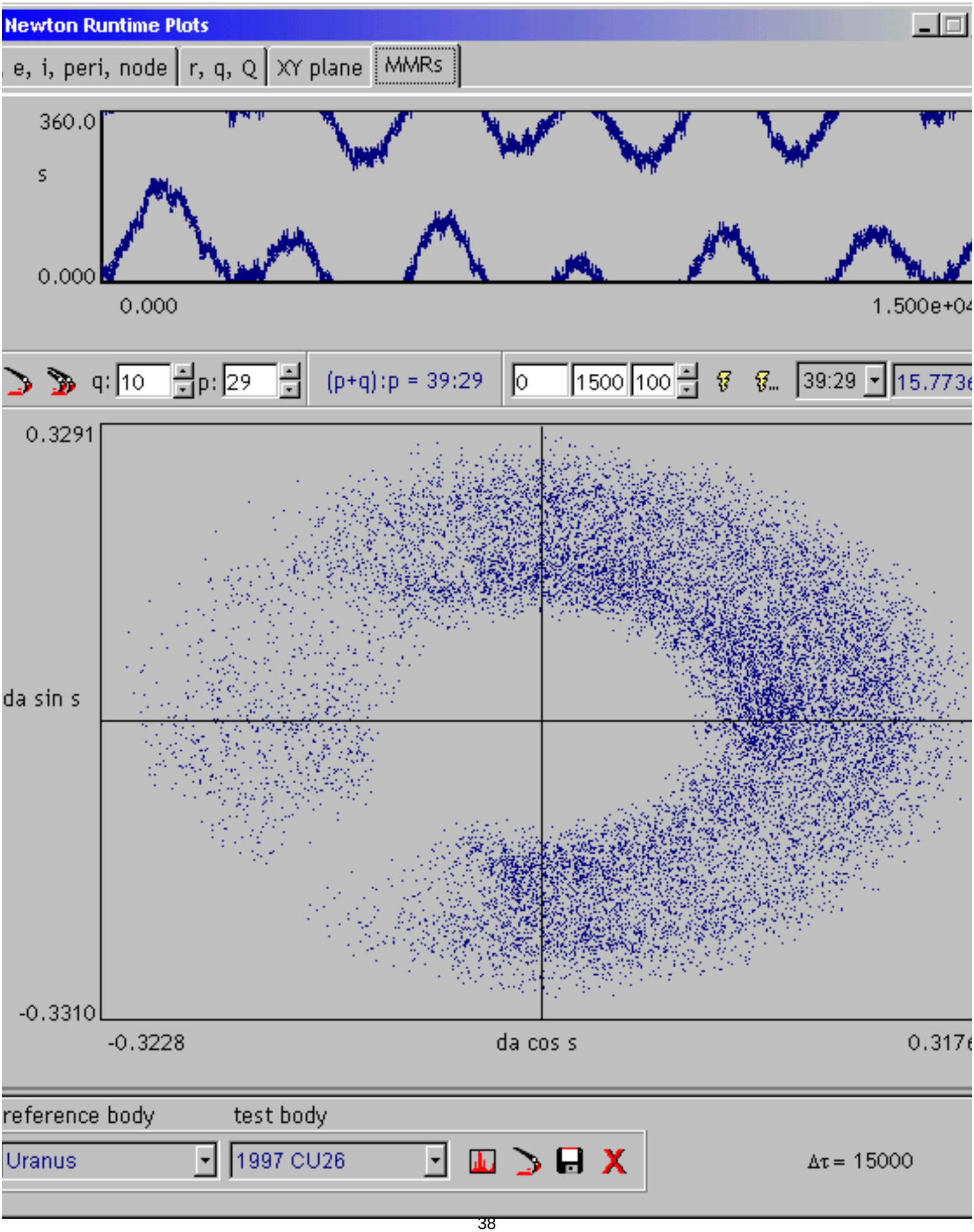

Newton Runtime Plots
e, i, peri, node
r, q, Q
[k,h]
MMRs
peri-peri
node-node
269.7
s
91.90
0.000
1.000e+07
q: -1
p: 3
(p+q):p = 2:3
0
1e+0
100
2:3
39.4574
1.411
da sin s
-1.484
-1.532
da cos s
1.525
reference body
test body
Neptune
1995 YY3
Δτ = 1e+07

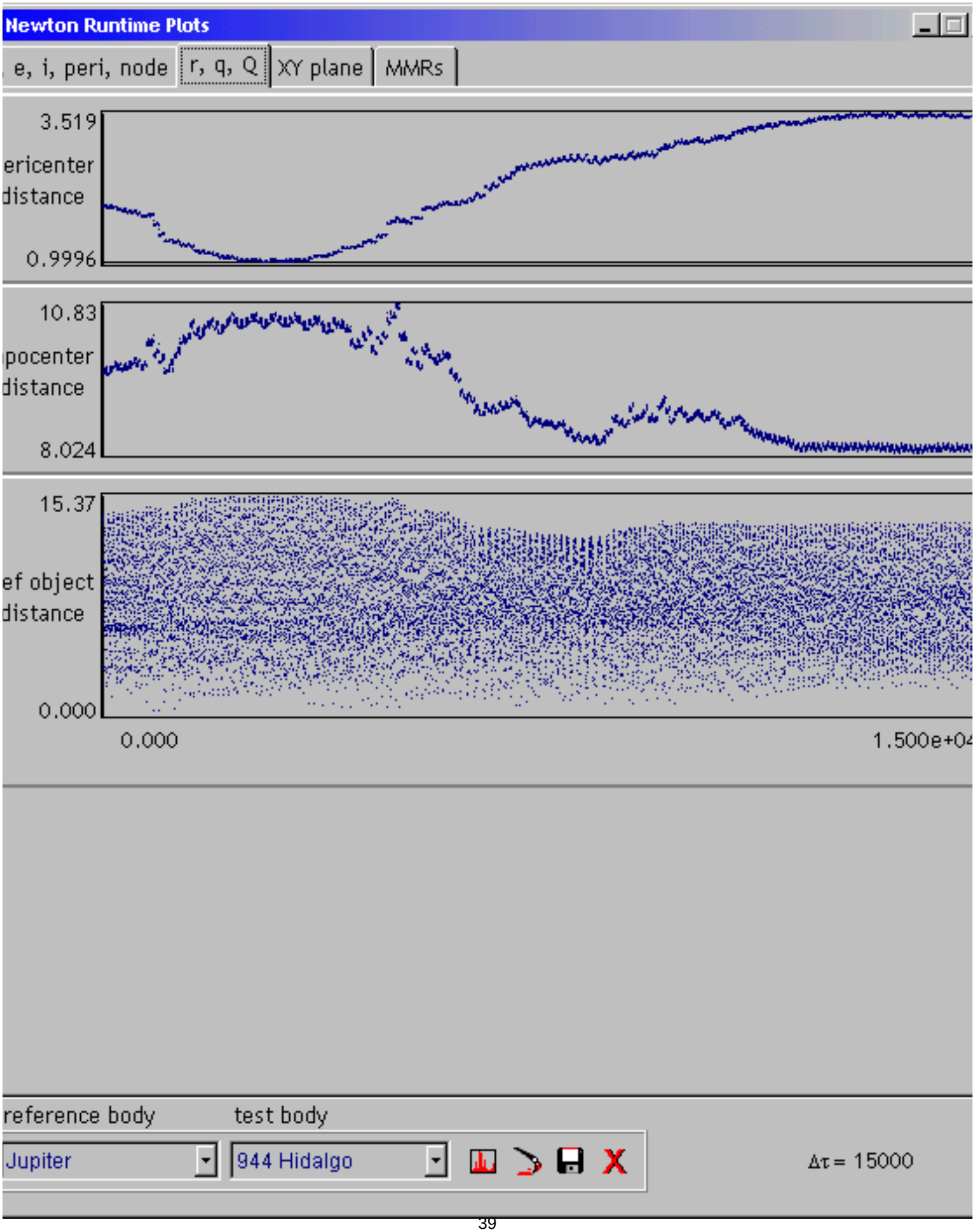

Newton Runtime Plots
e, i, peri, node
r, q, Q
[k,h]
MMRs
peri-peri
node-node
40.00
a
38.99
0.2350
e
0.2012
3.341
i
0.3978
360.0
arg peri
0.000
169.4
node
46.92
0.000
1.000e+07
reference body
test body
Neptune
1995 YY3
Δτ = 1e+07

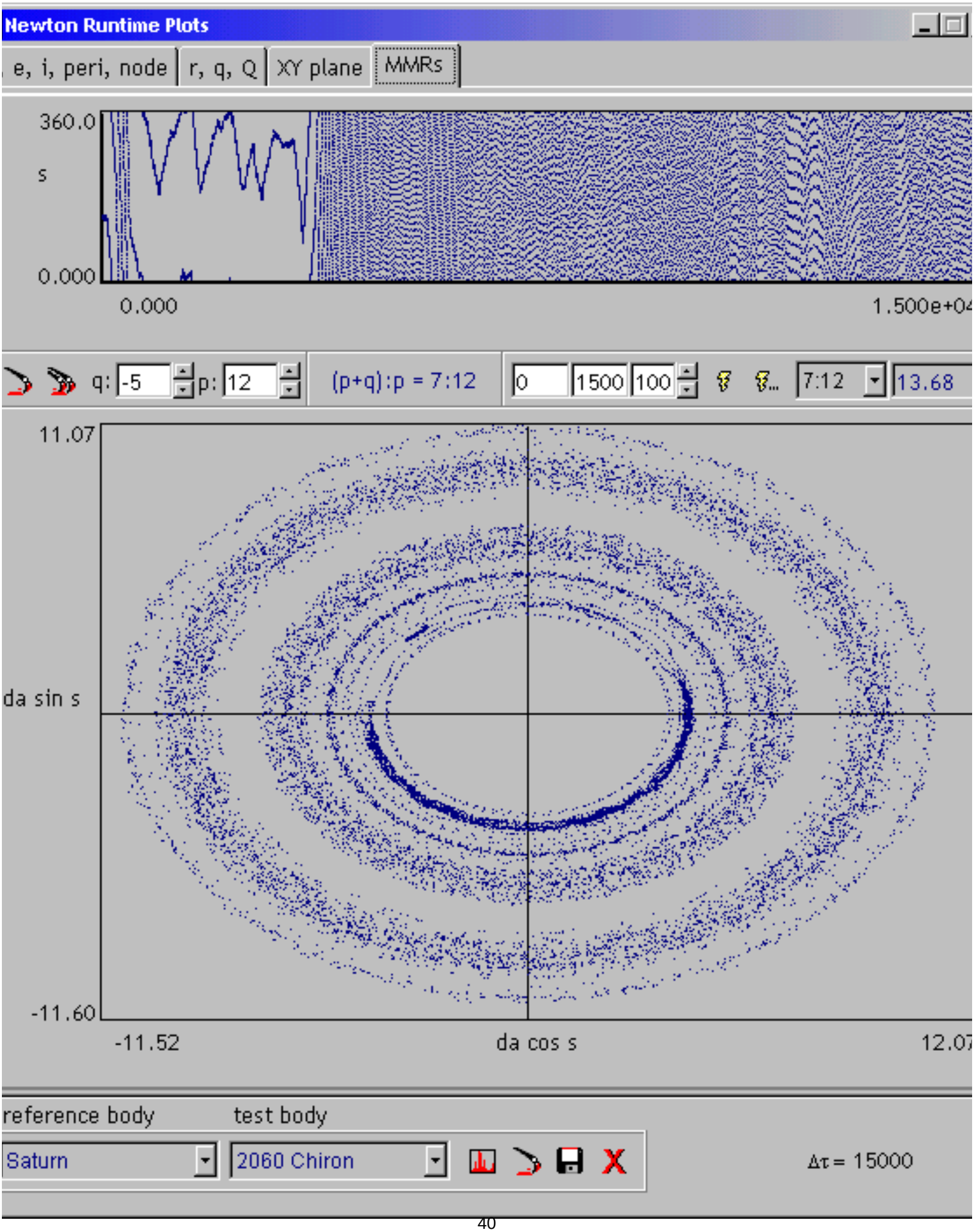

Newton Runtime Plots
e, i, peri, node
r, q, Q
[k,h]
MMRs
peri-peri
node-node
360.0
node -
node
0.000
0.000
t
1.000e+07
q: 0
p: 1
(p+q):p = 1:1
0.04300
-0.04157
-0.03624
0.04764
reference body
test body
Neptune
1995 YY3
Δτ = 1e+07

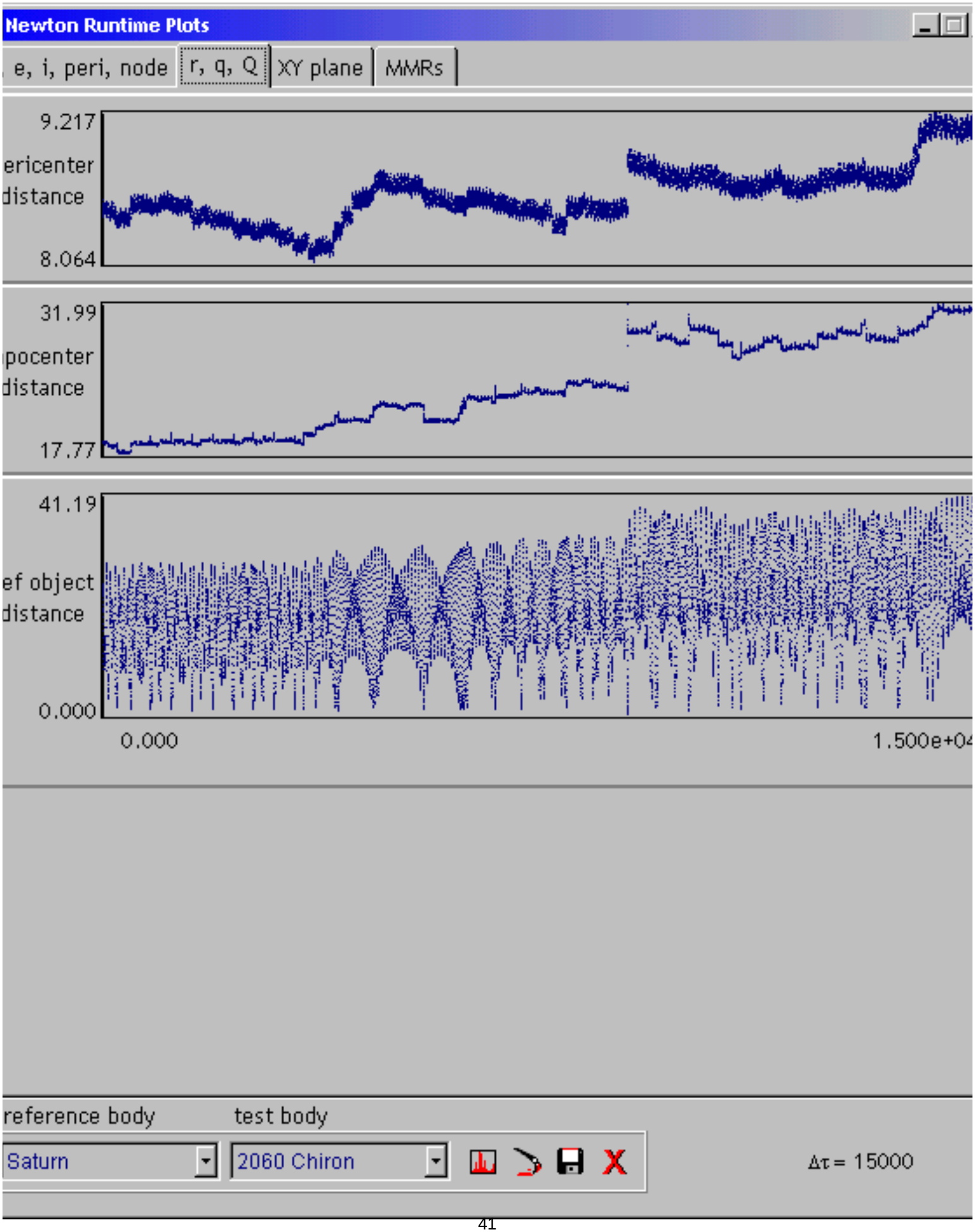
The Centaurs

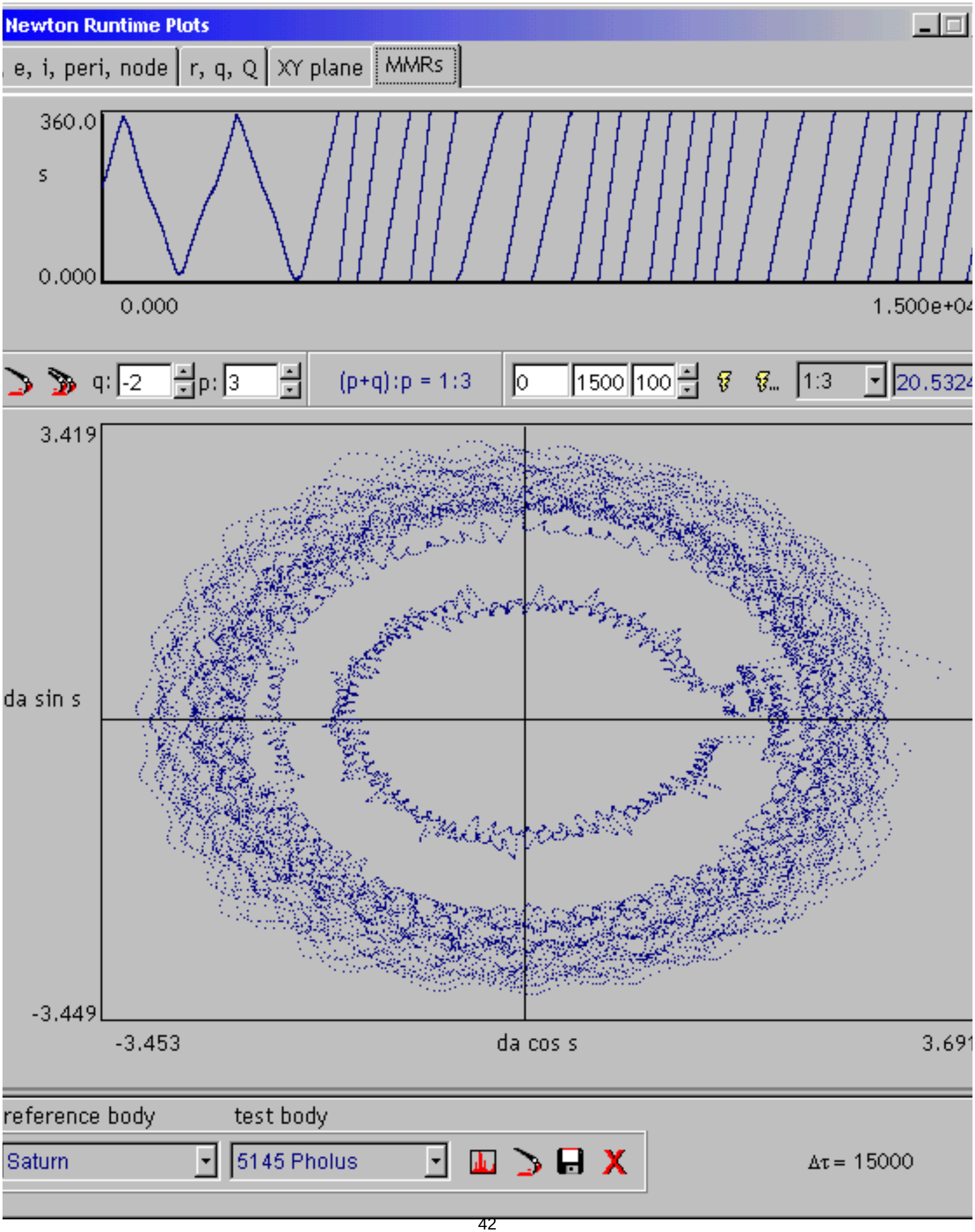

Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
peri-peri
node-node
2.399
Y
-2.494
-2.494
X
2.565
reference body
test body
Saturn
1994 TA
Δτ = 15000

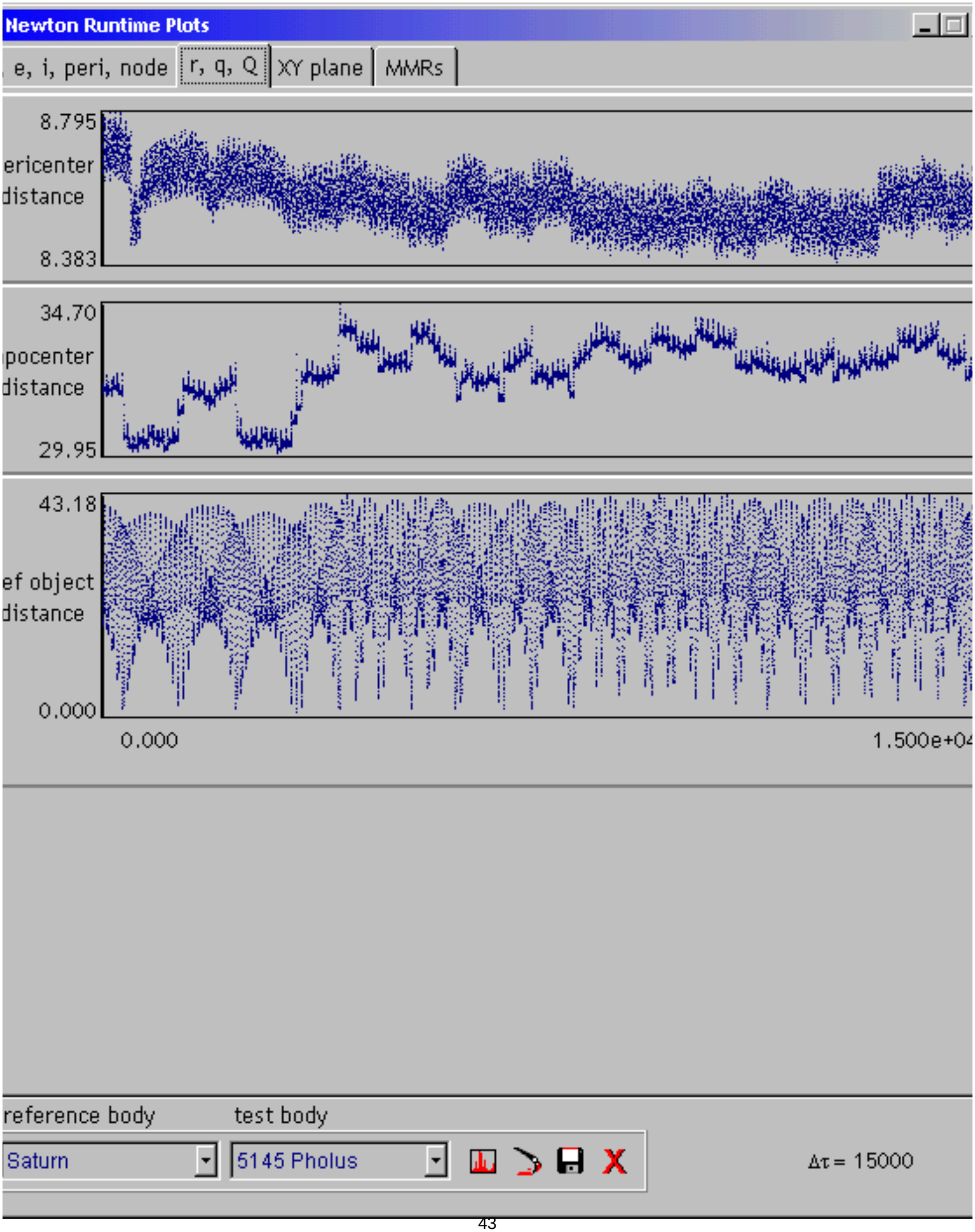

Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
360.0
s
0.000
0.000
1.500e+04
q: 10
p: 29
(p+q):p = 39:29
0
1500
100
39:29
15.773
0.3291
da sin s
-0.3310
-0.3228
da cos s
0.317
reference body
test body
Uranus
1997 CU26
Δτ = 15000


Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
3.519
ericenter
distance
0.9996
10.83
pocenter
distance
8.024
15.37
ef object
distance
0.000
0.000
1.500e+04
reference body
test body
Jupiter
944 Hidalgo
Δτ = 15000


Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
360.0
s
0.000
0.000
1.500e+04
q: -5
p: 12
(p+q):p = 7:12
0
1500
100
7:12
13.68
11.07
da sin s
-11.60
-11.52
da cos s
12.07
reference body
test body
Saturn
2060 Chiron
Δτ = 15000


Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
9.217
ericenter
distance
8.064
31.99
pocenter
distance
17.77
41.19
ef object
distance
0.000
0.000
1.500e+04
reference body
test body
Saturn
2060 Chiron
Δτ = 15000


Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
360.0
s
0.000
0.000
1.500e+04
q: -2
p: 3
(p+q):p = 1:3
0
1500
100
1:3
20.5324
3.419
da sin s
-3.449
-3.453
da cos s
3.691
reference body
test body
Saturn
5145 Pholus
Δτ = 15000


Newton Runtime Plots
e, i, peri, node
r, q, Q
XY plane
MMRs
8.795
ericenter
distance
8.383
34.70
pocenter
distance
29.95
43.18
ef object
distance
0.000
0.000
1.500e+04
reference body
test body
Saturn
5145 Pholus
Δτ = 15000

Resonance Summary

	MMR	$\Delta\sigma$ (deg)	ω	Ω	$\Omega - \Omega_N$
Pluto	2:3	163	x		
1993 RO	2:3	240			
1993 SB	2:3	138			
1993 SC	2:3	151			
1994 JR1	2:3	183			
1994 JS	3:5	122			
1994 JV	2:3	174			
1994 TB	2:3	95	x		
1994 TG2	2:3	358			
1995 DA2	3:4	160			
1995 HM5	2:3	146	x		
1995 KJ1	2:3	232		x	
1995 QY9	2:3	261			
1995 QZ9	2:3	66			
1995 YY3	2:3	172		x	x
1996 KX1	2:3	275			
1996 KY1	7:10	253			
1996 RR20	2:3	230			
1996 SZ4	2:3	145		x	
1996 TO66	11:19	300			
1996 TP66	2:3	19			
1996 TQ66	2:3	47			
1997 CR29	1:2	114		x	
1997 CV29	4:7	122		x	
1997 QJ4	2:3	198		x	
1997 RL13	1:2	97			
1997 TX8	2:3	360			
<u>Centaurs</u>					
1994 TA	3:7 S	133			
1997 CU26	39:29 U	348			
Nessus	8:33 S	250			
Pholus	1:3 S	360			
Hidalgo	6:7 J	110			
Chiron	7:12 S	180			

Review

- TNO Basic Properties
  - Outer solar system (~30-50 AU)
  - Difficult to observe
  - More "stuff" out there than in the asteroid belt — by two orders of magnitude
- Colors (and surface composition)
  - Wide range of colors so far unexplainable
  - Bimodal color population, with no readily-apparent dynamical association or known primordial cause
  - **It's a mystery!**
- Dynamics:
  - Orbital element distributions
  - Pile-up at major mean-motion resonances
    - Resonance sweeping
  - Resonance interactions create a dynamically interesting environment
  - Kuiper Belt is reservoir of short period Jupiter-family comets
  - 1996 TL_{66}: evidence of a Neptune-scattered population
- **Need more data!**