An Insight into the Solar System History through the Size Distribution of Jupiter's Trojans

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Introduction

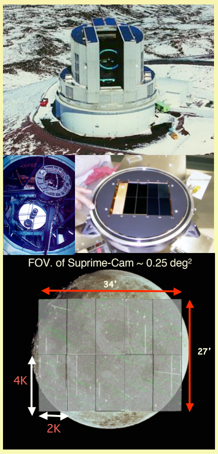
The Jupiter Trojans are asteroids sharing the orbits with Jupiter, but lay 60 degrees ahead or behind of Jupiter. We call the leading swarm the L4 Trojans, while the trailing swarm the L5 Trojans. 2538 Jupiter Trojans have been discovered so far (Aug. 10, 2008). The Trojans are far from the Earth and darker than main belt asteroids. That's why the knowledge of Jupiter Trojans has been limited, especially about physical properties. However, two systematic asteroids surveys performed recently (SDSS and SMBAS) revealed the size distribution of Jupiter Trojans with a wide size range of 2 km to 200 km in diameter. The surveys estimated the total population of the L4 and L5 swarms. Meanwhile, several theoretical studies proposed the origin of Trojans. Specially, people think the best model of planet migration is the Nice model which was proposed by **** et al. (2005). It can explain the complicated dynamical structure of TNOs, the orbital distribution of current Jupiter Trojans (especially inclination distribution) and the timing of Late Heavy Bombardment.

The Nice model suggests the origin of Jupiter Trojans is the Kuiper belt objects. Along the Nice model, Molvideri et al. (2005) simulated the orbital evolution of the Kuiper belt objects defused by Neptune which was scatterd by Saturn on the eccentric orbit when the Jupiter and Saturn got into the 2:1 resonance at the early stage of the solar system, and then found that a part of the Kuiper belt objects were trapped into the Trojan orbits by Jupiter and represent the orbital distribution and total mass of current Trojans. However, the Nice model can not explain the population asymmetry of the L4 and L5 swarms which recent asteroid surveys found.

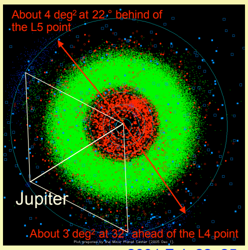
Here we explain our asteroid survey : SMBAS which is the deepest survey for Jupiter Trojans. Coupling the observational results and theoretical studies, we will discuss the formation process of Jupiter Trojans.

Survey observation of Jupiter Trojans

SMBAS: Subaru Main Belt Asteroid Survey



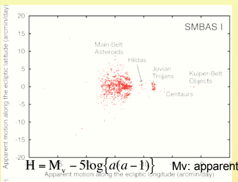
2001.Oct.21 SMBAS-II



SMBAS-I 2001.Feb.22, 25

Our surveys have been planned as the MBAs survey. The survey areas are a bit off from the exact Lagrangian points. But we could detect many Jupiter Trojans, as well as MBAs. The observations were done at oppositions. The R-filter was used.

Selection of Jupiter Trojans



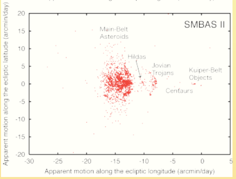


Fig.1 Ecliptic longitude and latitude components of apparent motions of asteroids detected in SMBAS-I (left panel) and SMBAS-II (right).

The relative velocity of Earth to asteroid get largest at opposition. If we observe near opposition, we can easily distinguish asteroids in each group of solar system bodies by their motion.

$H = M_v - 5\log\{a(a-1)\}$ Mv: apparent magnitude with the V-band, a: semi-major axis.

We chose asteroids having ~ -8 arcmin/day velocity as Jupiter Trojans.

Detected Jupiter Trojans

SMBAS-I 51 L4 Jupiter Trojans,
SMBAS-II 62 L5 Jupiter Trojans

The detection limit was ~ 24 mag (corresponding to 2km in diameter) in our both surveys.

Motion, Brightness → Size

Asteroid diameter (D) is estimated from its absolute magnitude (H). The H is estimated from apparent magnitude and distance of asteroid by following equation.

$$H = M_v - 5\log\{a(a-1)\}$$

Mv: apparent magnitude with the V-band, *a*: semi-major axis.

On the estimation of H, we assumed the mean color V-R of 0.48 based on known Trojan's data, because we used the R-filter. According to Dotto et al. (2006 Icarus,183, 420), Jupiter Trojans are quite similar in their spectra. Hence, a color deviation from the assumption of V-R=0.48 would affect the diameter estimate less significantly than does the uncertainty in *a* estimate, the latter being up to 20 %. Since we observed asteroids at opposition, we did not consider the phase effect. We ignored light variations due to asteroid's spin.

The *a* is estimated from the apparent motion of the asteroid. Since we can't determine the orbital eccentricity from the short term observation, we assume all asteroids have circular orbits (as for the estimation of *a*, and the evaluation of the errors, see our papers).

The D is calculated by the following equation.

$$\log D(\text{km}) = 3.31 - 0.5\log A - 0.2H$$

A: albedo=0.04

Here, we assumed albedo of 0.04, which is a typical value for the primitive small solar system bodies.

Size distributions of the L4 and L5 Trojans

We investigated the cumulative size distributions (N(>D)∝D^{-b}) of the L4 and L5 Trojans separately.

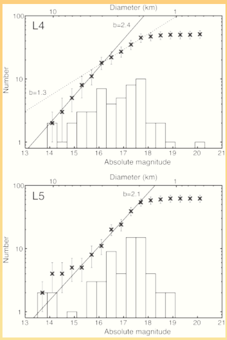


Fig.2 Size distributions of L4 (top) and L5 (bottom) Trojans from SMBASs. The box histograms show the differential H_v distribution and the crosses with error bars show the cumulative H_v distribution. Each upper abscissa represents the diameter corresponding to the H_v by assuming an albedo of 0.04. The solid and dashed lines in the top panel show the best-fit slopes of b=2.4+/-0.1 for 5km<D<10km and b=1.3+/10.1 for 2km<D<5km, respectively. The solid line in the bottom panel shows the best-fit slope of b=2.1+/- 0.3 for 2km<D<5km.

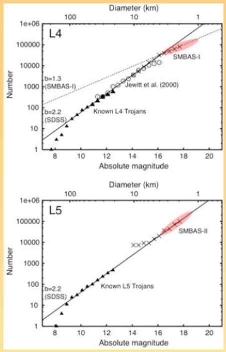


Fig.3 Fig.3 Composite cumulative size distributions of L4 (top) and L5 (bottom) Trojans. The scale values for combining are adjusted to the above distributions from three surveys and Trojan catalog to coincide each other at H=9.7, 12,1 and14.1 mag in the top panel. The ordinate scale values of the bottom panel are adjusted at H=9.7 and 16.1 mag.

We combined all size distributions obtained from different surveys (SMBAS-I, SMBAS-II, Jewitt et al. (2000), SDSS) and known Jupiter Trojans brighter than H=12.3 mag (corresponding to D~20km), whose statistics is claimed to be completed by Szabo et al. (2007), and then made up an overall size distribution covering 2km<D<~100km.

The size distributions of L4, L5 Trojans are basically identical except for smaller Trojans (D<5km).
The slope of cumulative size distribution of smaller L4 Trojans is shallower than others. It suggests a depletion of small L4 Trojans.

Table.1 Slopes of cumulative size distributions for L4 and L5 Trojans with different size ranges.

Group	Slope (b)	Size range D(km)	Reference
L4	1.3± 0.1	2<D<5	SMBAS-I (YN2005)
	2.4± 0.1	5<D<10	SMBAS-I (YN2005)
	2.0± 0.3	4<D<40	Jewitt et al. (2000 AJ, 120 ,1140)
	2.0± 0.1	20<D<93	Known Trojan catalog*
L5	2.1± 0.3	2<D<5	SMBAS-II (YN2008)
	2.1± 0.1	20<D<93	Known Trojan catalog*

*http://cfa-www.harvard.edu/iau/lists/JupiterTrojans.html

Total populations of the L4 and L5 Trojans

We made a new surface density model of Trojan cloud using the positions of known L4 Trojans.

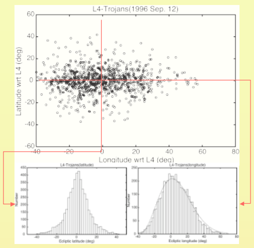
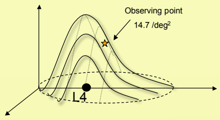


Fig.4 Sky plot of the positions in ecliptic coordinates for 970 known L4 Trojans at the opposition of 1996 Sep.12 (top). The histogram was composed of positions of 970 Trojans at 10 oppositions. Latitudinal marginal distribution of 9700 Trojans (left) and longitudinal marginal distribution of the same objects as the top panel (right).



We calculated sky number densities of each mesh. Then we estimated the total number so that the estimated sky number density matched the observed sky number density.

Sky number densities

32°ahead of L4 14.7/deg^2
22°behind of L5 13.8/deg^2

Estimated total number (D>2km)

L4 (6.3±1.0) × 10^4
L5 (3.4±0.54) × 10^4

The number ratio of total population from SMBASs L4/L5= 1.3~2.5

The L4 swarm has a larger population than L5. According to SDSS data analyzed by Szabo et al. (2007), the number ratio is L4/L5=1.6±0.1 (for D>10km).

<New finding from SDSS and SMBAS>

(1) The number ratio of L4 to L5 (L4/L5) is 1.3~2.5. The L4 population is larger than L5 one.
(2) The slope of cumulative size distribution is about 2.2 in both swarms in the size range of 5 to 200 km in diameter. Namely the size distribution is identical in the both swarms.
(3) As for small asteroids (D<5km), the slopes are different between L4 and L5 swarms. The slope of L4 swarm is shallower than L5.

Why is L4 population larger than L5 population?

There are two possibilities.

(a) planet migration, (b) long term perturbation from Saturn

(a) Gomes 1998, AJ 116, 2590

- The hypothesis of planet migration was tested by numerically integrating orbits of Trojan-type asteroids.
- He found that there is a significant trend of Jupiter Trojans survivors to the L4 point and most Trojans are expelled in the beginning of the migration when asymmetry between L4 and L5 is established. After that, this asymmetry is maintained through the migration process.

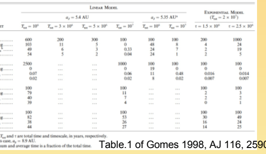


Table.1 of Gomes 1998, AJ 116, 2590

(b) Freistetter 2006, A&A, 453, 353

- A long term perturbation from Saturn causes an asymmetry for the size of stable area around L4 and L5 points of Jupiter. The larger stable area around L4 may be related to the larger population of L4 swarm.

However the Nice model does not predict the population asymmetry between L4 and L5 swarms (O'Brien & Morbidelli, Abstract of Asteroids, Comets, Meteors, 2008). Since this kinds of simulation derive totally different results with different initial conditions, further parameter search is necessary.

The Nice model suggesting the same capture rate around L4 and L5 points after catastrophic event caused by planet migration may welcome his results. Because his simulation suggests that, even if the initial population of L4 and L5 swarms were identical, the subsequent orbital evolution of asteroids can make the population asymmetry between L4 and L5.

(2) Why are the over all size distributions of L4 and L5 swarms almost identical?

probably the same origin

Generally, separate asteroid groups have different size distributions. Thus, it is natural to think almost identical size distribution suggests the same origin. Since the relative impact velocities and impact probabilities in L4 and L5 swarms are not so different (Davis et al., 2002, in ASTEROID III, p.548), colligional evolution in both swarms would not be so different. From visual and near infrared spectroscopic observations, Dotto et al. (2006, Icarus, 183, 420) found that the L4 and L5 Jupiter Trojans swarms are very homogeneous population. The result of their observations may be one of evidence that the both swarms are originated from the same source.

(3) What kinds of mechanism can deplete the small Trojans from L4 swarm?

A possible idea is the proto-planetary gas drag.

Peale 1993, Icarus 106, 308

- The stability of small planetesimals in the presence of a 13 M_{earth} proto-Jupiter and of the nebular drag was investigated.
- He found that during growth of Jupiter, the orbits of Trojans can be stabilized at L5 than at L4.

Marzari & Scholl 1998, Icarus 131, 41

- The trapping rate in Trojan orbit in the presence of growing Jupiter and gas drag was investigated.
- They found that L5 has more trapped bodies than L4 for small Trojans.

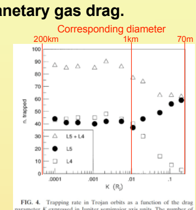


FIG. 4. Trapping rate in Trojan orbits as a function of the drag parameter *K* expressed in Jupiter semimajor axis units. The number of trapped bodies is intended on an initial sample of 200 bodies. Empty squares represent the number of captures in L4, filled circles those captured in L5, and the empty triangles are the sum of the two.

Fig.4 of Mazari & Scholl 1998, Icarus 131, 41

木星トロヤ群形成プロセスについての考察

上に述べた様々な理論モデルと観測データと惑星形成論を組み合わせて考えられる木星トロヤ群の形成シナリオは、おそらく次の2つにしぼられる。

シナリオ(A) **1.**大惑星の集積期に周囲の微惑星がトロヤ群軌道に取り込まれる。この時、原始太陽系星雲のガス抵抗のため小さいL4トロヤ群が取り除かれ、浅い傾きの累積サイズ分布がつくられる。**2.**惑星移動に伴いL5トロヤ群小惑星の数が全体的に減少する。これはトロヤ群の安定領域である1:1共鳴帯の移動により生じる。共鳴の効果はすべてのサイズの小惑星に働くので、惑星移動に伴うトロヤ群小惑星の数の減少はもとのサイズ分布を変えない。ただしこのシナリオでは、現在のトロヤ群小惑星に見られる高軌道傾斜角の天体群を形成するのが困難という問題点がある。

シナリオ(B) **1.**大惑星の移動過程で木星と土星が1:2平均運動共鳴を通過する際に起こった全太陽系的な大変動により、カイパーベルト領域から落下した天体がトロヤ群軌道に捕獲される(ニース・モデルに基づくトロヤ群小惑星の形成)。**2.**大惑星が現在の配置に落ち着いた後、土星からの重力摂動によりL4とL5群の総個数に非対称が生じる。シナリオ (B)では高軌道傾斜角の天体群を形成できるが、小さいL4群の浅い傾きの累積サイズ分布を説明できるかどうかは不明。

どちらのシナリオにも問題点は残されており木星トロヤ群形成プロセスの解明にはまだ些か遠い。さらに衝突進化を考えるとさらに混迷を深める。de ELia & Brunini (2007, A&A, 475, 375)はトロヤ群小惑星が最初に力学的に冷たい状態(軌道離心率が小さく、軌道傾斜角が低い)にあっても、衝突進化により1億年程度で現在のような軌道離心率と軌道傾斜角の分布に到達可能で、現在のトロヤ群の軌道分布からは初期のトロヤ群の軌道分布に制約を与えることはできないと主張する。O'Brien & Morbidelli(2008, Abstract of Asteroids, Comets, Meteors)は、ニース・モデルで木星トロヤ群の再構築時に統計的には無視できるくらいの数の違いが大きい小惑星にあったなら、その後の衝突進化でL4とL5群の数の違いが説明可能と考えた。しかしL4群だけで重大な衝突進化が起きたという仮定は、直径5km以上の小惑星で L4とL5群のサイズ分布が似ていることを説明しにくいかもしれない。

まとめ トロヤ群形成プロセスはまだ混沌としている。衝突進化モデルはもっと検討されるべきだろう。ただし衝突進化モデルは現在の小天体のサイズ分布がもとになるので、木星以外のトロヤ群小惑星のサーベイ観測も並行して行い、他の惑星のトロヤ群天体のサイズ分布や総数を決めることが重要である。大惑星の移動プロセスは、惑星の初期位置や移動速度が様々なパラメータで検証される必要がある。しかし、おそらく最も大きな決め手となるのは、木星トロヤ群小惑星とカイパーベルト天体の内部組成の情報である。もし両者が一致していれば、木星トロヤ群小惑星はニース・モデルが言うようにカイパーベルトから落ちて来た天体なのであろう。両者が一致していなければ、大惑星の移動はトロヤ群の完全破壊を伴わない程度の穏やかな過程で、近くの微惑星をトロヤ群軌道に引き連れての移動であったのかもしれない。カイパーベルト天体の内部組成はカイパーベルト起源の彗星の観測から得られるかもしれないが、木星トロヤ群小惑星は彗星のように地球に接近してくれないので、地上からの観測は難しい。宇宙船による探査から情報を得るしかないかもしれない。JAXA/ISASでは「ソーラー電力セイル」を用いた外惑星領域探査実現の一環として、史上初めて木星L4点のトロヤ群小惑星へのフライバイ観測の検討が始まっており、実現が期待されるところである。天体表面の調査だけでなく、天体の内部情報を得る仕掛けも搭載してもらいたいところである。

Related papers: *Yoshida et al. 2001 PASJ **53** L13, Nakamura & Yoshida 2002 PASJ **54** 1079, Yoshida et al. 2003 PASJ **55** 701, Yoshida & Nakamura 2005 Astron. J **130** 2900, Yoshida & Nakamura 2007 Planetary and Space Science **55** 1113, Yoshida & Nakamura 2008 PASJ **60** 297, Nakamura & Yoshida 2008 PASJ **60** 293.*

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