이학석사 학위논문

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정진훈의 이학석사 학위논문을 인준함

2014년 2월

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Abstract

Consideration of a Circumsolar Dust Ring in Resonant Lock with the Venus

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Interplanetary space is filled with dust particles. It has been considered that the dust particles are supplied predominantly by comets and asteroids. Once dust particles are ejected from the parent bodies, they lose their angular momentum by solar radiation pressure, causing the dust grains to slowly spiral inward (Poynting-Robertson effect). As the dust particles move toward the Sun under the influence of Poynting-Robertson effect, they have a chance to encounter planetary resonances forming a local enhancement of dust cloud surrounding the sun (circumsolar resonance ring). The circumsolar resonance ring on the Earth orbit was detected in the zodiacal cloud through observations with infrared space telescopes. There was no definitive evidence other than Earth because of the difficulty in observation from Earth bounded orbit. However, Leinert et al. (2007) suggested that Helios spacecraft might detect the ring structure in 1970's when it passed the orbit of Venus, which motivated the present research.

We thus performed a dynamical simulation with the MERCURY6 Integrator to examine whether the circumsolar resonance ring associated with Venus is detectable or not. We considered solar radiation pressure, solar gravity, and planetary perturbations for the simulation. As the result, we found that (i) asteroidal dust particles are preferentially trapped in mean motion resonances of both Venus and Earth, (ii) the Venusian resonance ring definitively formed theoretically but the surface brightness would be 20 % of the Earth resonance ring. Finally, it should be noticed that the Venusian resonance ring has just been detected with a space telescope recently (Jones et al. 2013) as we predicted in this thesis.

Keywords : interplanetary dust particle, mean motion resonance, Venus dust ring

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Contents

1. Introduction

There is a great deal of dust particles in interplanetary space. Such particles are detectable through the scattered sunlight (zodiacal light) in optical wavelength or the thermal radiation (zodiacal emission) in infrared, and the existences are well known more than a century ago. It is considered that interplanetary dust particles are predominantly originated from comets or asteroids. Some of them can be ejected from comets together with sublimating ice and others generated through mutual collision among asteroids grinding the building blocks into small grains. Once they escaped from these bodies, the trajectories of dust particles evolve differently from the big (meter-sized or larger) parent bodies. Because dust particles are sensitive to the solar photon pressure (i.e. radiation pressure), and lose their angular momentum by the solar photon drag, they are migrated spirally into the Sun. The effect, which is caused by the solar radiation pressure tangential to the orbital motion of dust particles, is referred to as Poynting-Robertson (hereafter PR) effect.

The efficiency of PR effect can be parameterized by a parameter, β, a ratio of solar radiation pressure with respect to solar gravity. β is thus a critical parameter to determine the orbital motion of dust particles via PR effect. It depends on the diameter, mass density, and radiation pressure coefficient, Q_{pr} of dust particles. Assuming dust particle has a spherical shape consisting a perfect absorbing material, Q_{pr} is equivalent to unity. Otherwise, it can be calculated by using Mie theory (Burns et al. 1979). In addition, the trajectories of dust particles are influenced by the gravitational forces of planets (hereafter, we call them as planetary perturbations). During spiral migration, the particles suffer planetary perturbations and sometimes locked with planets in mean motion resonance (MMR). Dust particles captured in MMR with a planet temporarily keep their semi-major axis. This effect implies that there can be a local enhancement in the number density of dust particles near planetary orbits. As a result, this bottleneck process makes dust accumulation on planetary orbits forming a local enhancement of dust cloud around the sun (resonance ring).

The history of the research on the resonance ring goes back to the era of IRAS. Reach et al. (1991) noticed that the brightness of zodiacal emission in the trailing side of the Earth motion was always brighter than that in the leading side through the intensive analysis of IRAS data, and argued that the systematic brightness asymmetry is attributed to either artifact (a possible calibration problem in IRAS data) or real feature of dust local enhancement. After that, Dermott et al. (1994) performed a numerical simulation of dust orbits and suggested that the brightness asymmetry detected with IRAS could be caused by the trailing blob of MMR structure. Reach et al. (1995) firstly showed the two dimensional image of the MMR structure through COBE/DIRBE observation. They extracted not only the trailing blob but also the leading enhancement suggesting that these are a cross-section of MMR cloud on Earth orbit.

On the contrary, little was known about MMR structure associated with Venus. It was generally believed that such a resonant structure could not be formed around the Venusian orbit (Dermott et al. 1994). Because the PR drag force at Venusian orbit is more effective than that at Earth orbit, dust particles would be too fast to be trapped in MMR. Leinert et al. (2007), however, implied that the brightness of zodiacal light would increase by a few percent when a space craft passed around the orbit of Venus, suggesting that the dust accumulation by MMR with Venus. They obtained the result by analyzing Helios data.

The purpose of this study is to investigate the detectability of the Venusian resonance ring through numerical simulation as Dermott did about Earth resonance ring. We described initial conditions and assumptions of our simulation in next section. Our approach differs from Dermott et al. (1994) in that we consider different size of particles (10 μm and 30 μm) from different dust sources (i,e, comets and asteroids) while they considered only 10 μm particles from asteroids. It is worth noting that this is the first research to address the question about the detectability of Venusian resonance ring through theoretical approach.

2. Method

2.1. Mercury6 code

In order to predict dust ring structure around the Venusian orbit, we performed dynamical simulation with numerical integration code named *Mercury6*(Chambers, 1999). It is designed to simulate dynamical evolution of orbital elements of objects in the Solar system. Originally it considers solar gravity and planetary perturbations only. In addition to this, we inserted a subroutine to consider solar radiation pressure, solar wind, and Poynting Robertson drag force on our micron-sized test particles. The force on the particles due to solar wind, often called corpuscular drag, is assumed as 30 % of Poynting Robertson drag in same direction(Gustafson, 1994). The motion of dust particles under the solar radiation field can be described as the equation shown below.

$$F_{dp} = -\frac{GM_{\odot}}{r_{\odot}^2}\left[(1-\beta)\mathbf{e_r} - \beta\left(\frac{\dot{r}}{c}\mathbf{e_r} + \frac{\mathbf{v}}{c}\right)\right] + \sum_{i=1}^{N_p}\frac{GM_i}{r_i^2}\mathbf{e_{ri}}, \qquad (1)$$

where β is the ratio of the force due to radiation pressure to gravitational force on the particle, c is speed of light and G is the gravitational constant. And β parameter is shown as below(Burns et al. 1979).

$$\beta = 5.7 \times 10^{-5}\, Q_{pr}/\rho s \qquad (2)$$

where particles radius s and density ρ are in cgs units. In our simulations, we assumed Q_{pr} as unity and set ρ as 1 g/cm^3 (Wiegert et al. 2009). Note that even though there are a few opinions about density of IDPs, those values are at range of 1 ~ 3 g/cm^3 so $\rho = 1$ is not a bad assumption. With these equations and assumptions, we modified the mercruy6 code.

2.2. Initial conditions

It is general opinion that diameter of interplanetary dust that main brightness source of zodiacal light is in the range of 10 to 100 μm(Reach et al. 2003). The test particles we released in our simulation have diameter of 10 and 30μm. If dust particles are smaller than 10μm, than it falls to Sun too fast to form a resonant structure on Earth or Venus orbit because the PR drag is more effective to smaller objects. On the other hand, if dust particles are bigger than 100 μm, it takes too much time to perform numerical simulation. That is the reason why we selected 10 and 30 μm as diameters of the test particles.

We set constraints on semi-major axis of test particles that if it is larger than 50 AU, we assumed it has been kicked out of solar system and will not return. On the contrary if it is smaller than 0.05 AU, we thought it has fallen to the Sun. As a result, this code tracked the orbital evolution of test particles surrounding the Sun until they are kicked out from solar system(if it reaches > 50 AU) or evolve to near the Sun(< 0.05 AU). By using these constraints we could reduce unnecessary integration time.

To determine initial orbital parameters of dust particles, we assumed the dust particles are originated from asteroids or comets, especially Main-belt asteroids and Jupiter Family comets(JFCs). In previous study of Wiegert et al. (2009), they selected a few sample of JFCs to represent the whole(The list of selected JFCs ; see appendix 1). We follow their assumption in the dynamical simulation of cometary dust particles. For the asteroidal particles, in Nesvorny et al., 2010, they used asteroids which bigger than 15 km as representative of main-belt asteroids. We used the ASTORB catalog (Bowell et al. 1994) to obtain list of asteroids larger than 15 km.

We assumed that the dust sources above distributed dust particles uniformly spread over 2π in mean anomaly. In other words, dust particles originated from a single dust source has same orbital parameters except mean anomaly. Each cometary dust sources distributed 360 particles while asteroidal dust sources did only 10 particles. We did not have enough computing resources to calculate, so we had to reduce particles originated from asteroidal dust sources. Still, because asteroidal dust sources are 1,919 and cometary dust sources are only 25, so asteroidal dust particles used more than cometary dust particles in our simulation.(see Table 1)

	Cometary dust particles	**Asteroidal dust particles**
Source(Origin)	JFCs	Main-belt asteroids (D>15km)
Number of Source	25	1919
Size(μm)	10, 30	10, 30
Number of particles distributed by each source	360	10
Total number of simulated particles	18,000	38,380

Table 1 Initial conditions of dust particles in our simulation

2.3. Analytically predicted orbital decay time vs. Orbital decay time in simulation

As explained in introduction, the particles eventually will fall into the Sun because of PR drag force. The size of dust particles is one of the important thing that determines their Poynting-Robertson orbital decay time as described equations below, (Burns et al., 1979)

$$\left\langle \frac{da}{dt} \right\rangle = -\left(\frac{\eta}{a}\right) Q_{pr} \frac{2+3e^2}{(1-e^2)^{3/2}} \tag{3}$$

$$\left\langle \frac{de}{dt} \right\rangle = -\frac{5}{2}\left(\frac{\eta}{a^2}\right) Q_{pr} \frac{e}{(1-e^2)^{1/2}} \tag{4}$$

where a is semi-major axis, e is eccentricity, Q_{pr} is PR constant, η is 2.53 x $10^{11}/\rho s$, where ρ is density and s is size in cgs unit. If we assume that dust particles' shape is sphere, than Q_{pr} is unity. By solving these two equations, we can predict how much time takes to orbital decay of dust particle due to PR drag force. Besides, we will obtain the real orbital decay time from our simulation. By comparing these two kind of orbital decay time(one is predicted and the other is obtained from simulation), we can estimate how planetary perturbation affects the dynamical evolution of dust particles. See 3.3. to see details and result of this comparison.

3. Result

3.1. Fraction of particles migrated toward inner part of solar system($\lesssim$ 1.4 AU)

After calculation, we got orbital parameters of dust particles during our simulation. As our study is related to Venus, we could exclude some dust particles which did not migrated toward inner part of solar system(see Fig.1). For that, we set a constraint on semi-major axis, that is, if semi-major axis of a particle do not drop under 1.4 AU during the simulation, we exclude that particle from our study.

As a result, more than half of dust particles originated from comets were excluded while none of asteroidal dust particles were(Table 2.). So the particles which were not excluded are first candidates who have potential to be trapped in mean motion resonance with Earth or Venus.(Fig.2)

Cometary particles	Asteroidal particles
43 % of 10 μm particles were migrated inward while 24 % of 30 μm particles were.	All particles were migrated inward.

Table 2 Fraction of dust particles which were migrated toward inner part of the solar system.

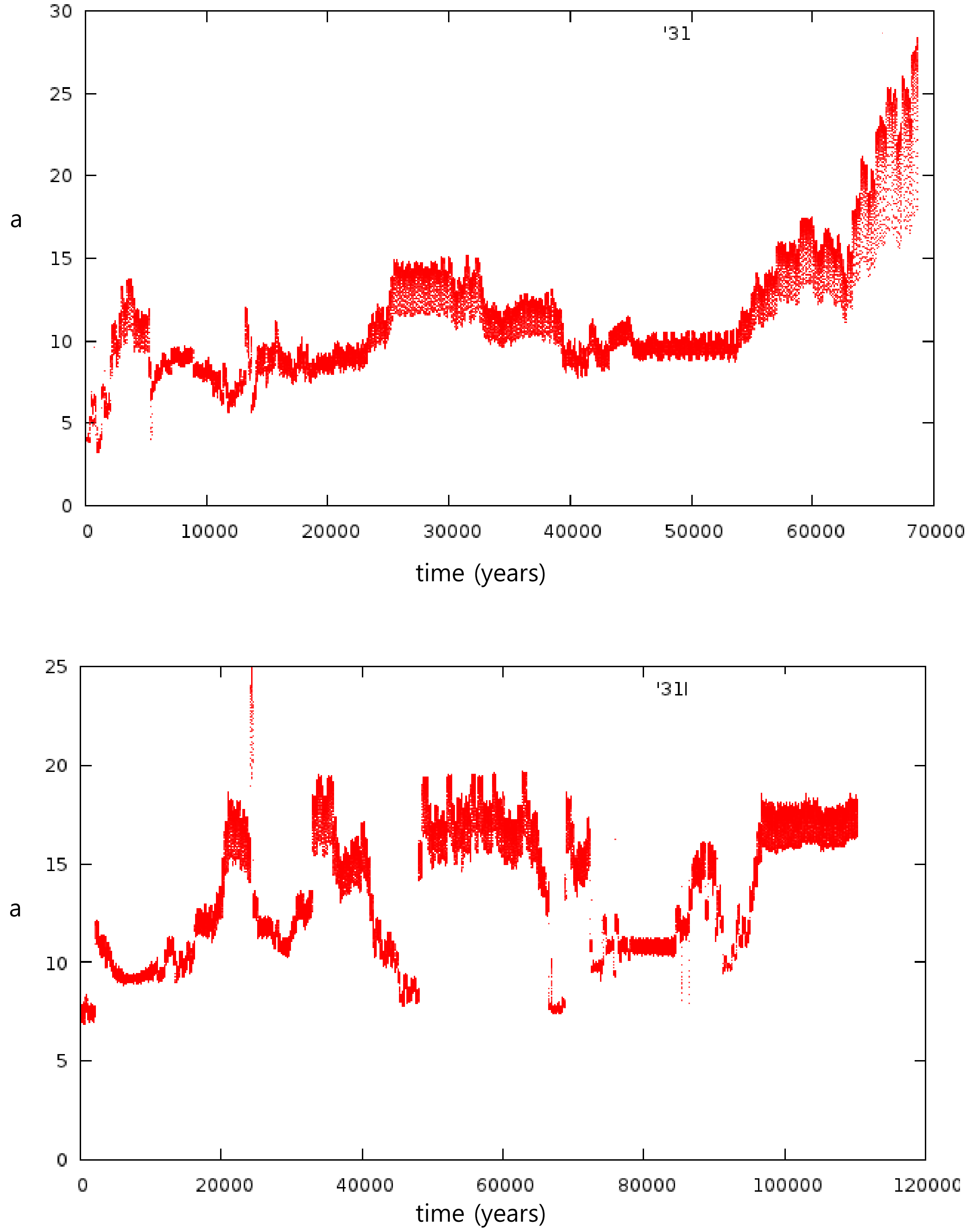


Figure 1 Examples of excluded dust particles. Both of them heavily perturbed by giant planets, especially the Jupiter. Upper one shows a particle kicked out from the solar system, and lower shows a particles could not migrate toward inner part of solar system during simulation.

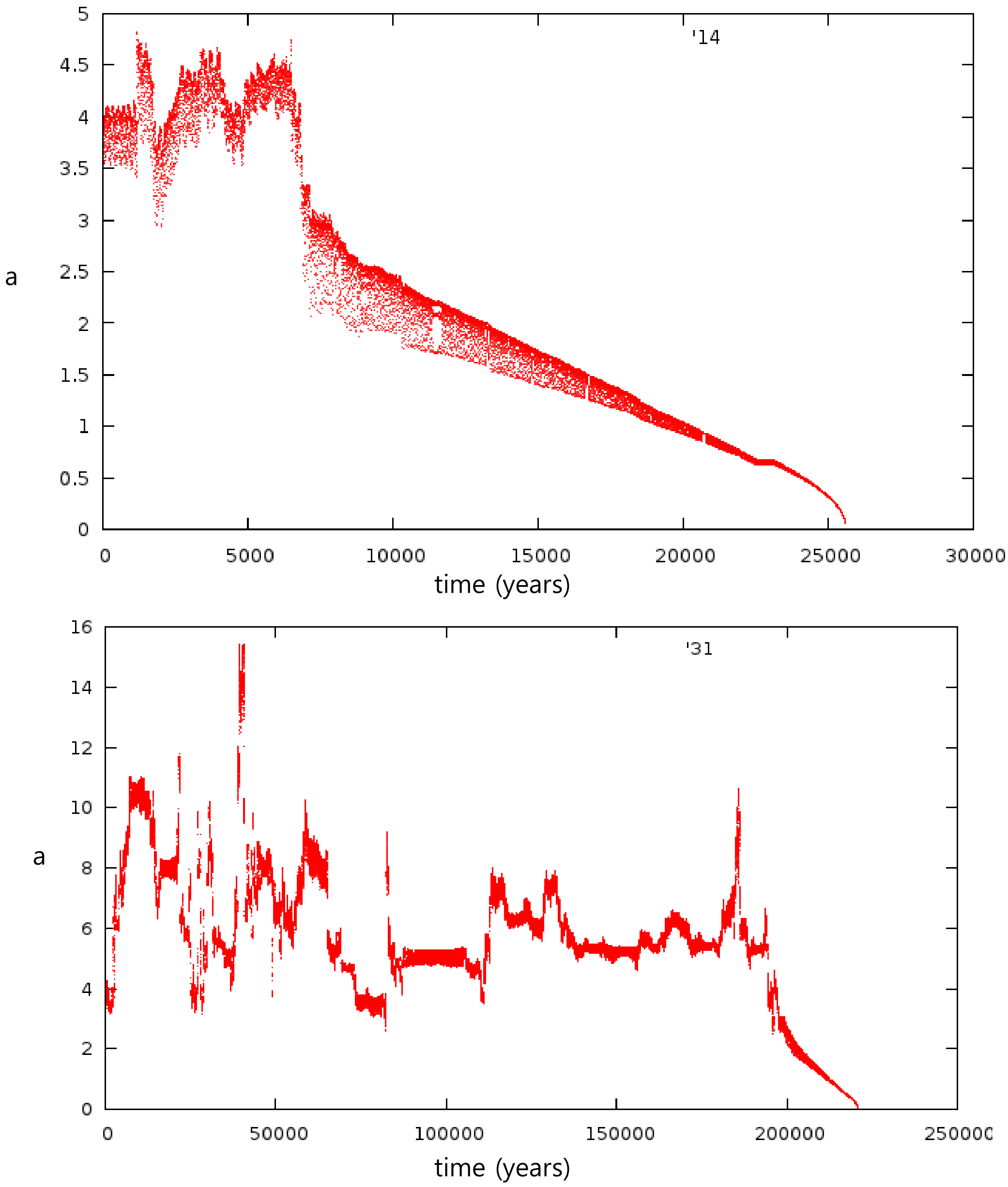


Figure 2 Examples of the particles which migrated to inner part of solar system. Both particles flowed to Sun though they scattered by giant planets during journey.

3.2. Particles trapped in mean motion resonance with Earth/Venus

As explained in introduction, some dust particles can be trapped in mean motion resonance(MMR) with the planets. Once a dust particle trapped in MMR with a planet, period of the dust particle and the planet are synchronized to simple integer ratio. During MMR, the particle's semi-major axis remains constant(see Fig.3) and eccentricity increases until end of MMR trapping.

We measured how many particles are trapped in MMR with Earth/Venus. To do that, we performed fourier analysis on $\lambda - \lambda'$, where λ is summation of argument of pericenter, longitude of ascending node, mean anomaly, and λ' is λ of reference planets. For more details of fourier analysis method to confirm whether a dust particle trapped in MMR with Earth/Venus, see Appendix 2.

With this method, we could count number of trapped particles(Fig. 4, Fig. 5, Table 3)

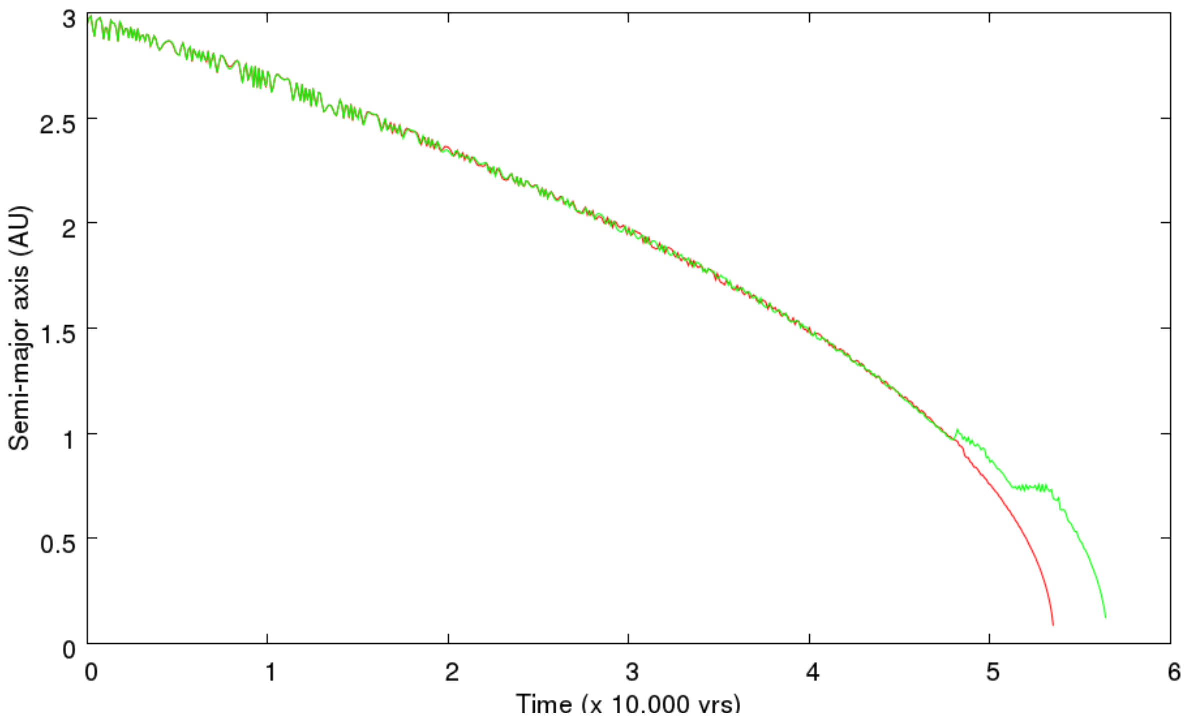
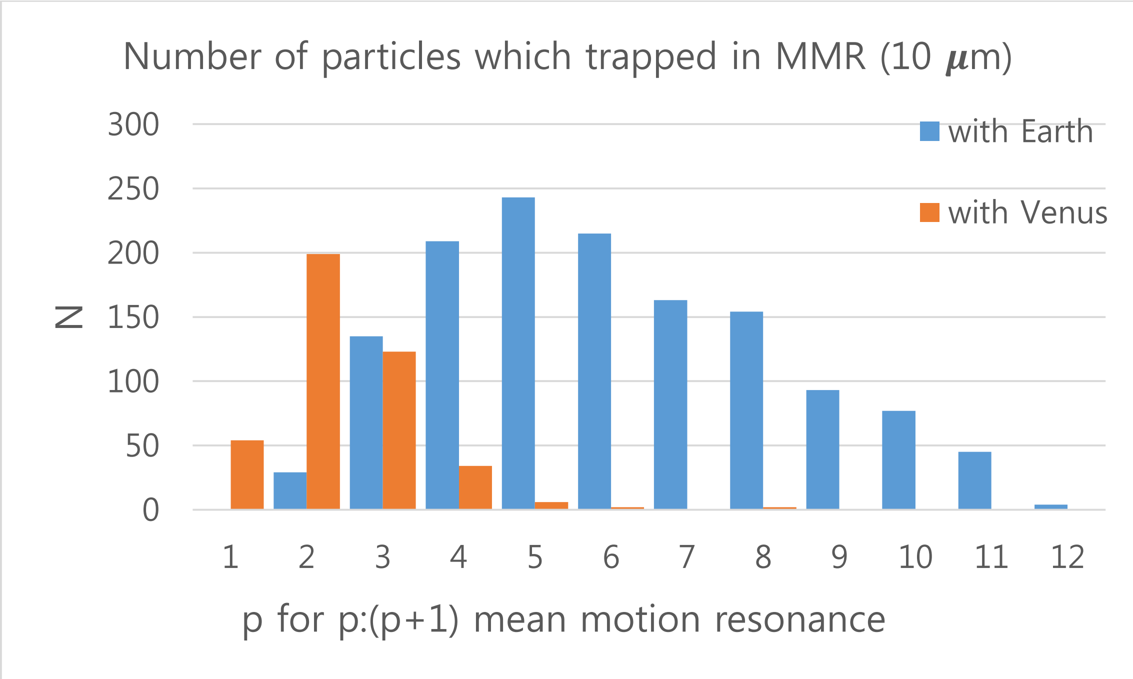


Figure 3 Green line shows a particle trapped in MMR with Venus. Compare to red, it stayed near Venus region due to MMR with Venus.



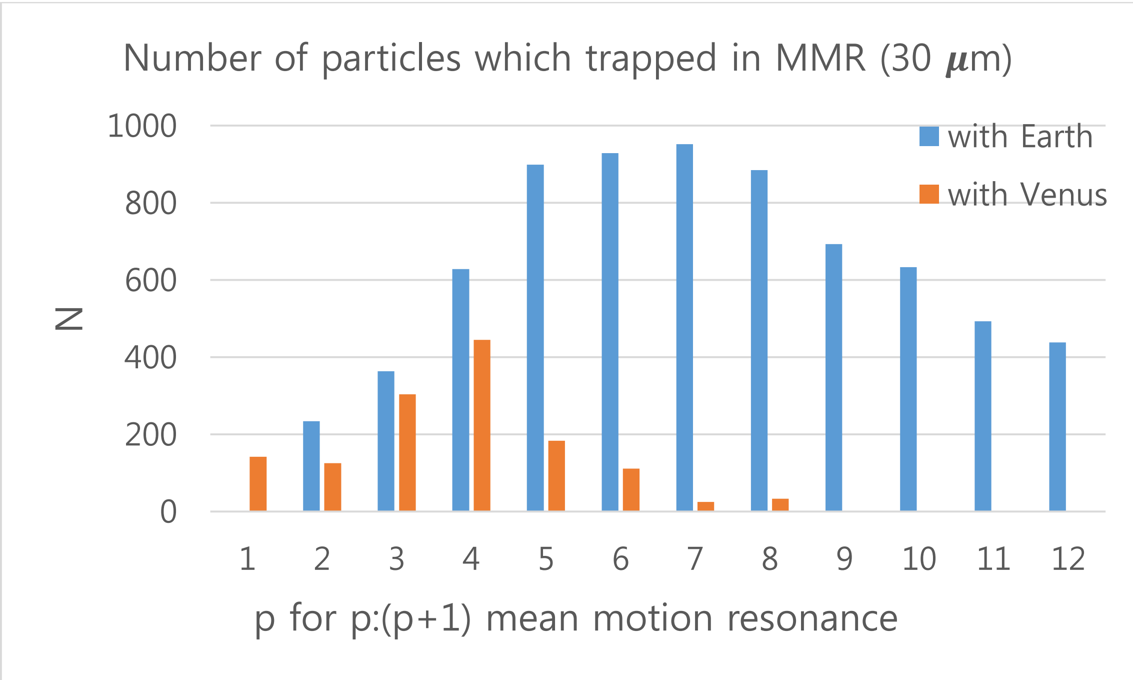
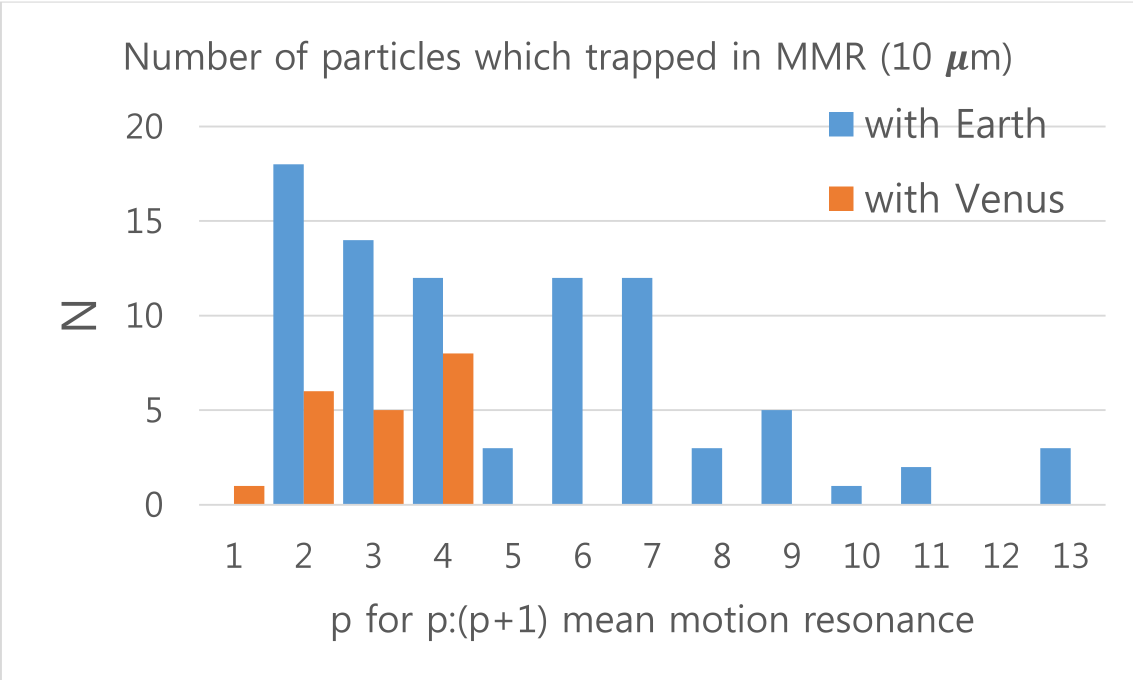


Figure 4 Number of asteroidal dust particles trapped in MMR with Earth and Venus. In this figure, p means p:(p+1) mean motion resonance. For example, if a particle's p is 2, it means that the particle trapped in 2:3 mean motion resonance with Earth(or Venus).



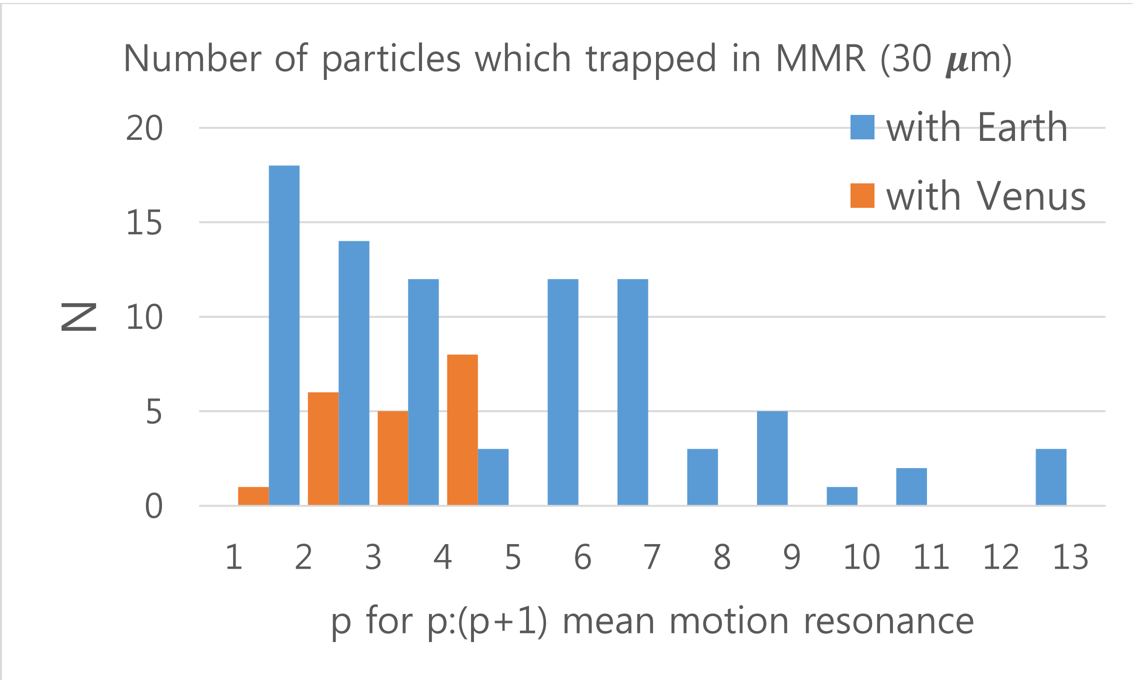


Figure 5 Number of cometary dust particles trapped in MMR with Earth and Venus.

		Asteroidal dust particles	**Cometary dust particles**
10 μm	MMR with Earth	7 %	Less than 1 %
	MMR with Venus	3 %	
30 μm	MMR with Earth	37 %	Less than 1 %
	MMR with Venus	7 %	

Table 3 Fraction of dust particles trapped in mean motion resonance with Earth and Venus. For more detailed result, see Appendix 3

3.3. Staying time of dust particle in the vicinity of Earth/Venus orbit

Existence of the planets considerably affect dynamical evolution of the dust particles. In 3.1. and 3.2., we already showed various examples how dust particles and the planets interact; sometimes particles can be scattered, kicked out from the solar system, or trapped in MMR. By doing so, a planet can reduces or increases orbital decay time of dust particles. In our study, we measured how much Earth or Venus reduces or increases during dust particles passing near Earth or Venus region. We set 'near Earth region' as 0.95 AU to 1.35 AU (in semi-major axis) and 'near Venus region' as 0.67 AU to 0.95 AU. And we counted how much time the particles stayed in those regions. Besides to this result, in the last part of Method section, we already explained about comparing two orbital decay time. As we have orbital decay time of dust particles in the simulation, now we can compare it with the predicted orbital decay time near Earth/Venus region. The result is shown in Table 4.

Cometary	10 $\boldsymbol{\mu}$**m** particles		30 $\boldsymbol{\mu}$**m** particles	
Dust particles	Near Earth	Near Venus	Near Earth	Near Venus
Staying time(avrg.±stddev.) (years)	3,600±1,200	2,200±500	7,400±3,200	4,600±1,700
Predicted staying time (years)	4,600	2,600	12,000	8,400

Asteroidal	10 $\boldsymbol{\mu}$**m** particles		30 $\boldsymbol{\mu}$**m** particles	
Dust particles	Near Earth	Near Venus	Near Earth	Near Venus
Staying time(avrg.±stddev.) (years)	5,600±1,500	2,700±600	19,000±10,000	7,400±2,100
Predicted staying time (years)	4,700	2,500	14,000	7,300

Table 4 Comparing between analytically predicted staying time and real orbital decay time in the simulation.

4. Discussion

4.1. Trapping in mean motion resonance

As you can figure out in section 3.2., asteroidal dust particles are more favorable to be trapped in mean motion resonance with dust particles. There can be several reasons for that, the first thing is asteroidal dust particles are mostly have smaller semi-major axis and eccentricity then cometary dust particles. Smaller semi-major axis and eccentricity means that asteroidal particles are easier to avoid influence of Jupiter gravity. The result in 3.1. supports this because more than half of cometary dust particles could not migrate toward inner part of the solar system because of the giant planets, especially the Jupiter. We assumed that cometary particles are originated from JFCs, so it is inevitable to them encountering with the Jupiter. As a result of close encountering with the Jupiter, they heavily scattered and this leads to result shown in 3.1..

Another important parameters for possibility of trapping in MMR is diameter of the dust particle. Asteroidal dust particles shows in section 3.2. that bigger particles are more easy to be trapped because bigger particles are more slowly migrated than smaller particles, which means that they have more chance to be trapped in MMR with Earth or Venus. Because β is bigger in smaller particles, they quickly passed near Earth or Venus region so have smaller chance to interact with Earth and Venus. But this is only applicable for asteroidal dust particle. For cometary particles, their primary goal to be trapped in MMR with Earth/Venus is escaping from the Jupiter. In this cometary case, smaller particles are more favorable because they can penetrate the Jupiter resonance regions faster than bigger particles.

4.2. Existence of Venusian resonance ring

We confirmed that Earth resonance ring can be exist in section 3.3., although we already know about Earth resonance ring through previous studies. For example, in Table 4, 10μm asteroidal dust particles 19% more stayed than expected on the vicinity of Earth orbit, while 30μm asteroidal particles 36% more stayed in average. On the other hand, cometary dust particles did not effectively contribute to Earth resonance ring. We suggest high eccentric and inclined orbit of cometary dust particles can be the reason. As mentioned in 4.1. section, first they failed to migrating near Earth/Venus orbit and second even if they manage to reach Earth/Venus orbit, their high eccentricity makes difficult to be trapped in MMR with Earth/Venus.

Ironically, existence of Earth resonance ring suggest non-existence of Venus resonance ring. We already explained that bigger eccentricity is not a favorable condition to be trapped. Based on that, we can expect a scenario; once a particle trapped in mean motion resonance with Earth, during trapping its eccentricity increases, which leads to non-trapping in MMR with Venus. This can explain why in table 4 staying time near Venus region so short even though staying time near Earth remarkably increased than predicted. In addition, 30 μm asteroidal dust particles showed only 1% increased staying time near Venus region while 10 μm showed 8% increasing. We think that 30 μm asteroidal dust particles undergo MMR with Earth very long timescale so they have bigger eccentricity at the vicinity of Venus orbit can be a reason.

According to table 3, if we assume that interplanetary dust are produced by comets and asteroids in same ratio and only consist of 10 and 30 μm size, ratio of number of trapped particles in MMR with Earth and Venus will be 44 : 10. It is very bold and rough estimation, still we can expect that brightness of Venusian resonance ring will be few times fainter than that of Earth ring.

4.3. Larger particles

We also wanted to use 100 μm dust particles with the same initial condition, however, we had restricted time and computing resources, and that was not enough to simulate 100μm dust particles, which are required to calculate considerably long timescale(~ 1 Myr). Besides, we doubted whether 100 μm particles can pass through the $\nu6$ resonance region(~ 2AU) or not, so tested it with small number of test particles. In this brief simulation, we used mercury6 code and distributed four 100 μm particle originated from Karin asteroids family. If they cannot pass $\nu6$ resonance region, it means that they may not evolve to inner part of solar system by PR drag force. As a result, they did not show any remarkable fluctuation in semi-major axis near $\nu6$ resonance region, however, all 100 μm particles also had shown eccentricity increasing during passing $\nu6$ resonance. The amount of increased eccentricity was 0.05~0.1. Few more things we found are, i) in the case of 10, 30 μm particles, they rarely interact with Mars. But all four 100

μm particles had shown small fluctuation in semi major axis during passing near Mars region, ii) passing near Mars region causes 5~10 degree increase in inclination of 100 μm particles, iii) these four 100 μm particles had been trapped in mean motion resonance with Earth. These results imply that 100 μm or larger particles will be difficult to captured in MMR with Venus, because larger particles migrate inward slowly which leads to more chance to interact with Earth. Interaction with Earth cause increase in eccentricity of dust particle and as we already mentioned in 4.2., high eccentric orbit is not a favorable condition for trapping in MMR with Venus. Based on these results, we guess if dust particles larger than 100 μm, it is more difficult to penetrate near Mars region and $\nu 6$ resonance region. In short, 100 μm or larger particles cannot migrate toward inner part of solar system easily.

5. Summary and Concluding Remarks

So far, we outline the method and assumptions of our numerical simulation of dust particles originating from Main-belt asteroids and Jupiter-Family comets as the source regions. We examined how much time they spend in MMR with Earth and Venus orbit through numerical simulation. In addition, we address the question about the possible origin of dust particles in MMR structures.

The findings of our theoretical study are as followings:

1. Dust particles from a parent body with low eccentricity provide a favorable condition to be trapped in MMR with terrestrial planets like Earth and Venus. Accordingly, we consider that asteroids are predominant dust source of dust particles in MMR structures.

2. On the contrary, it is difficult for dust particles of cometary origin. They initially have large eccentricities, and therefore, a significant fraction (more than a half) of them could encounter with Jupiter, the most massive planet in the solar system, and be kicked out to the outer region. Even if they would do not encounter with Jupiter and be migrated into terrestrial planet region, they would not be able to be trapped in MMR because of the large eccentricity.

3. Our simulation suggest that Venusian MMR structure do exist but fainter than the Earth structure. About a quarter of asteroidal particles can be trapped in MMR with Earth while 5% of them in MMR with Venus, suggesting that the number density of Venusian MMR structure is five times lower than that of Earth MMR structure.

We would like to emphasize that our result is not an armchair theory. Very recently (on 2013 November), the detection of Venusian MMR structure is announced. According to Jones et al. (2013, Science Volume 342, page 960-963), they found a local enhancement of dust cloud associated with Venusian MMR. The image was obtained with a sophisticated space probe (STEREO) designed to investigate the sun and solar phenomena such as coronal mass ejection. As we predicted, it existed just outside the Venus orbit.

The research of Venusian MMR has just begun. The future direction of this research is, as long as we understand, to make a quantitative estimate through the comparison between STEREO observation and numerical simulation as we did in the present study, and investigate the size and origins in the MMR structures.

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6. Appendix

6.1. Appendix 1 : Cometary dust sources

Name	**a (AU)**	**e**	**i (degree)**
2P/Encke	2.216	0.847	11.769
3D/Biela	3.525	0.755	12.550
4P/Faye	3.837	0.568	9.049
6P/d'Arrest	3.493	0.612	19.497
7P/Pons-Winnecke	3.438	0.634	22.284
9P/Tempel 1	3.121	0.517	10.530
10P/Tempel 2	3.070	0.535	12.017
14P/Wolf	4.069	0.407	27.522
16P/Brooks	3.611	0.491	5.548
17P/Holmes	3.682	0.412	19.187
31P/Schwassmann-Wachmann 2	4.235	0.195	4.549
32P/Comas-Sola	4.255	0.569	12.927
42P/Neujmin 3	4.855	0.585	3.985
53P/Van Biesbroeck	5.391	0.551	6.610
56P/Slaughter-Burnham	5.109	0.503	8.155
59P/Kearns-Kwee	4.468	0.476	9.352
63P/Wild 1	5.597	0.649	19.934
64P/Swift-Gehrels	4.383	0.694	8.437
65P/Gunn	3.589	0.318	10.384
74P/Smirnova-Chernykh	4.163	0.148	6.652
79P/duToit-Hartley	3.030	0.594	2.894
91P/Russell	3.888	0.330	14.092
140P/Bowell-Skiff	6.396	0.691	3.835
142P/Ge-Wang	4.995	0.500	12.173

Table 5 Cometary dust sources we used in the simulation. We followed assumption of Wiegert et al.(2009).

In previous study of Wiegert et al. (2009), they selected dozens of comets as representative of JFCs and we followed their assumption. The list of them is shown in Table 5.

6.2. Fourier analysis method for finding particles trapped in MMR

To confirm which dust particles are trapped in mean motion resonance(MMR) with Earth or Venus, we used the Fourier analysis method. This method follows four step, and the first step is selecting particles which succeed to migrate to inner part of solar system. Since we only interested in dust particles that have interaction with Earth or Venus, dust particles did not migrated toward inner part of the solar system can be excluded. We traced which particles migrated less than 1.5 AU in semi-major axis and they became first candidates who have potential to be trapped in MMR with Earth or Venus. Second, we performed fourier analysis on $\lambda - \lambda'$ (λ is summation of argument of pericenter, longitude of ascending node and mean anomaly, λ' is λ of reference planet). Because if two bodies bind in a MMR then their period are synchronized to simple integer ratio, there should be periodic signal in $\lambda - \lambda'$. A particle passing near Earth region(1.35AU to 0.95 AU), we assumed this particle has potential to be trapped in MMR with Earth and applied fourier analysis on $\lambda - \lambda'$ obtained during passing this region(in the case of the Venus, the region would be 0.95 AU to 0.67 AU). Third, after the fourier analysis, if the particle trapped in MMR, it will show periodic peaks on Power-Frequency space. Count them if power of the peak exceed specific value, and we set the value as three sigma above average. The number of peak becomes *p* (for p:p+1 mean motion resonance). We prepared an example for this method in Fig. 6.

We developed this method and worked well, however this method has several limitation. First, in some case, dust particles can be trapped in MMR with a planet twice or more. This is rare case but clearly occurred and this method can only detect the highest order of MMR. For instance, if a dust particle trapped in 2:3 and 4:5 MMR with Earth, it will be detected as 4:5 MMR. Second, this method cannot detect high order MMR, because the power of peak in power-frequency space is related to the order of MMR. When the order becomes higher, the power becomes smaller. This infers that at some level of order, it is impossible to distinguish a peak due to MMR from the noise. We guess the limitation is 12:13 MMR with Earth, 8:9 with Venus. Third, rarely an unidentified and irregular peak can appear even the dust particle is not in MMR with planet. In this case, this can be detected as wrong order of MMR. In total, we can guarantee about 90% accuracy of this method to detect MMR of dust particles with planets.

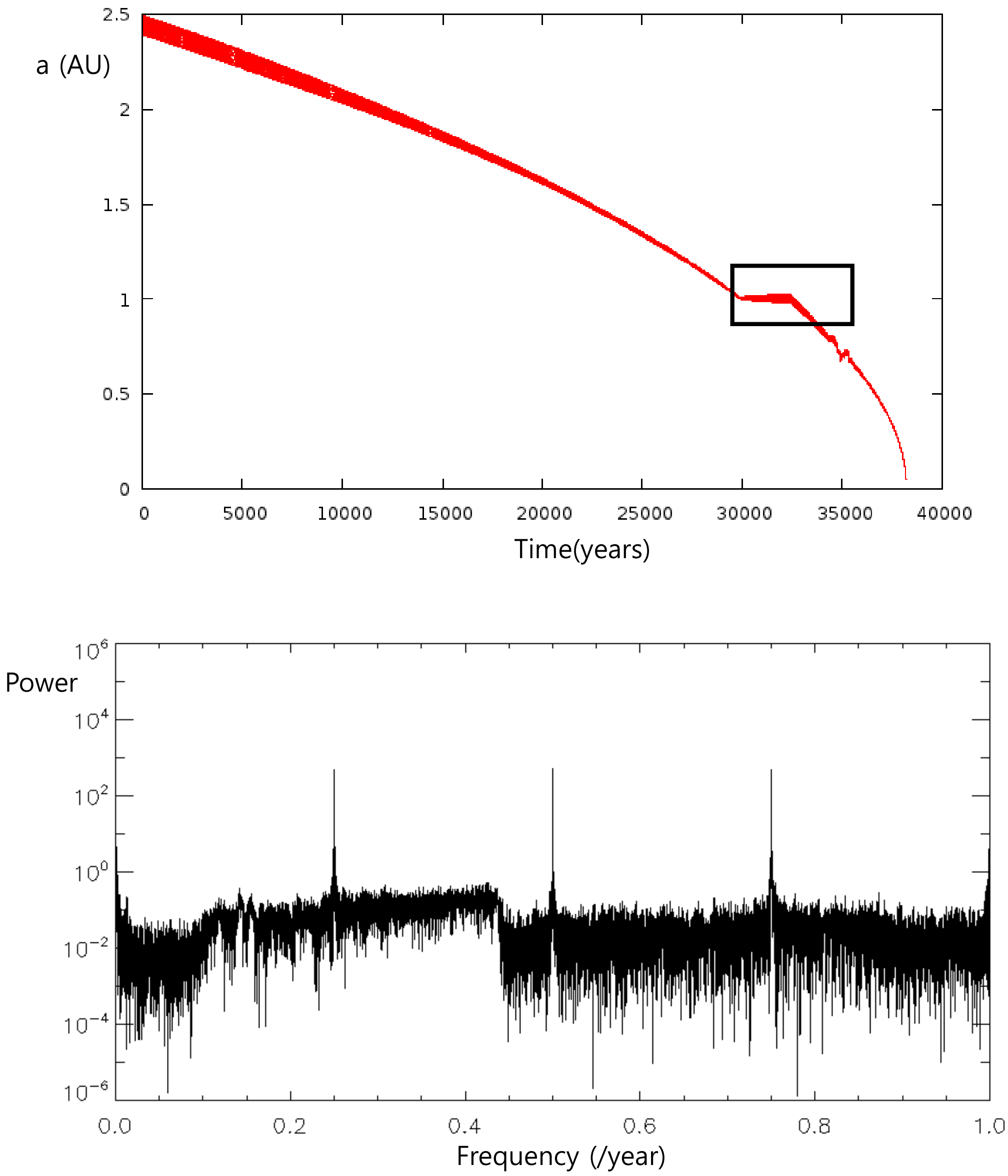

Figure 6 Example of Fourier analysis method application. Upper graph shows semi-major axis evolution of a dust particle which migrated inner part of solar system. In the black box region, it had been trapped in MMR with Earth and this is where we applied fourier analysis on $\lambda - \lambda'$. The result is shown in lower power-frequency graph, we can easily figure out that this particle had been trapped in 3:4 mean motion resonance with Earth.

6.3. Fraction of dust particles trapped in mean motion resonance with Earth and Venus

6.3.1. Cometary dust particles

10 μm				**30 μm**			
Earth		**Venus**		**Earth**		**Venus**	
p	**N**	**p**	**N**	**p**	**N**	**p**	**N**
1	0	1	3	1	0	1	1
2	12	2	8	2	18	2	6
3	12	3	7	3	14	3	5
4	11	4	7	4	12	4	8
5	6	etc	16	5	3	etc	12
6	7	**sum**	**41**	6	12	**sum**	**32**
7	10	**ratio(%)**	**0.46**	7	12	**ratio(%)**	**0.36**
8	3			8	3		
9	1			9	5		
10	1			10	1		
11	2			11	2		
12	2			12	0		
13	1			13	3		
etc	7			etc	13		
sum	**75**			**sum**	**98**		
ratio(%)	**0.83**			**ratio(%)**	**1.09**		

Table 6 Fraction of cometary dust particles trapped in MMR with Earth and Venus. p denotes p:(p+1) MMR, N is number of them.

6.3.2. Asteroidal dust particles

10 μm				30 μm			
Earth		**Venus**		**Earth**		**Venus**	
p	**N**	**p**	**N**	**p**	**N**	**p**	**N**
1	0	1	54	1	0	1	142
2	29	2	199	2	234	2	125
3	135	3	123	3	363	3	304
4	209	4	34	4	628	4	445
5	243	5	6	5	899	5	183
6	215	6	2	6	929	6	111
7	163	7	0	7	952	7	25
8	154	8	2	8	885	8	33
9	93	etc	170	9	693	**sum**	**1368**
10	77	**sum**	**590**	10	633	**ratio(%)**	**7.13**
11	45	**ratio(%)**	**3.07**	11	493		
12	4			12	438		
etc	15			**sum**	**7147**		
sum	**1382**			**ratio(%)**	**37.24**		
ratio(%)	**7.20**						

Table 7 Fraction of asteroidal dust particles trapped in MMR with Earth and Venus. p denotes p:(p+1) MMR, N is number of them.

초록

우리가 아는 행성간 공간에는 혜성과 소행성들이 뿌린 먼지티끌들로 가득 차있다. 이런 먼지티끌들은 태양복사압에 의해 각운동량을 잃어 천천히 나선형을 그리면서 태양계 안쪽으로 떨어지게 된다(포인팅-로버트슨 효과). 이 먼지티끌들은 떨어지는 도중에 행성중력에 반응하여 일시적으로 그 행성 궤도에 머물며 평균 운동 공명(mean motion resonance) 상태를 겪는다. 그러한 티끌들이 모여서 행성 궤도에 주변보다 약간 더 밀도가 높은 먼지고리를 형성하게 되는데(circumsolar resonance ring), 지구 궤도에 있는 것은 적외선 우주망원경을 통해 이미 발견된 바 있다. 아직까지 지구궤도 외에서 이러한 형태의 먼지고리가 확실하게 관측된 바는 없지만, 최근 헬리오스 관측선이 얻은 정보를 해석한 결과 금성에도 관측가능한 먼지고리가 있을 수 있다는 연구결과가 있었다(Leinert et al. 2007). 이런 상황에서 우리는 MERCURY6 포트란 코드를 이용하여 금성의 궤도먼지고리를 시뮬레이션을 통해 예측해보고자 한다. 이 실험에서 태양복사압, 태양중력, 행성들의 중력에 의한 섭동 등을 고려했으며, 결과적으로 혜성에서 기원한 먼지티끌들은 소행성의 티끌들보다 이러한 궤도먼지고리를 이루기에 적합하지 못하다는 결론을 얻었으며, 금성의 먼지고리는 존재는 하지만 지구의 먼지고리보다 5배 정도 희미할 것이라 예측한다. 이에 더하여 가장 최근 연구결과에 의하면 2013년에 STEREO 미션을 통해 금성 먼지고리가 관측적으로 확인되어 이 연구를 뒷받침한다 (Jones et al. 2013).

키워드 : 행성간먼지입자, 궤도공명운동, 금성 먼지 고리