

# Inner solar system dynamical analogs of plutinos

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Manuscript pages: 24

Figures: 10

Tables: 1

**Proposed Running Head:** Inner Solar System Analogs of Plutinos

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**ABSTRACT:**

By studying orbits of near-Earth asteroids potentially in 2:3 mean motion resonance with Earth, Venus, and Mars, we have found plutino analogs. We identify 23 objects in the inner solar system dynamically protected from encounter through this resonance. Plutinos in the Kuiper belt share similar remarkable 2:3 mean motion resonant properties of Pluto with respect to Neptune. They orbit the Sun twice for every three Neptune orbits, in such a way that close approaches to Neptune are impossible. Inner solar system “plutinos” similarly avoid their respective associated planet. As many as 15% of Kuiper Belt objects share the 2:3 resonance, but are poorly observed. Since the resonant condition does not allow the secondary body to have ever been near the primary, a resonance sweeping mechanism is preferred to explain the origin of Pluto and plutinos. This mechanism likely did not operate in the inner solar system, but scattering by the next outer planet is a potential entry to 3:2 resonance with Venus and Earth. Mars plutinos, on the other hand, may be primordial objects as they are not planet crossing. The analogue resonant systems apparently arise from a different mechanism than the resonance sweeping and scattering thought to apply in the Kuiper Belt.

**Keywords:** Celestial Mechanics; Resonances, Orbital; Pluto; Asteroids, Dynamics

## 1. Outer solar system 2:3 mean motion resonance

Pluto has a remarkable 2:3 mean motion resonance with Neptune. Neptune orbits the Sun three times for each two circuits by Pluto, and Pluto in its eccentric orbit is never at perihelion when Neptune is close. In terms of mean motion this means that Pluto's is  $2/3$  that of Neptune: following Gallardo (2006) we will refer to this as a 2:3N mean motion resonance, with N representing Neptune. This allows a stable orbit for Pluto despite its orbit effectively crossing Neptune's. Pluto's motion also features libration, or systematic motion, of the whole orbit with respect to Neptune, over a period of about 20,000 years. In Fig. 1 the motion of Pluto relative to Neptune is shown for two Pluto revolutions or three Neptune revolutions. The path does not close due to the libration, and the orbit of Pluto is presently near one end of its librational swing. Although Rabe (1957) noted the 2:3N resonance in 1957, it was only in 1964 (Cohen and Hubbard, 1964), 34 years after Pluto's discovery, that the libration aspects and dynamical protection mechanism were found (see also Cohen and Hubbard, 1965). Coincidentally, the only other well-known example of 2:3 resonance, that of Mercury's spin:orbit locking, was also found near this time (Pettengill and Dyce, 1965).

### [Figure 1]

In recent years many plutinos, which share the 2:3N resonance in the outer solar system, have been discovered. Due to the observation periods being short compared to those required to show small effects, it is not sure to what extent they share this protection mechanism or other, more subtle resonances which further stabilize Pluto (Wan et al., 2003). When corrected for observational bias (Luu and Jewitt, 2002) perhaps



10% to 15% of the Kuiper Belt population in the outer solar system is in the 2:3N resonance, and may be protected from being destabilized by gravitational interaction with Neptune. Only portions of Pluto's or of any plutino's orbits (Jewitt and Luu, 1996) have been observed, due to long orbital periods. Only in the case of Pluto has the orbital interaction in 2:3N resonance been relatively well observed, although discovery in 1930 allows this to be for only about one quarter of a sidereal period. From orbital parameter statistics it would appear that most plutinos actually are trapped in the resonance (Morbidelli, 2004). The librational motion of Pluto and Neptune is characterized by an angular resonant argument  $\sigma = 2\lambda_N - 3\lambda + \varpi$ , where  $\lambda$  is the mean longitude,  $\varpi$  is the longitude of perihelion, and N denotes Neptune. This is shown in Fig. 2, librating around  $180^\circ$  with a period of 20000 years.

**[Figure 2]**

## **2. Inner solar system 2:3 mean motion resonance**

We report here the presence in the inner solar system of asteroids whose relation to Earth, Venus, and Mars, in turn, is remarkably similar to that of Pluto and the plutinos to Neptune. Due to this similarity and the wide understanding of the term “plutino”, we feel that the generic term “inner plutinos” to designate this class of resonant asteroid is appropriate. In turn, the association with each planet and resonance can be designated: Venus plutinos (3:2V); Earth plutinos (3:2E); and Mars plutinos (3:2M). No asteroid with a semimajor axis corresponding to 2:3 Mercury mean motion resonance is known, and discovery circumstances and likely stability are not favorable. The known objects are

shown in Table 1. Several new objects have been found since the initial report on inner plutinos (Connors et al., 2004).

### [Table 1]

An asteroid in 2:3 mean motion resonance with a planet must have a semimajor axis  $a_{3/2}^{2/3} = 1.3104$  times larger than that of that planet. This suggests that the resonant zones for Venus, Earth, and Mars are at 0.9478 AU, 1.3104 AU, and 1.9966 AU, respectively. Assuming a resonant eccentricity of  $\sim 0.1$ , the resonant width is approximately  $\Delta a/a = 7.2 \times 10^{-4}$  (Murray and Dermott, 1999). These limits indicated resonant zones and we examined behavior of known objects with semimajor axis placing them in or near the respective resonant zones of the inner planets.

## 2.1 Earth Plutinos

### [Figure 3, Figure 4]

We found five known objects to currently be in 2:3E mean motion resonance. For example, Earth-associated asteroid 67367 was discovered on June 7, 2002 by the LINEAR project (Stokes *et al.*, 2000) and originally designated 2002 LY<sub>27</sub>, but its orbit could subsequently be traced back to 1976, and thus is extremely well known. Its orbit in space relative to Earth bears great resemblance to that of Pluto relative to Neptune (Fig. 3), and the minimal distance between the orbits is 0.045 AU (a source of detailed information about near\_earth asteroids is <http://newton.dm.unipi.it/cgi-bin/neodys/neoibo>). However, like Pluto, its longitude of perihelion and position within

its orbit prevent it from ever coming to the minimal orbit distance to the associated planet. This is reflected in the angular resonant argument shown in Fig. 4, indicating libration about  $180^\circ$  much as for Pluto, but with a much shorter timescale of 430 years. Unlike the case for all plutinos, where only a small portion of even one orbit has been observed (see Fig. 1), not only the orbit but a meaningful portion of the librational motion have been observed for this object. The elements, some also subject to libration in the 2:3 resonance, have also been observed to vary, and their computed variations over 600 years, showing more than one libration, are shown in Fig. 5. In terms of physical properties, the H magnitude of 17.2 implies a diameter of 1 to 2.5 km. It appears to be a reddish object, with V-R possibly 1 or larger, although no intercalibrated color measurements appear to be available. Some of the other Earth plutinos are notably smaller, but for the timescales considered, an object of this size will not be notably affected by the Yarkovsky mechanism.

### [Figure 5]

Having examined the orbital properties of other objects with similar semimajor axis  $a$ , we also find asteroids 2005 GP<sub>21</sub>, 2001QE<sub>96</sub>, 2000 YJ<sub>11</sub> and 2002 AV<sub>31</sub> to be librating in 2:3E resonance. As shown in Table 1, these librating objects are close in  $a$  to the nominal value of 1.31037 AU required for resonance. We also find the eccentricities of 67367, 2005 GP<sub>21</sub>, 2000 YJ<sub>11</sub> and 2002 AV<sub>31</sub> to be in the limited range of 0.213 to 0.250, comparable to that of Pluto. The inclinations range from  $7^\circ$  to  $19^\circ$ , typical values for asteroids, with Pluto included in this range. Some aspects of the motion of Pluto are not reproduced: its libration of  $\varpi$  about  $90^\circ$  is associated with the Kozai resonance (Nesvorný and Roig, 2000). None of the Earth-resonant objects has values of  $\varpi$  near this value. Only

one known plutino shows this resonance. The presence of the 2:3E resonance and absence of Kozai resonance enhance the resemblance of the dynamics to that of plutinos.

Since asteroids in this libration mode spend little time near opposition as seen from Earth, there is an observational selection effect acting against their discovery. This is made clear in Fig. 3 where part of the motion is indicated by dots equally spaced in time. As already pointed out by Cohen and Hubbard (1965), the loops in the corotating frame trajectory are the location relative to the planet where such objects spend a relatively large amount of time, and opposition a considerably lesser amount. As seen from Earth in the case of 2:3E, elongations far from opposition, and at some times near the Sun in the sky, are the best places to search for 2:3E objects, yet most present searches concentrate on the opposition region. Thus the objects mentioned here are likely only representative of a larger population, undersampled by current searches.

## 2.2 Venus Plutinos

In the case of Venus, the asteroid 5381 Sekhmet had been noted to be in 2:3V (V for Venus) mean motion resonance (Bykova and Galushina, 2002). By coincidence, this object has been found to share (Nolan *et al.*, 2003; Neish *et al.*, 2003) the binary nature of Pluto-Charon (whose recently discovered outer satellites (Weaver *et al.*, 2006) are quite small). We have further found that asteroid 2000 ET<sub>70</sub> is also resonant with Venus. Apart from having  $a$  close to 0.947 AU required for resonance, the orbits of these objects are not markedly similar (see Table 1). Sekhmet's eccentricity of 0.296 is slightly larger than

that of Pluto and the Earth plutinos, but its inclination of nearly  $50^\circ$  is considerably larger than that of any other object studied here. 2000 ET<sub>70</sub> has a low eccentricity orbit that does not cross that of Venus, and an inclination slightly exceeding that of Pluto. Sekhmet's resonant argument librates with a period of about 390 years, and that of 2000 ET<sub>70</sub> has a large amplitude and period of 383 years. We find that both of these objects are in a short-lived libration, and in both cases it is nearly ending after having been effective for only several hundred years. Sekhmet at present makes close approaches to Earth approximately every 12 years and 2000 ET<sub>70</sub> makes paired close approaches, also every 12 years at present. The effect of these on orbital parameters is shown in Fig. 6. Such approaches limit the lifetime of these objects.

#### **[Figure 6]**

Inner solar system objects with small eccentricity are difficult to discover due to being apparently near the Sun in the sky at all times. Only in certain cases do large eccentricity objects come to opposition as seen from Earth. Due to having large parts of their orbit inside that of Earth, once more there is a selection effect, acting against discovery of objects in this resonance with Venus.

### **2.3 Mars Plutinos**

Sixteen asteroids of many near the semimajor axis needed for resonance have been found to be in (2:3M) resonance with Mars: these are 12008 Kandrup, 37479, 76828, 1999 RO<sub>37</sub>, 2000 RO<sub>8</sub>, 2001 RT<sub>46</sub>, R001 XB<sub>48</sub>, 2002 SS<sub>28</sub>, 2002 GO<sub>6</sub>, 2002 TQ<sub>31</sub>, 2003 AJ<sub>34</sub>, 2003 EP<sub>43</sub>, 2003 GK<sub>21</sub>, 2004 CN<sub>50</sub>, 2004 DJ<sub>25</sub>, and 2005 CU<sub>5</sub>. Their orbital

parameters are listed in Table 1. We also noted resonant behavior for 2005 TM<sub>55</sub>, 2005 UT<sub>107</sub>, and 2005 ER<sub>224</sub>, but have not regarded these short-arc orbits as reliable enough to class these objects as Mars plutinos. 2005 CU<sub>5</sub> is identical to 2003 QX<sub>6</sub>, thus having a good orbital determination. Despite its recent discovery, 2004 CN<sub>50</sub> has had its orbit linked back to 2001 (<http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo> is the source for this and most other asteroidal reference information in this work), making it well determined. We have integrated this orbit back 500,000 years and find that it is in resonance with Mars over that time period. The stable Mars plutinos have orbits crossing no planet's but Mars, which they avoid due to the resonance dynamics. This avoidance of planetary encounters explains the long-term stability of their orbits.

There are enough Mars plutinos that some statistical aspects may be examined. The limits where objects with similar orbital parameters to those librating no longer librate are  $a=1.9953$  AU and  $a=1.9978$  AU (in current osculating semimajor axis). The average  $a$  for the zone is 1.99655 AU, which compares well with the 1.9966 AU nominal value of the center of the resonance. The width of libration of 0.0025 AU corresponds to  $\Delta a/a=1.24 \times 10^{-3}$ , about twice the nominal value. However, that value does not take into account inclination, and assumes circular orbits. Thus the agreement is acceptable. The average eccentricity of the Mars plutinos is 0.21 but with a standard deviation of 0.096. The average inclination is 17° with standard deviation of 7.4 °. Thus the view that inner plutino orbits must be “Pluto-like” in being eccentric and inclined is supported somewhat: these are of course general characteristics of asteroid orbits in any case. The true test of trapping in the resonance is libration, and we have found that of 30 asteroids

in the range indicated above, 19 show long-term resonant behaviour (including the three short-arc objects). Several other objects show a relatively slow circulation of the resonant argument of the resonance and may be nearly trapped. Over the small resonant range in  $a$ , the 2:3 resonance has noticeable effects. However, we do not find that there is an excess of known asteroids in the vicinity of the resonance to the point that one would call it a Kirkwood-type enhancement, nor is the region of 2:3 trapped bodies prominent on a graph of  $a$  versus  $i$  or  $e$  as is the case for the plutinos (e.g. Luu and Jewitt, 2002).

Despite being located slightly inside (i.e. sunward of) the 4:1J mean motion resonance with Jupiter, the position of a Kirkwood gap depleted of asteroids, Mars plutino dynamics is apparently dominated by Mars, and likely has been on the time scale of the Solar System. We advance the possibility that Mars-zone solar nebula material may be trapped in this resonance, and it would be useful to conduct spectral studies. Since these Mars-resonant objects can have favorable oppositions as seen from Earth, their orbits tend to be well-determined and there is no particular selection effect acting against their discovery. Since there are preferred spots in the Mars corotating frame (the “loops”) where Mars plutinos are slow-moving with respect to Mars, there are places where Mars plutinos are most likely to be discovered. However, the loop zones are quite large in extent on the sky and directed searches in these areas are not likely to be fruitful compared to the current all-sky searches already underway.

### 3. Method

We examined candidates initially selected to now be in or near the resonant zones described above, and determined numerically whether libration was taking place. In most cases studied, an initial integration over a 600 year period was done using the Horizons online system at JPL (Giorgini *et al.*, 1996). While checking the motions of objects with  $a$  near the value needed for resonance, in many cases it was clear that objects were currently nonresonant, and these objects were not followed up. For those of interest a longer run using the Mercury integrator (Chambers, 1999) allowed us to examine the resonant argument. All nine planets were included. Further calculations on most objects included here were also done with the Wisdom-Holman algorithm (Wisdom and Holman, 1991) with a time step of several days, and in some cases with another symplectic algorithm (Mikkola and Palmer, 2001). In all such cases substantial agreement between the results of the various codes was seen.

To study changes in orbital behavior, the Mercury integrator was used with large output time steps to near the time that a change of interest was noted. Then small output steps were used to study the circumstances. Such small steps, as little as one day, are needed if close approaches are to be properly characterized.

Although objects discussed in detail here have well determined orbits, we have not performed clone studies which would be needed to understand chaotic effects. Since the behaviors described characterize many objects, we do not claim to provide exact descriptions of the distant past or far future of any given object, but that the dynamics described apply generally to the various sorts of inner plutinos.



## 4. Origin and lifetime

An asteroid is planet crossing if attaining perihelion distance  $q=a(1-e)$  or aphelion distance  $Q=a(1+e)$  results in crossing at least the next inner or outer planet's orbit. Due to relative motions of orbits, an asteroid of moderate inclination that has perihelion inside the aphelion distance of an inner planet, or aphelion outside the perihelion distance of an outer planet, will generally interact with that planet relatively quickly. Such interactions can lead to changes in the resonance and presumably, more rarely, larger changes that correspond to injection or extraction into a quite different orbit.

### 4.1 Venus Plutinos and Earth

By librating in  $a$  about 0.947 AU, Venus plutinos need only a very small eccentricity of about 0.05 to become Earth crossing. In addition, Venus has close to an 8:5E mean motion resonance with Earth (Chapman, 1986), so that any object resonant with Venus is already nearly in resonance with Earth. Venus plutinos thus are presumably injected or extracted mainly by Earth encounters, and the two presently known examples (5381 Sekhmet and 2000 ET<sub>70</sub>) have close encounters with Earth regularly, and short lifetimes in the 2:3V resonance. It is possible that future objects will be found which are relatively long-lived in the resonance, but at present it does not merit much discussion. The nearly 49° inclination of 5381 Sekhmet implies an origin through a very close approach and strong scattering at Earth. Whether its binary nature arose in this scattering

or is a constraint speaking against the scattering hypothesis is impossible to say at this time. In Fig. 6, the effects of Earth encounters on the elements of 2000 ET<sub>70</sub> were shown near the present when it is in resonance. This object enters and leaves the resonance intermittently over the near future but we find it to leave definitively only in approximately 12000 AD as shown in Fig. 7. At this time, the close encounters seem to accumulate stochastically to take  $a$  below the resonant region, with no particular close encounter involved. Considering the cases of Sekhmet and 2000 ET<sub>70</sub>, it appears that either very close approaches or the cumulative effect of near-resonant ones can play a role in injection or extraction in 2:3V resonance.

**[Figure 7]**

#### **4.2 Earth Plutinos and Mars**

Earth plutinos could presumably be injected or extracted by Mars or Venus encounters. The perihelion of Mars is approximately at 1.38 AU, while the aphelion of Venus is at 0.728 AU. Since in this case  $a \approx 1.3104$ , Venus crossing requires  $e \geq 0.44$ , while Mars crossing requires only  $e \geq 0.05$  approximately. Of the five known Earth plutinos, only 2001 QE<sub>96</sub> has an eccentricity (0.028) less than the value to cross Mars, while none cross Venus. Thus Mars should play a role in the orbital evolution and presumably injection or extraction of most of the known objects. Even 2001 QE<sub>96</sub> is aligned so that the minimum distance from Mars attained is near the minimum possible, and it is a small object of approximately 100 m diameter, subject to non-gravitational forces that could alter an orbit after an interaction with Mars.

**[Figure 8]**

As for Venus plutinos, both close approaches to the next outer planet and near-resonant ones are important. In this case the resonance involved is a strong first order resonance 5:4M with Mars; 2:5V with Venus is nearby as well (Gallardo, 2006) but we do not find its effects discernable. This is likely because 5:4M allows repeated close passages to Mars given the eccentricities of many of the Earth plutinos. The near-term behavior of 2000 YJ<sub>11</sub> is shown in Fig. 8. This object has a good orbit, with many observations since its discovery, so the near-term behavior shown is quite close to reality. The center of the 5:4M resonance is at 1.3130 AU, and the libration of  $a$  in the 2:3E resonance takes it to or beyond this value. When the geometry is appropriate, repeated close encounters with Mars take place and change the resonant argument of the 2:3E resonance, most notably in amplitude. On the timescale shown, some very close approaches to Mars, of order 0.001 AU, take place and step-like element changes (for example visible in  $a$  in Fig. 8) take place. However, their overall effect during this period is small compared to that of the resonant interactions. The object 2002 AV<sub>31</sub> also has a well-determined orbit, however Fig. 9 illustrates its behavior far in the future so must be regarded as indicative. In this case the object, already with a very large 2:3E librational amplitude, apparently switches into 5:4M resonance and for the most part, unlike in the previous example, avoids Mars while in that resonance. The system appears very finely balanced, as Mars approaches are in general not close.

**[Figure 9]**

### **4.3 Stability of Mars Plutinos**

Mars plutinos are not subject to planet crossing in general. Crossing Earth would require  $e \approx 0.54$ , and few of the Mars plutinos have high eccentricity. Those that do may be discerned in Fig. 10, where they are the only ones in the resonant  $a$  range that do not resonate or do so intermittently. We have not numbered these nonresonant objects, nor included them in Table 1, but discuss here some typical cases.

**[Figure 10]**

The object 2004 FP<sub>4</sub> is located in semimajor axis between the resonant objects 37479 and 76828 (23 and 24 respectively in Table 1 and Fig. 10). It has  $e \approx 0.47$  and  $i \approx 2^\circ$ , and despite not crossing Earth's orbit, it has frequent close encounters. Although at the present time its resonant argument is librating around  $180^\circ$ , this behavior is short-lived and we have not considered it to be a Mars plutino. Somewhat similar behavior is shown by 2000 PD<sub>3</sub>, with slightly lower  $a$  than 2001 XB<sub>48</sub> (22 in table and figure). This object has  $e \approx 0.59$ , making it Earth-crossing, so despite inclination of about  $8^\circ$ , it has frequent close encounters with Earth. Lower in the range of  $a$  which could permit resonance, 86819 (2000 GK<sub>137</sub>) has  $e \approx 0.51$ , and can approach closely to Earth, explaining its instability.

2004 CN<sub>50</sub> (object 14) was noted as having been in the 2:3M resonance for 500,000 years. This object has very low libration amplitude, meaning that it does not deviate much from the resonant condition of Mars avoidance. In contrast, 2004 RZ<sub>1</sub> (object 21) has a very large libration amplitude and prior to about 2000 years in the future has a circulating resonant argument. When it does circulate, it is about approximately  $90^\circ$ . This object has  $e$  of only about 0.02, so that it cannot have close approaches with Mars in any

case, so that being in the resonance does not greatly enhance its stability and it may only dubiously be considered a Mars plutino. The same applies to 2002 EB<sub>9</sub>, the unlabelled circulating object above it in Fig. 10, and both are well out of the plane of Mars' orbit on their closest encounters, keeping them further far from Mars. Asteroid 2001 TN<sub>103</sub>, the slowly circulating object between 2002 SS<sub>28</sub> and 2004 DJ<sub>25</sub> (objects 11 and 12 respectively), shares similar properties that make circulation relatively stable, despite a somewhat larger eccentricity of 0.08. As noted, 2004 RZ<sub>1</sub> does enter the resonance eventually, but there appears to be a class of low eccentricity objects associated with Mars that can be relatively stable near, but not in, the 2:3M resonance. These objects have slow circulation of the resonant argument which may switch to large-amplitude libration. Objects with a larger eccentricity, such as 2004 CN<sub>50</sub> with  $e \approx 0.18$ , can be stable in the resonance if their libration amplitude about 180° is small, making them have Pluto-like orbits with avoidance of the associated planet. Since Mars' orbit itself has large eccentricity, the limits on the amplitude of the angular argument before encounters with the planet affect the resonant motion are more severe than in the case of most other planets. This is reminiscent of the effects of Mars' eccentricity on its own co-orbital objects (Connors et al., 2005).

## 5. Other behaviors

For some objects close in  $a$  to Earth plutinos, we have noted that it is possible to see libration of the resonant argument about 0° rather than 180°. We have not included them as Earth plutinos since their behavior is strange and unstable. These objects are 1999

VF<sub>22</sub>, 2004 FA<sub>5</sub> (as of about 2000 years ago), and 1996 AJ<sub>1</sub> (about 1kyrs ago, and 2.5kyrs in the future). Both 1999 VF<sub>22</sub> and 1996 AJ<sub>1</sub> have extremely eccentric orbits, with  $e = 0.738$  and  $e = 0.781$  respectively. The former has a 23 day arc and the latter a 9 year arc, so that the latter at least is a well established orbit. Such objects are usually discovered on close approaches to Earth which sample a small portion of the space available to them. Thus they could be representative of a larger population. In contrast, 2004 FA<sub>5</sub> has a relatively small eccentricity. It has only a four day arc so that we cannot consider its orbit well known, and we will not discuss it further here.

The highly eccentric objects open the possibility that relatively stable 2:3 resonant motion can be stable at high eccentricity since encounters with the associated planet are then distant. For example, 1996 AJ<sub>1</sub> has very close approaches in this epoch with Mercury, Mars and Venus, but not as close to Earth. Such potentially stable, high-eccentricity orbits are not stable in our solar system since they imply multiple planet crossing. However, there may be orbits in this class in other planetary systems.

## 6. Conclusions

The outer Solar System plutinos were likely captured into 2:3N resonance due to resonance sweeping accompanying radial migration of Neptune (Malhotra, 1995). In some ways this mechanism is similar to that proposed for the origin of Mercury's spin:orbit coupling, in which changing orbital eccentricity sweeps through the conditions needed for resonant lock (Correia and Laskar, 2004). The timing of a giant collision that led to the duplicity of the Pluto-Charon inner system relative to migration is unclear

(Canup, 2005). However our understanding of resonance sweeping continues to improve, and migration seems the most likely way in which to understand the present-day dynamics of Pluto and the plutinos (Morbidelli, 2004; Wiegert, 2003). This mechanism was not dominant in the early inner Solar System, and other mechanisms are responsible for the dynamics of “inner plutinos”.

The same interactions with the next outer planet that limit the lifetime of Venus and Earth plutinos presumably also account for their injection into the resonance. These are likely not primordial objects since the conditions of resonance appear to need a relatively high eccentricity and thus for Venus and Earth, the plutinos are necessarily planet-crossing and subject to disruptive perturbations from Earth and Mars, respectively. On the other hand, some Mars plutinos appear to have been in the 2:3M resonance for lengthy periods. If they have been trapped in this resonance since the beginning of the solar system, there could be interesting cosmogonic information associated with them. A spectroscopic investigation could reveal whether there are any common physical properties possibly reflecting a common formation zone in the solar nebula.

Inner plutinos also offer the possibility to study the dynamics of the 2:3 mean motion resonance with observational timescales allowing libration and other potential subtle details to be measured and compared to theory. Their lifetimes and injection/extraction rates should inform studies of transport of asteroids in the inner solar system.

## **Acknowledgements**

We wish to thank D. P. Hube for use of space and computing facilities. The Canada Research Chairs program and NSERC provided partial support. Use of the public asteroid and dynamics facilities of the University of Pisa and Jet Propulsion Laboratory, via Internet, is gratefully acknowledged.

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Table 1. Osculating orbital elements on MJD 53200 for 5381 Sekhmet and 2000 ET<sub>70</sub> associated with Venus, five 2:3E librators associated with Earth, seventeen 2:3M librators associated with Mars (from AstDys), and for Pluto.  $\varpi = \Omega + \omega$ . The number (#) column corresponds to numbering in Fig. 10. Elements cited from <http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo>.

Object	#	a (AU)	e	i (deg)	Asc node	Arg Peri	M	Long Peri
					(deg) $\Omega$	(deg) $\omega$		(deg) $\varpi$
5381 Sekhmet	1	0.947455	0.296058	48.971	58.565	37.422	210.605	95.987
2000 ET <sub>70</sub>	2	0.946917	0.123499	22.323	331.213	46.355	33.891	17.568
2005 GP <sub>21</sub>	3	1.308261	0.224529	18.79693	10.058988	1.251084	1.905944	11.310072
67367 2000 LY <sub>27</sub>	4	1.30862	0.212712	9.022	264.6	184.723	56.505	89.323
2001 QE <sub>96</sub>	5	1.310477	0.027692	7.25575	150.317593	278.798667	237.431216	69.11626
2000 YJ <sub>11</sub>	6	1.3115	0.23118	7.264	65.066	338.943	158.269	44.009
2002 AV <sub>31</sub>	7	1.31161	0.250052	14.977	119.423	267.123	305.056	26.546
2003 AJ <sub>34</sub>	9	1.995349	0.209114	3.541108	171.487663	292.065294	188.65716	103.552957
2003 EP <sub>43</sub>	8	1.995375	0.123441	24.3328	183.991957	309.620757	193.247669	133.612714
2002 TQ <sub>31</sub>	10	1.99573	0.121264	22.295	197.36	195.946	218.27	33.306
2003 GK <sub>21</sub>	17	1.996063	0.270143	6.739574	66.244152	345.10195	288.600654	51.346102
2002 SS <sub>28</sub>	11	1.9961	0.237733	20.528644	252.811942	120.309577	224.987001	13.121519
2004 DJ <sub>25</sub>	12	1.996265	0.268697	6.740936	184.862041	251.504441	106.706713	76.366482
2004 CN <sub>50</sub>	14	1.99634	0.180487	17.145	347.864	248.489	346.961	236.353
2002 GO <sub>6</sub>	13	1.99637	0.11997	20.374	213.008	130.397	163.285	343.405
2001 RT <sub>46</sub>	16	1.996389	0.315416	23.274075	151.983729	267.877352	328.797888	59.861081
1999 RO <sub>37</sub>	19	1.99656	0.314439	20.039	144.462	268.979	224.04	53.441
12008 Kandrup	15	1.99657	0.316204	29.74	263.41	344.815	15.803	248.225
2005 CU <sub>5</sub>	20	1.9968885	0.0965804	20.13121	328.63091	236.61246	82.16867	205.24337
2004 RZ <sub>1</sub>	21	1.997071	0.022607	20.63472	232.42433	85.902717	170.46771	318.327047
2000 RO <sub>8</sub>	18	1.997417	0.344277	17.945564	180.356056	234.196574	99.987248	54.55263
2001 XB <sub>48</sub>	22	1.99753	0.105013	12.32	325.308	220.317	256.876	185.625
76828 2000 SL <sub>161</sub>	24	1.9976	0.22188	11.693	245.416	27.905	199.868	273.321
37479 1130 T-1	23	1.99777	0.277961	7.748	196.61	285.419	322.785	122.029
Pluto	25	39.58229	0.251514	17.1561	110.2639	113.5081	omitted	223.7719

## Figure Captions

Figure 1 Pluto's orbit in the frame corotating with Neptune. The double-loop figure is typical of the 2:3 mean motion resonance. Two sidereal orbits are shown, corresponding to three sidereal orbits of Neptune around the Sun, and corresponding to the years 1507 to 2007. The orbit in this frame is not closed due to librational motion over the period of the orbit. The top view is from the ecliptic north pole. A scale bar of length 30 AU is shown starting at the Sun (centre) and Neptune is shown as a dot 30 AU below the Sun, very close to the average position it holds in its very circular orbit as transferred to this frame. To illustrate the short observed portion of plutinos' orbits, that of 1993 RO, the first discovered, is shown for 1993 to 2006 as a very short arc below the right hand end of the scale bar. The bottom view is inward toward the Sun looking past Neptune and the positions of Neptune and the Sun are shown as a short bar. The sizes of Neptune and the Sun are not to scale with the orbits. Data from JPL Horizons DE406+DE405+DE413 ephemerides.

Figure 2 Resonant argument of Pluto for the next  $10^5$  years. The argument librates about  $180^\circ$ , which permits avoidance of near-perihelion close approaches to Neptune. Values shown were calculated using the Mercury integrator with only the four outer planets and Pluto.

Figure 3 Orbit of asteroid 67367 in the frame corotating with Earth, illustrating a 2:3E mean motion resonance pattern very similar to that of the 2:3N pattern relative to

Neptune shown in Fig. 1. The geometry is identical to that of Fig. 1 but with Neptune replaced by Earth and the scale changed to 1 AU. A period of 3000 days from early 2004 to early 2012 is shown. The observational record stretches back to 1976, almost four times longer than the period shown. In this short time, the libration is clearly visible. In addition, the final three year (one cycle) part is indicated by dots every 26 days in the top view. These dots make clear the stationary points in the loops and in addition make it clear that the libration of the orbit is currently counterclockwise relative to Earth.

Figure 4      Resonant argument of the 2:3E resonance for asteroid 67367, showing libration around  $180^\circ$  with a period of 157000 days (430 years), from 1600 to 2200. Data from JPL Horizons system.

Figure 5      Elements of asteroid 67367 from 1600 to 2200. From top: semimajor axis  $a$  (AU) librates around the average 1.31 AU value typifying the resonance; eccentricity  $e$  librates around 0.214, inclination  $i$  (degrees) librates with low amplitude around  $9.02^\circ$ ; argument of perihelion  $\omega$  advances, nodal longitude  $\Omega$  regresses, and their sum, the longitude of perihelion ( $\varpi$ ), changes slowly on this timescale.

Figure 6      Elements of asteroid 2000 ET<sub>70</sub> from 1600 to 2200. Semimajor axis  $a$  (AU) librates around the average 0.948 AU value of the 2:3V resonance; notable features of all parameters (see caption of Fig. 5) are abrupt changes, readily visible in panels with appropriate scale, upon (often paired) close approaches to Earth which repeat each 12 years.

Figure 7      Libration of asteroid 2000 ET<sub>70</sub> near the time of leaving 2:3V resonance related to planetary distances. From the bottom are  $a$ , resonant argument, distance to Venus and to Earth. Upon leaving the resonance, approximately 250 years after the 11500 AD reference point,  $a$  decreases below the resonant limit and the resonant argument circulates. The distance to Venus decreases only slightly, and the leaving the resonance is mainly due to stochastic effects of the close encounters with Earth, visible for example as small step-like changes in  $a$ .

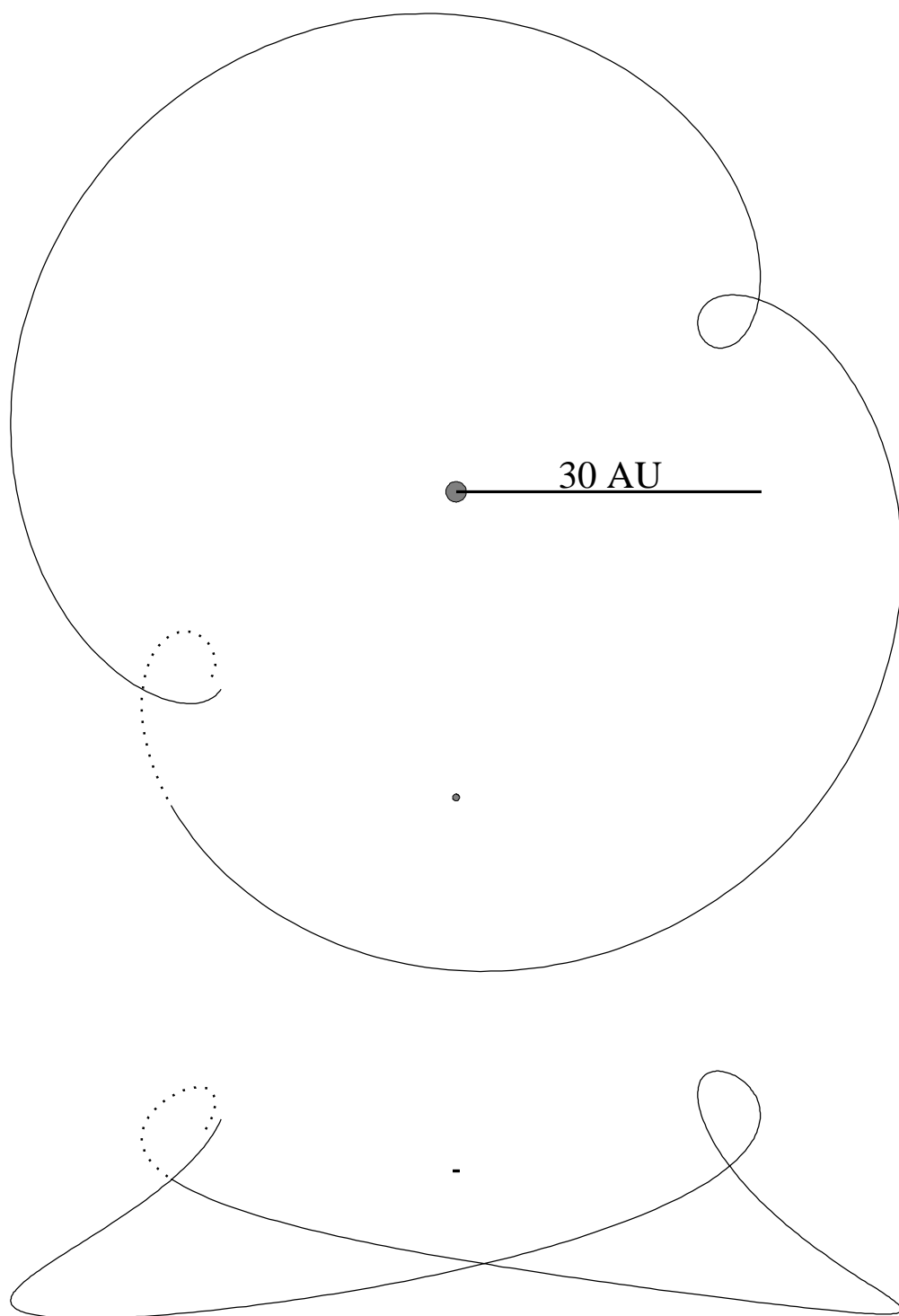
Figure 8      Libration of asteroid 2000 YJ<sub>11</sub> showing near-term changes in 2:3E resonant behavior related to close approaches and 5:4M resonant interaction with Mars. From the bottom are  $a$ , resonant argument, distance to Earth and to Mars. Step-like changes in  $a$  at  $t=450$  and  $t=1500$  are directly related to very close approaches to Mars at those times, evident in the upper panel. Larger changes in the resonant argument take place when, as at times 600 to 750 and 1250 to 1400,  $a$  as part of its 2:3E libration goes into the range of the 5:4M resonance, and the geometry is appropriate for repeated close approaches to Mars.

Figure 9      The same quantities as in Fig. 8 are shown for asteroid 2002 AV<sub>31</sub>. In this case, 5:4M Mars resonance leads to periods of avoidance of Mars.

Figure 10      Resonant argument of Mars plutinos as a function of semimajor axis, which increases from the bottom. Each subplot has a central line indicating 180°, and the

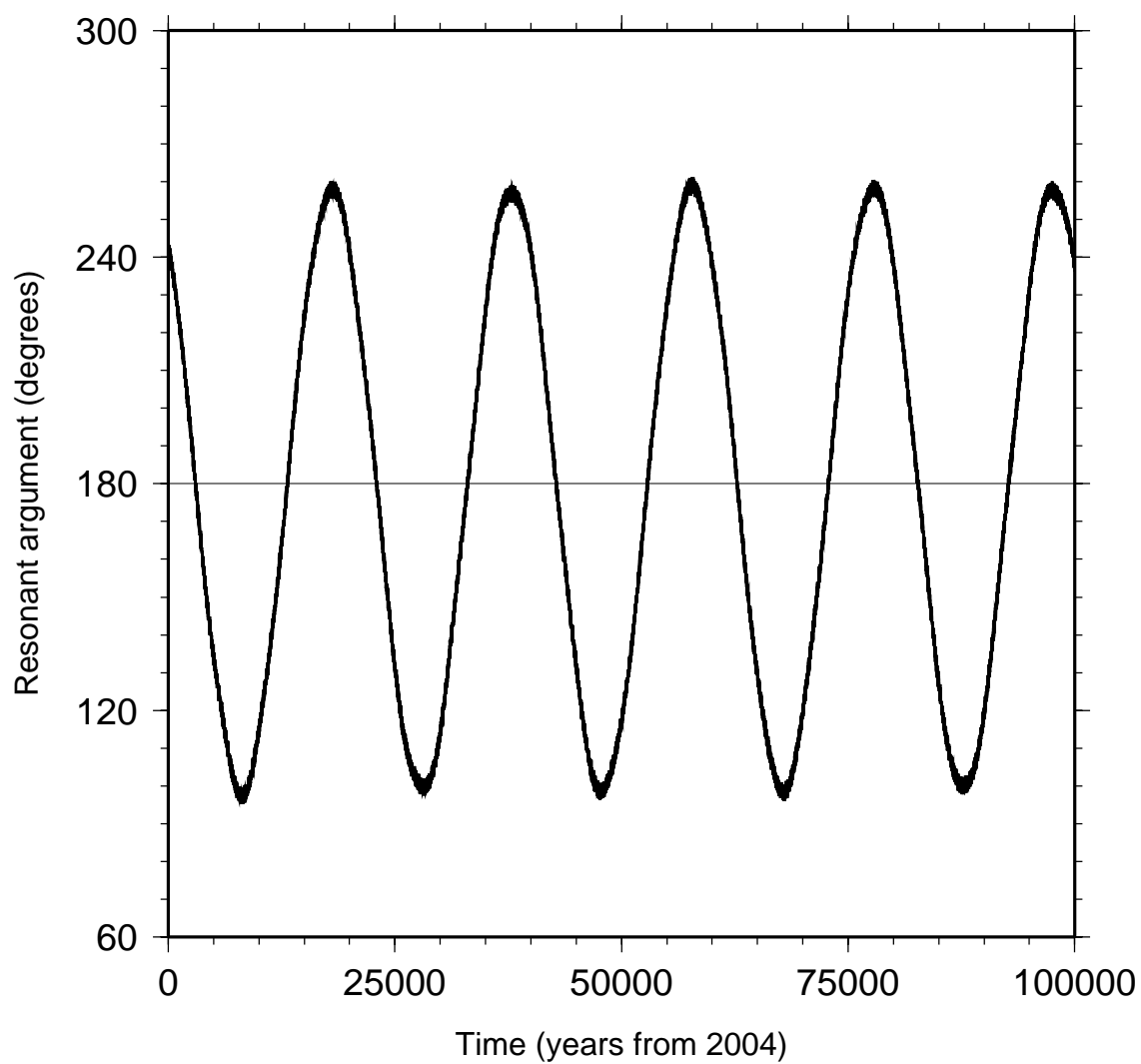


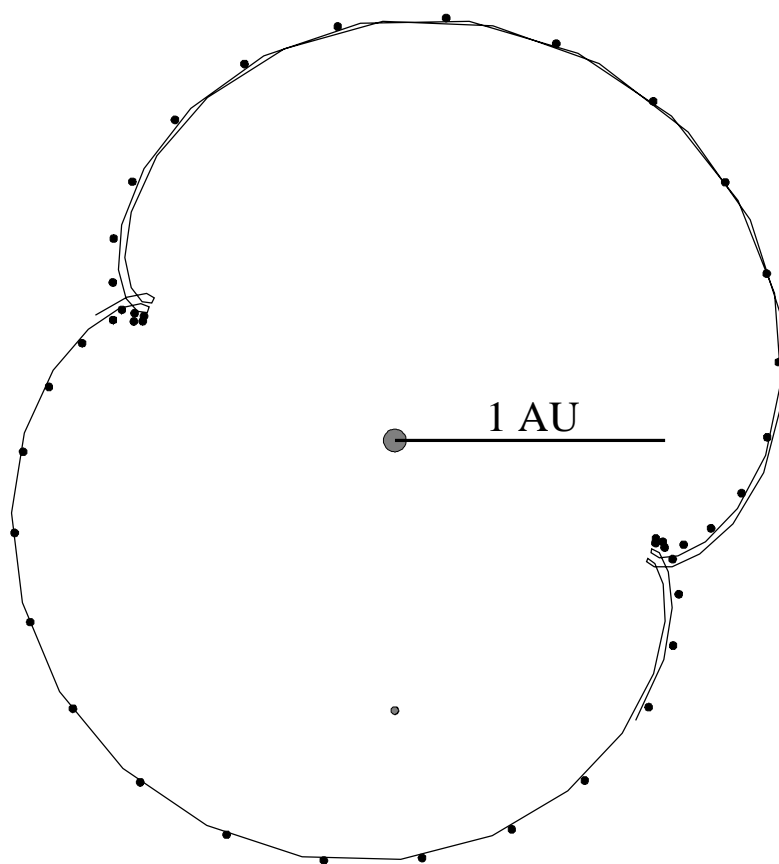
wave-like patterns indicate libration, typical in the central part of the graph (i.e.  $a$  range). Oblique lines indicate circulation, i.e. objects not in the 2:3M resonance. Those objects in the central  $a$  range which circulate rapidly or alternate between libration and circulation all have large  $e$  and thus are affected by other planets (mainly Earth). Sorting was done by osculating elements on MJD 53800 and numbering is given in Table 1.



Pluto 1507 - 2007

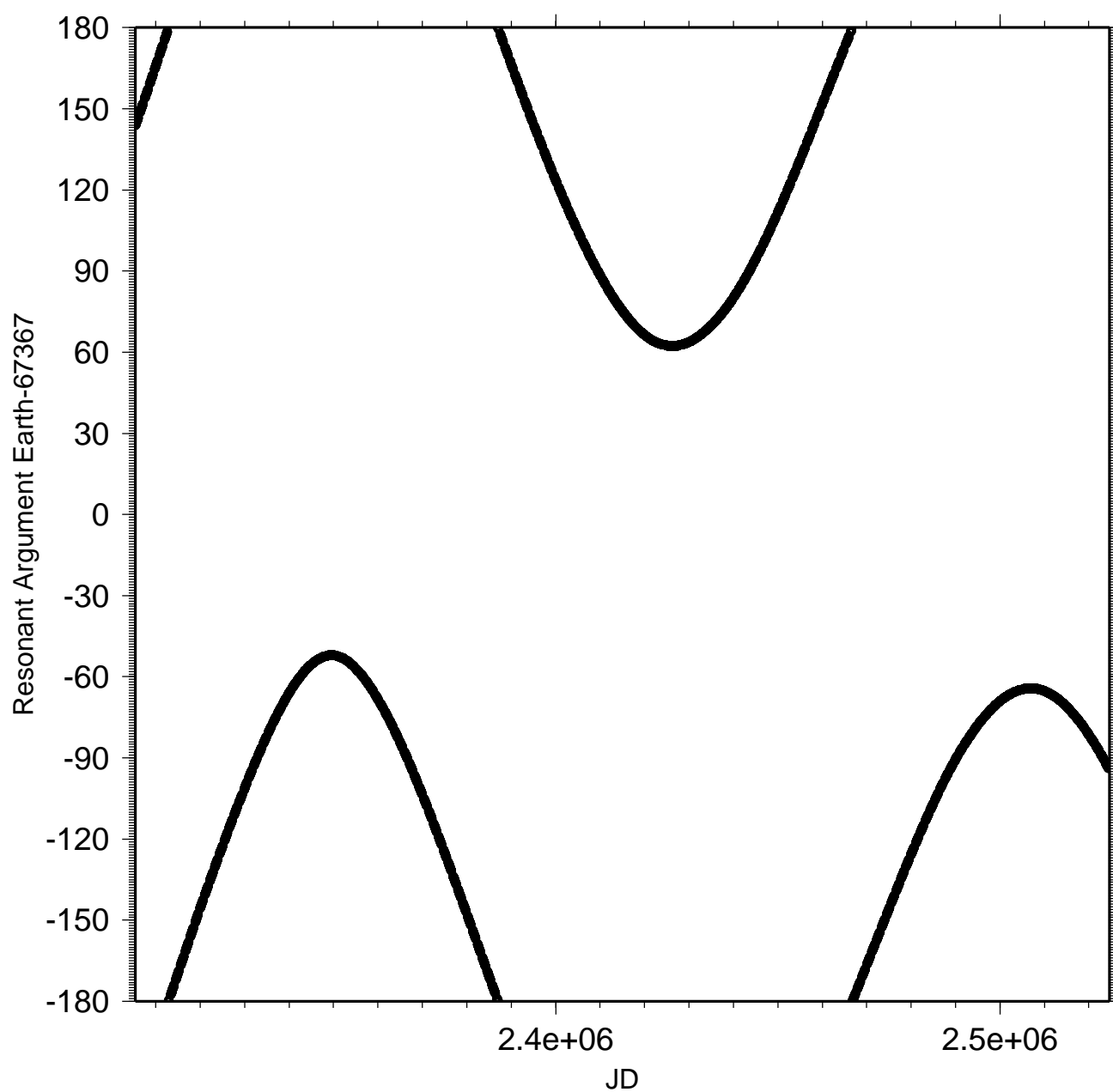
## Resonant Argument of Pluto



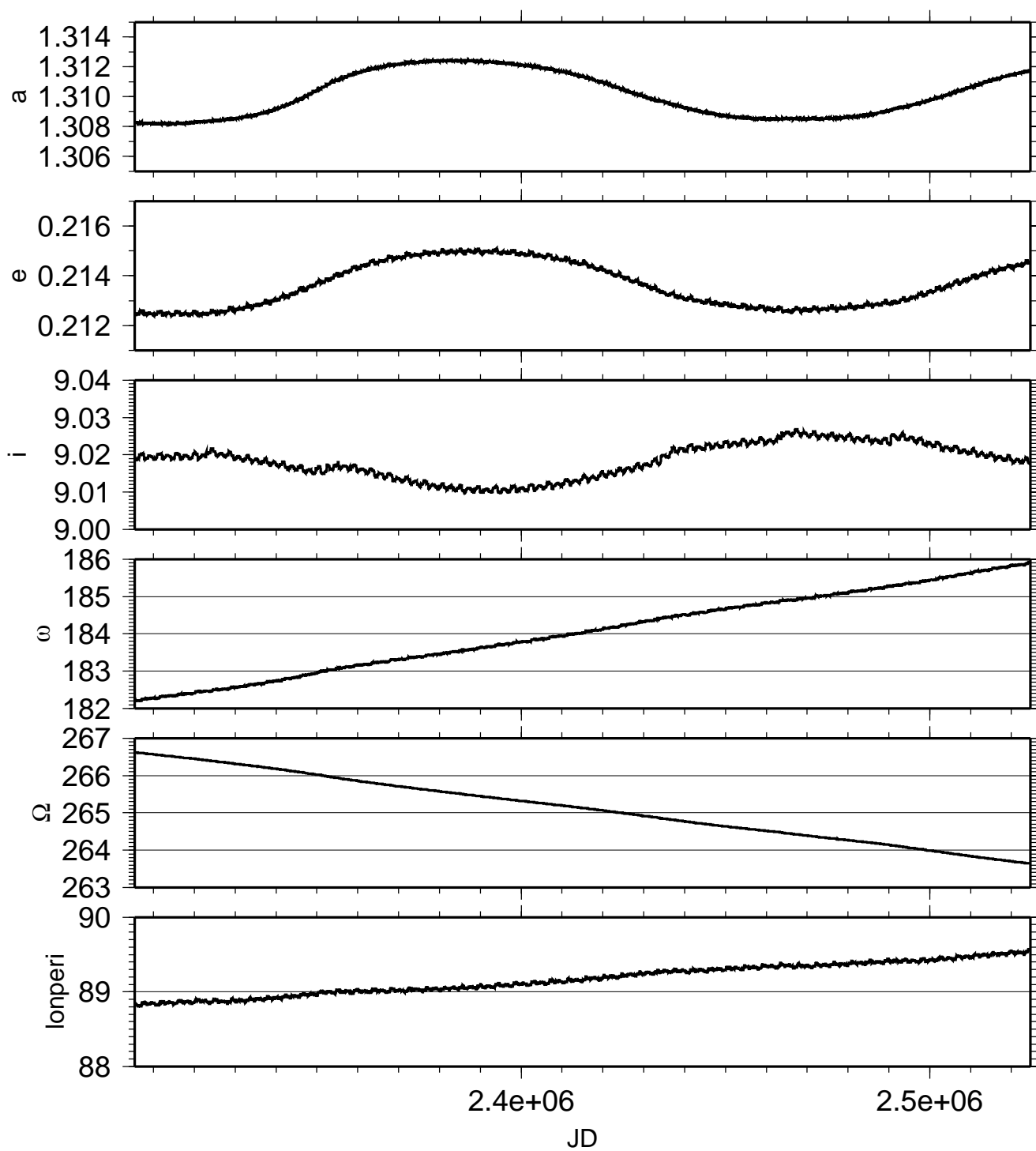


67367 2453000 - 2456000

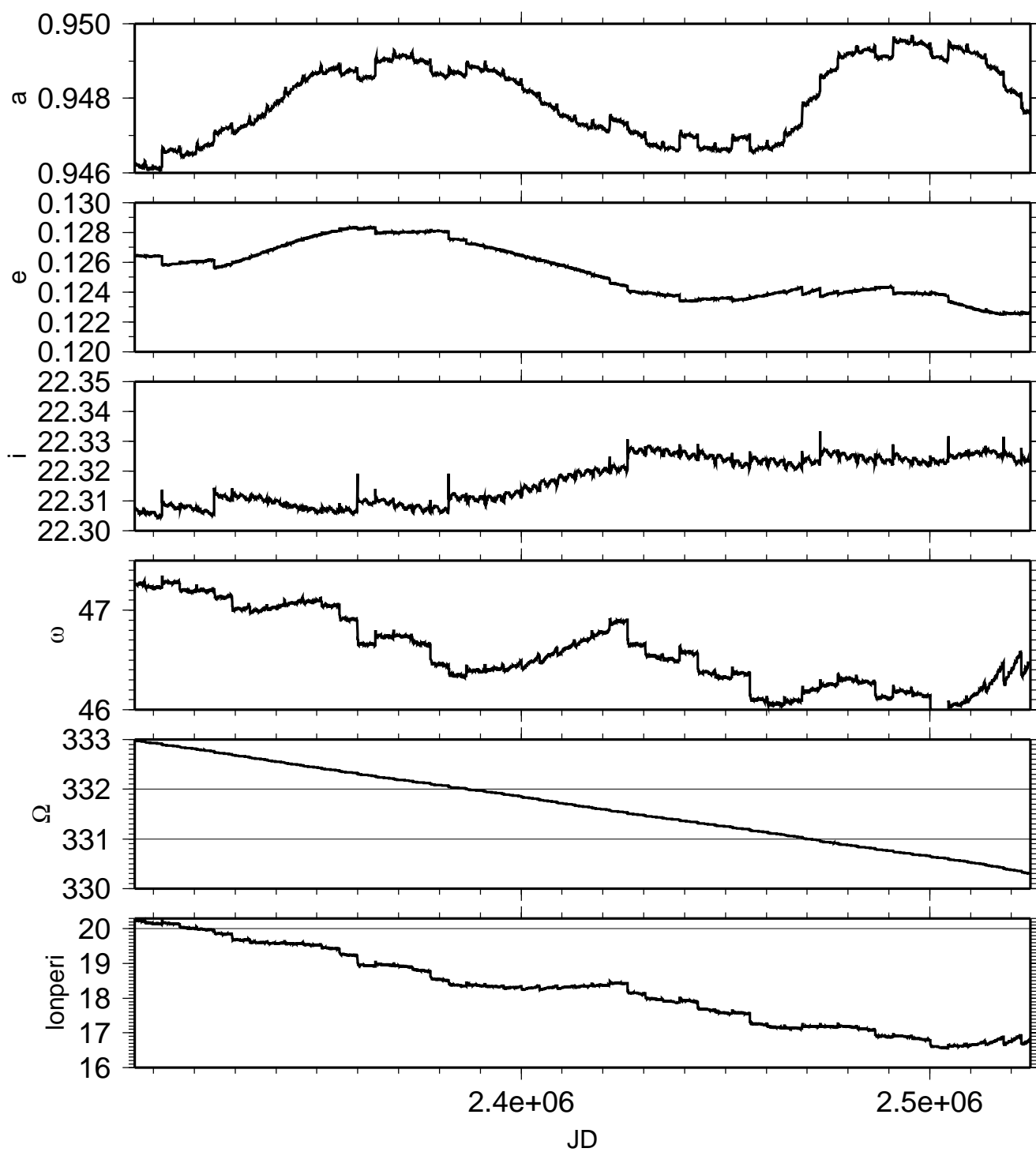
67367 1600-2200

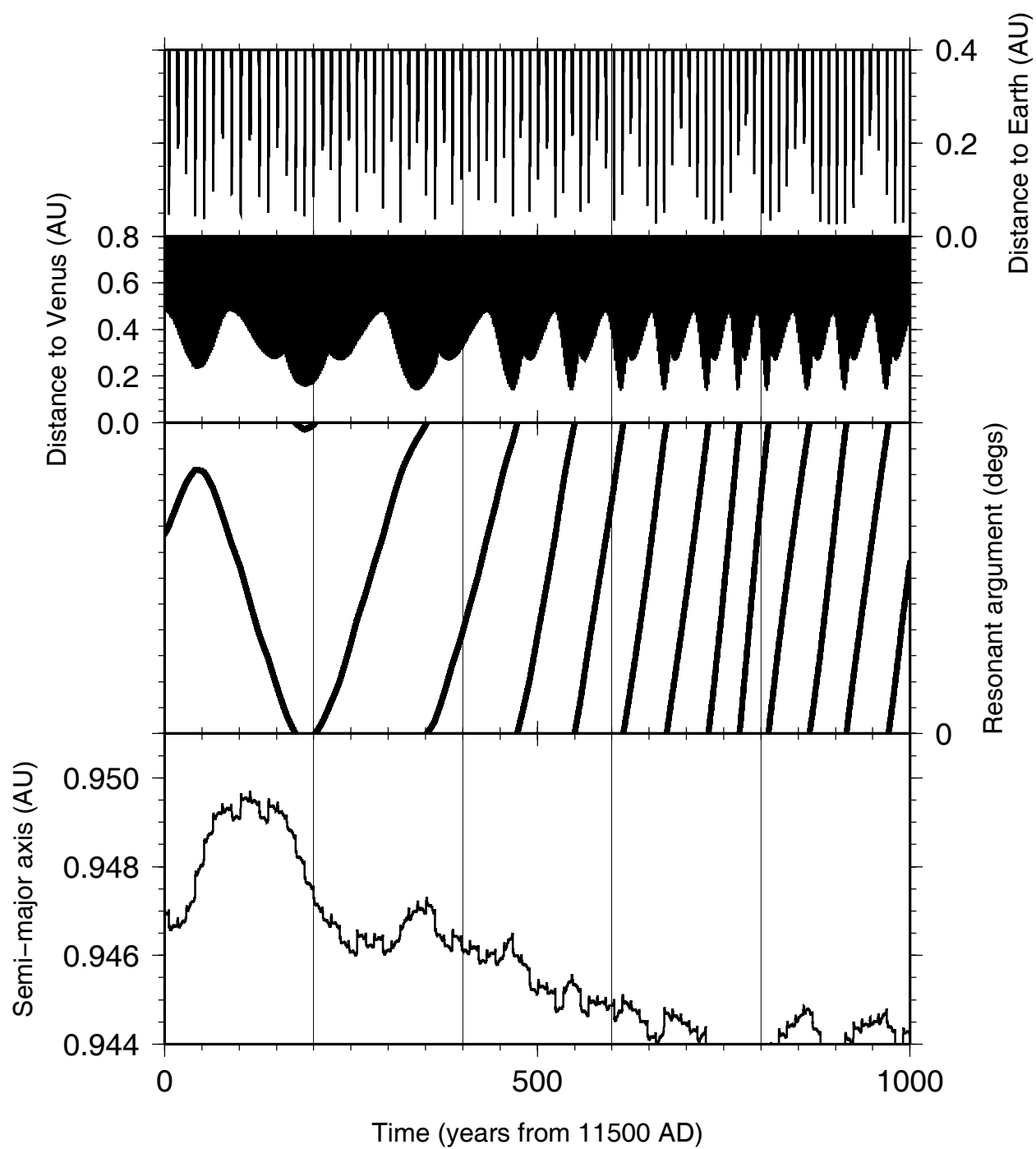


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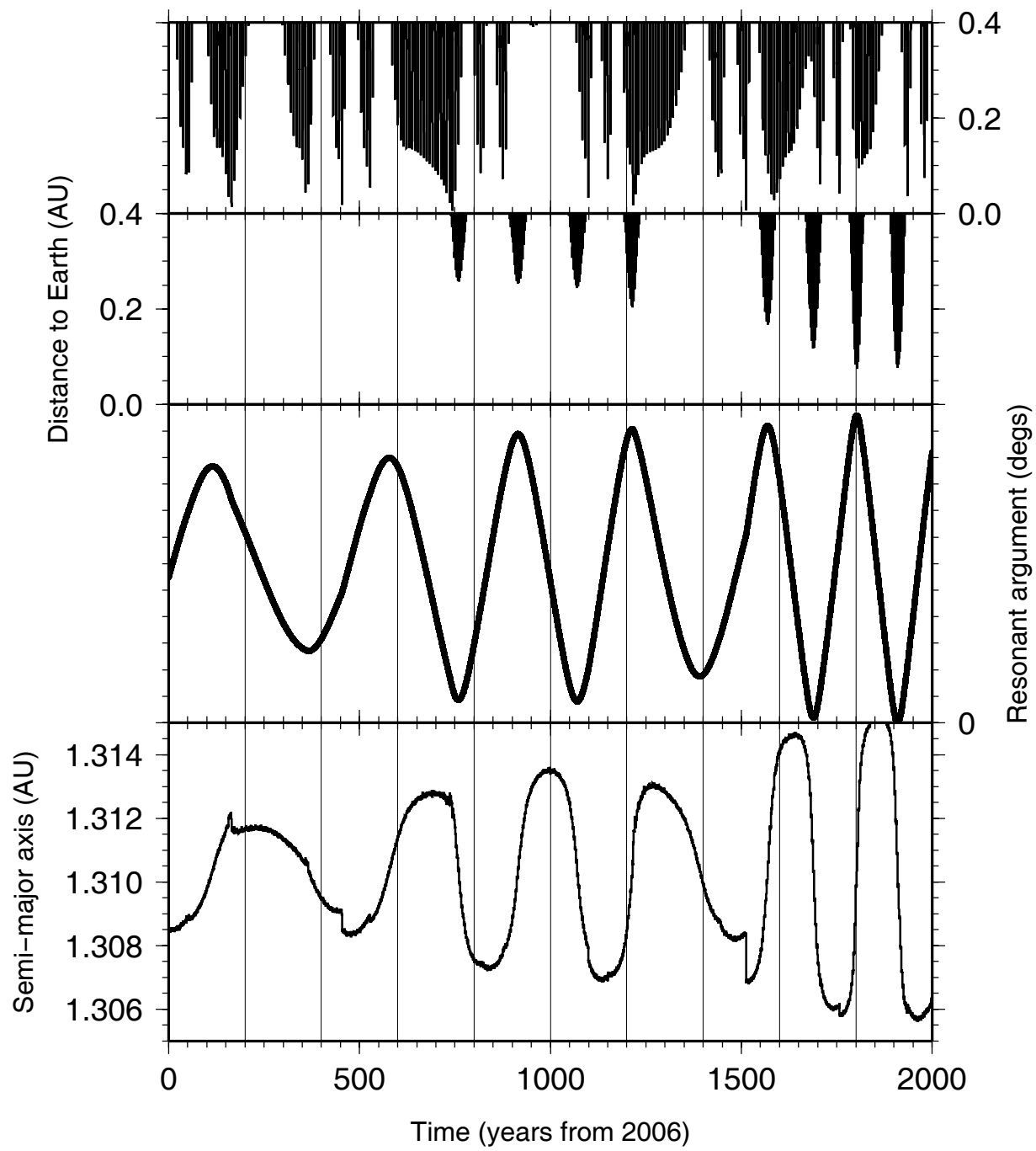
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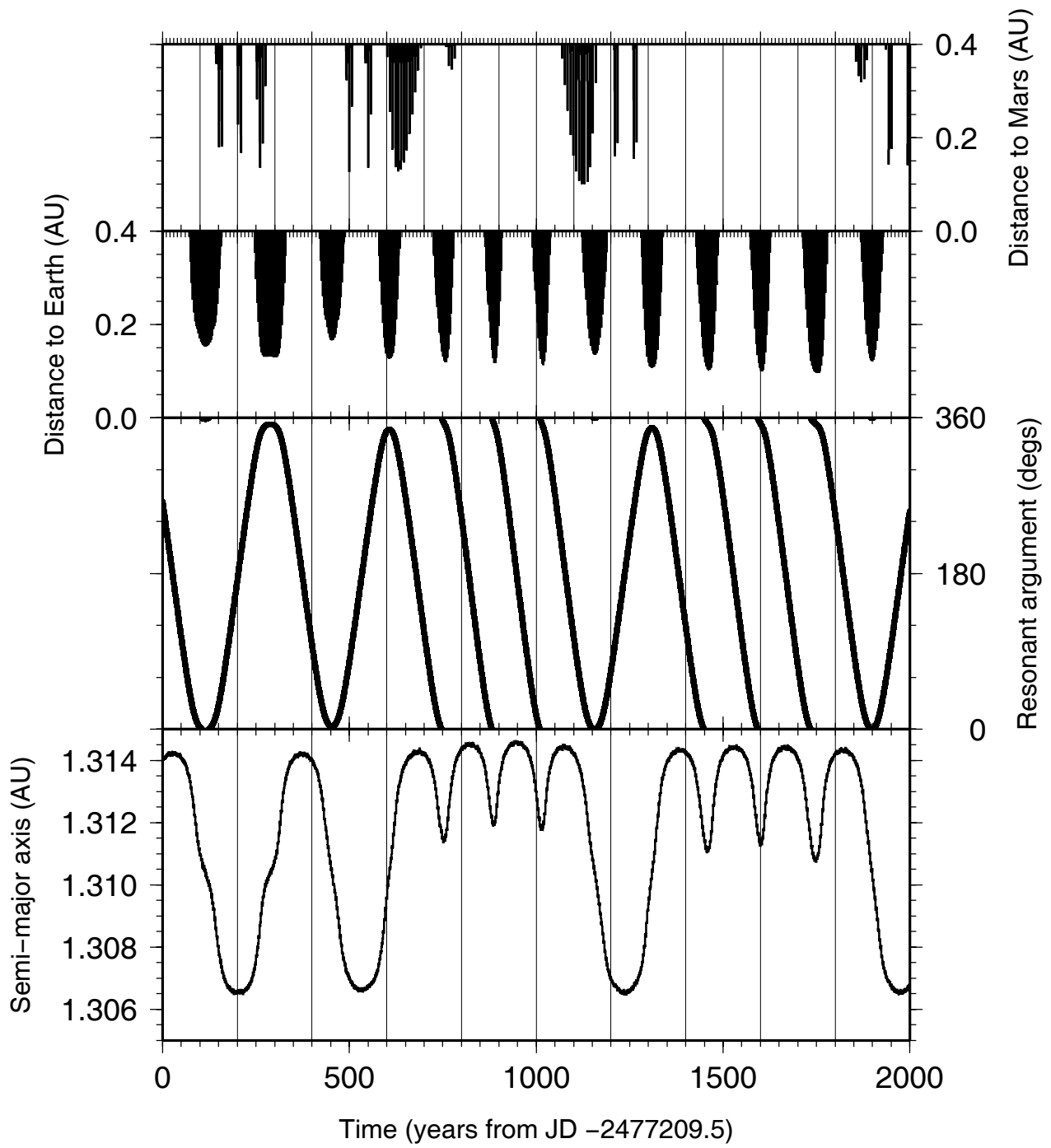




K00Y11J



# K02A31V



## Resonant Arguments, Sorted by Semi-major Axis

