FORMATION OF THE OUTER SOLAR SYSTEM - AN ICY LEGACY

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1. What is the FOSSIL Survey?

Formation of the **O**uter **S**olar **S**ystem – an **I**cy **L**egacy

Solar system archaeology:
Explore the history of the solar system by digging up fossils.

FOSSIL is a survey project for the icy world of the Solar System. It is carried out using the Subaru telescope and the wide-field CCD camera HSC. Although FOSSIL does not have many nights to survey a large area, its powerful point is to detect smaller outer solar system bodies than previous surveys (such as OSSOS) by taking advantage of the large aperture of the Subaru telescope and the wide field of view of the HSC.


Subaru telescope


Hyper Suprime-Cam (HSC)

2. Purpose of the survey

FOSSIL I FOSSIL II FOSSIL III

FOSSIL aims to detect previously undetected small icy sources, determine their orbits, and determine the following.

A. The **total mass** (estimated by studying the size distribution), **color** distribution, **rotation period** distribution and **bulk density** of resonant and classical objects in the Kuiper belt.

B. The presence or absence of a **Kuiper belt cliff**.

C. The distribution of icy bodies in the regions beyond the Kuiper belt (e.g. **detached** and **ninth planets**).

The above information provides clues to the early history of the formation of the Solar System, such as the outer edge of the protoplanetary disk, the appearance of large-scale planetesimal scattering during and immediately after planet formation, and the intrusion of extrasolar bodies.

We have planned three types of surveys: FOSSIL I, II, III

3. FOSSIL I

Brief summary of results and findings from FOSSIL I

Rotation period survey

- FOSSIL I surveyed 37.7 deg², including the Jupiter Trojan (JT) region (L4 and L5). During this survey we found 1241 JTs [1], 315 Hildas[2] and 438 TNOs[3].
- The rotation period of 53 JTs could be determined. From the lower limit of their rotation period distribution, the bulk density of the JT group was found to be about 0.9 g/cm³.
- The rotation period of 17 Hildas could also be determined. From the lower limit of their rotation period distribution, the bulk density of the Hildas was found to be about 1.5 g/cm³.
- The rotation periods of 29 TNOs were determined, but the lower limit of the rotation period distribution could not be estimated because of the small number of whole TNOs with known rotation periods. However, the average rotation period of the TNOs obtained with FOSSIL I is 11.2 hours, which is significantly longer than other small body's groups, so the bulk density is likely to be small.

✳ Other observations show that the bulk density of the main belt asteroids (MBAs) was about 3.0 g/cm³, so the bulk density gradually decreases as one moves outwards from the MBAs to the TNOs. This result is consistent with the theory of planetesimal composition and accumulation process.

✳ Interestingly, fast rotators were found in the Hilda group. Does this reflect collisional disruption events in the present Hilda group? Or are there other mechanisms accelerating rotation?

Observations

- A summary of the observations for each survey block

The total survey area is 37.7 deg².

Covered L5 area of Jupiter : 17.4 deg² (19Apr, 20May)

Covered L5 area of Jupiter : 20.3 deg² (20Aug, 20Oct)

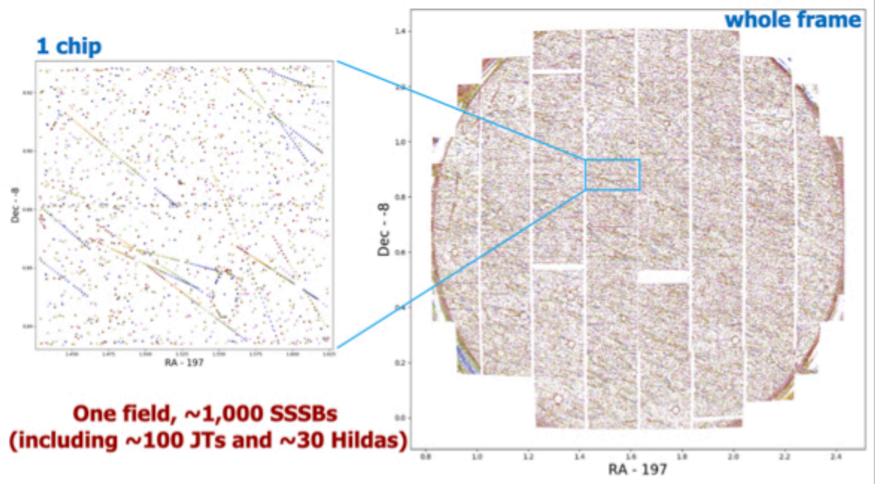
Block ID	RA (deg)	Dec (deg)	Number of Pointings	Filter	Exposure Time (s)	Limiting Magnitude	Cadence (min)	Date (UTC)	Exposures per Pointing	Time Span (hr)	
19Apr	197.526	−6.763	5	g	90	24.5	10	2019-04-10	53	8.8	Full night
20May	224.351	−14.596	2	$r2$	300	25.6	11	2020-05-19	23	3.8	Half night
						25.7		2020-05-20	21	3.8	
20Aug	341.656	−6.039	3	$r2$	300	25.6	16	2020-08-21	16	4.5	
						25.6		2020-08-22	15	4.0	
						25.5		2020-08-23	15	4.1	
20Oct	10.119	5.754	3	$r2$	150	25.5	15	2020-10-14	24	3.4	
						25.4		2020-10-15	24	3.4	
						24.0		2020-10-16	8	1.0	
						24.0		2020-10-17	8	1.0	

Observation time reduced due to bad weather

Note that we were originally allocated four full nights for S20A from 15-18 May 2020, but our observing time was rescheduled due to Covid-19. Instead of these nights we were awarded the observing blocks 20May, 20Aug and 20Oct, for a total of nine half nights. A full night's observation is much better than half a night for determining the rotation period of an asteroid. Yes, we know that the average rotation period of asteroids is 7 or 8 hours, so a full night of continuous observation of a single asteroid would have given a better chance of determining the rotation period. However, because of Covid-19, the staggered observing period made it impossible to observe the L4 region for a full night.

Data reduction, Moving object detection and Photometry

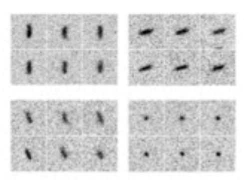
- A combination of the official HSC pipeline, hscPipe v8.3[4], and difference imaging was used to process all images and to create catalogues of transient sources.
- The Pan-STARRS 1 catalogue[5] was used for astrometric and photometric calibration. Moving objects were picked out from the source catalogues using the Hough transform[6][7], an algorithm to group multiple detected objects in intra-night observations into single moving objects by finding linear motion[8].
- We required a detection in a minimum of five images before we added a moving object to the FOSSIL catalogue.
- Next, the source fitting software package TRIPPy[9][10] was used to obtain the photometry used in our lightcurve analysis. TRIPPy was used to better measure the photometry of trailed sources in FOSSIL images, although, unlike the Jupiter Trojans and Main Belt Asteroids, trailing was not an issue for the TNOs.



Detected objects

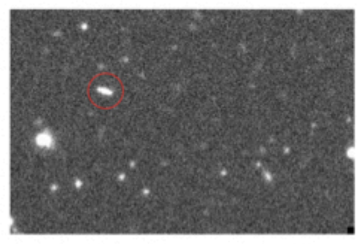
- We found many moving objects and classified them into groups of small solar system objects based on their movement across the sky plane.

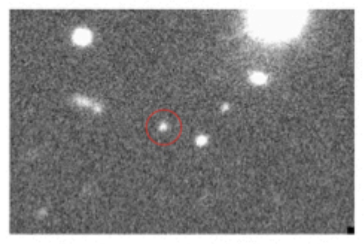
Populations	Number
TNOs	438
Centaurs	34
Jupiter Trojans	1241
Hildas	315
Main-belt	13510
Near-Earth	188

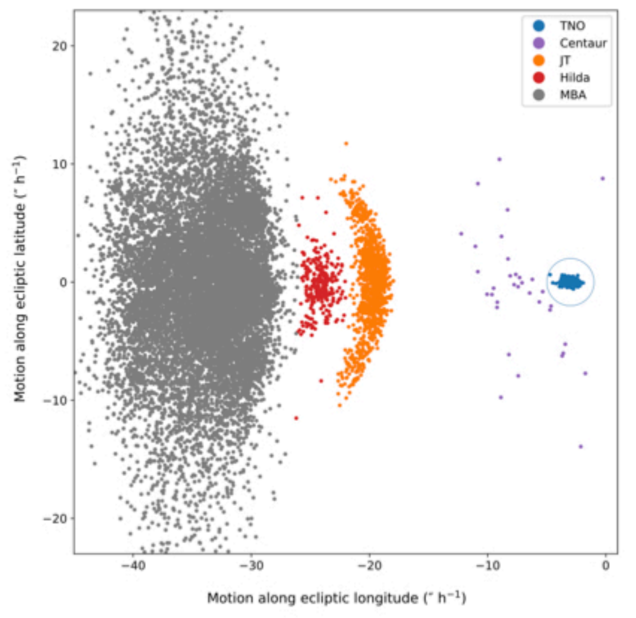


Cut-out image

Relatively fast-moving JTs will appear elongated, while slow-moving TNOs will appear round.


A Jupiter Trojan discovered by FOSSIL on 21 August 2020.

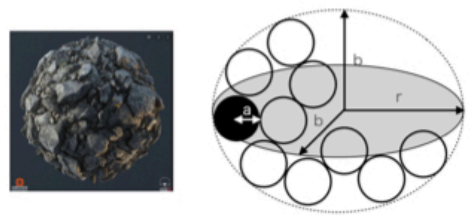

A TNO discovered by FOSSIL on 21 August 2020.



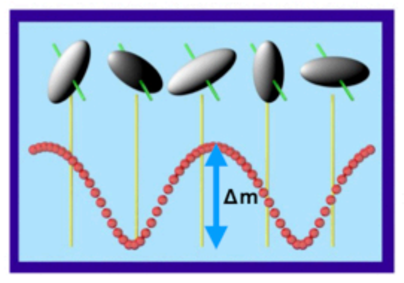
On-sky motion along the ecliptic longitude and latitude of the moving objects detected in the FOSSIL I survey. The motions allow the objects to be separated into different populations of small solar system objects: Main Belt asteroids (grey), Hilda asteroids (red), Jupiter Trojans (orange), Centaurs (magenta) and Trans-Neptunian objects (blue).

Internal Structure/Bulk Density of Small bodies

- The history of planet formation in our Solar System is a history of collisions. In the Solar System, during the period of planet formation, collisions and mergers of planetesimals occur in the protoplanetary disk.
- It is thought that the interior of small bodies still retains the information from the period of planetesimal collisions and mergers. Since small bodies are the products of collisions and mergers of planetesimals, they are expected to have voids in their interiors.



If the rotation is slow, the small body can maintain its rubble-pile structure, but if it rotates faster than a certain spin rate, the centrifugal force prevails over gravity and the body gets to be elongated and then finally collapses.



The spin-rate limit (gravity = centrifugal force)

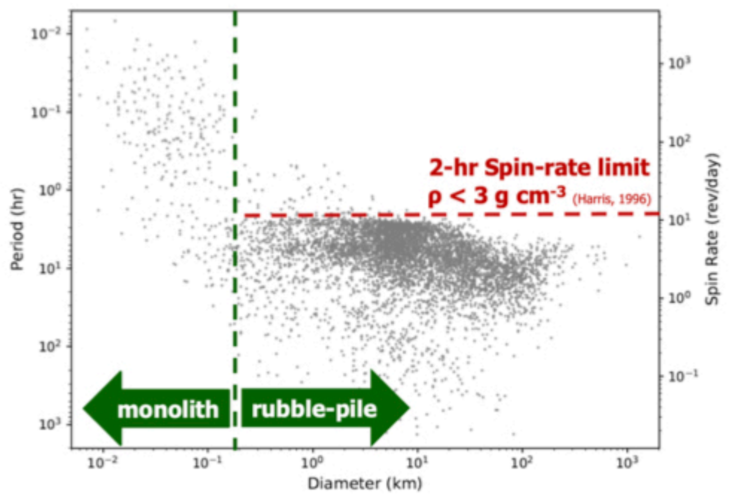
$$P_{lim} \sim 3.3\sqrt{\frac{1+\Delta m}{\rho}}\ (\mathrm{hr})$$

↓↓↓↓

A proxy of internal structure and bulk density
Constraints on asteroid groups & solar system formation

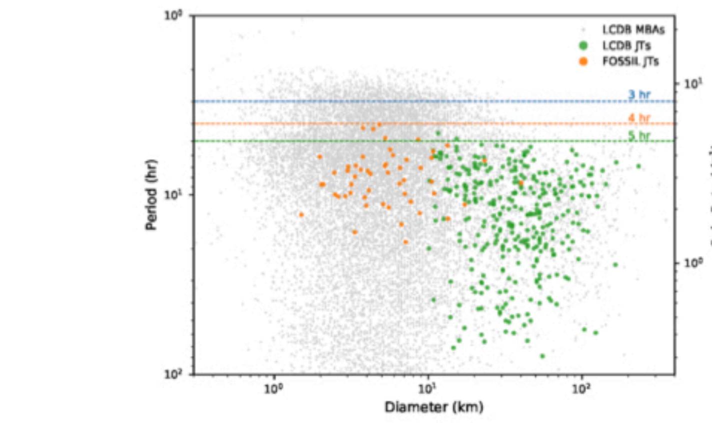
Internal Structure/Bulk Density of MBAs

- The MBAs have been well studied these relationships (P_{lim}, Δm, ρ).
- There are no MBAs with rotation periods shorter than two hours.
- Almost all the objects in the Monolith region are near-Earth asteroids.
- Recently, however, surveys have been conducted more frequently and some MBAs have been found in this area. Since the rotation period of NEAs and MBAs is known to change due to non-gravitational effects such as the YORP effect, these are probably the objects just after the collapse by the YORP effect.
- The bulk density of MBAs is about 3 g/cm³, which is consistent with the idea that rocky planetesimals are loosely assembled to form a single body (rubble-pile structure).

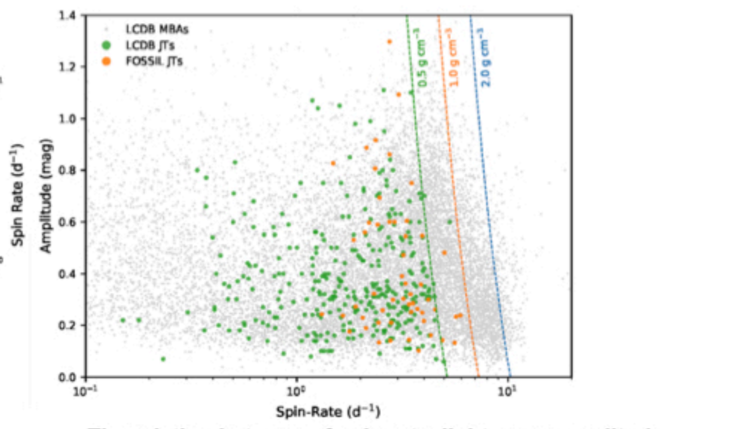


Internal Structure/Bulk Density of Jupiter Trojans (JTs)

- We detected 1241 JTs, we could determine the rotation period of 53 JTs.



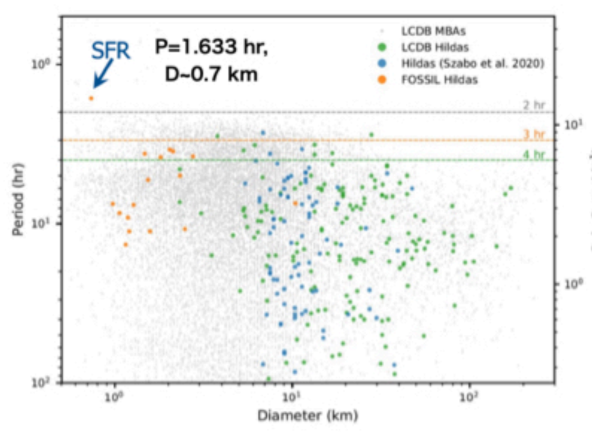
MBAs and known JTs are also plotted together for comparison.
Gray is MBAs, green is known JTs, and orange is the result from the FOSSIL survey. Clearly, the FOSSIL survey was able to detect smaller JTs and determine the rotation period.
The spin limited looks about 4 hours for the Jupiter Trojan group.

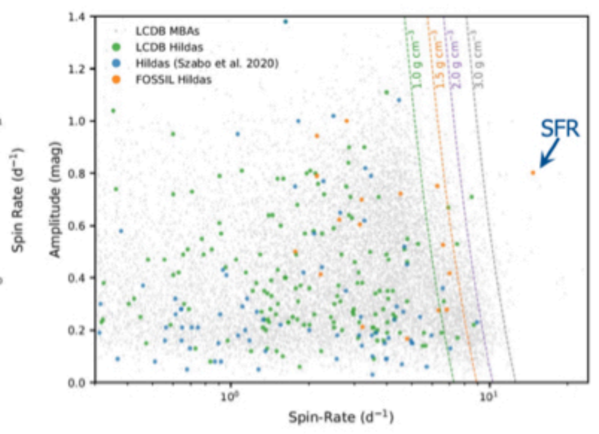


The relation in terms of spin rate, light curve amplitude, and bulk density.
The bulk density of the JTs to be about 0.9 g/cm³ — good agreement with ~0.8-1.0 g/cm³ for (617) Patroclus-Menoetius system, binary JT. This bulk density of JTs supports the idea that the member of JTs has a rubble-pile structure composed of ice-dominated planetesimals, as inferred from the location of formation of the Jupiter Trojan group.

Internal Structure/Bulk Density of Hildas

- We detected 351 JTs, we could determine the rotation period of 17 Hildas.





In addition, we found one fast rotator in Hildas. This is the first discovery of a fast rotator in the Hilda group. The Hilda group may be experiencing spin-up due to the YORP effect as well as MBAs or NEAs.

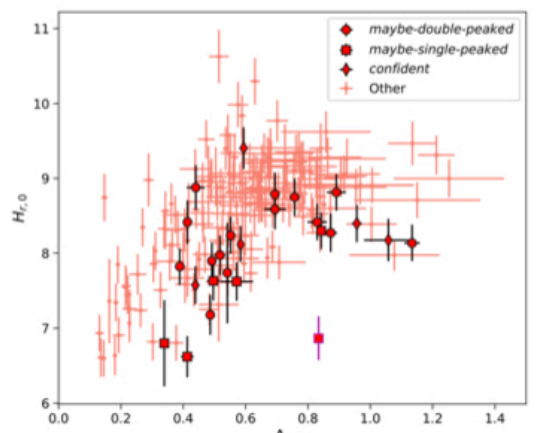
As in the case of JTs, MBAs and known Hildas are also plotted together for comparison.
Gray is MBAs, green is known Hildas, blue is Hildas from Szabo et l. (2020) and orange is Hildas from the FOSSIL survey. The FOSSIL survey (orange ones) clearly detects the smaller Hildas. Estimated the spin limited of Hildas is about 3 hours.

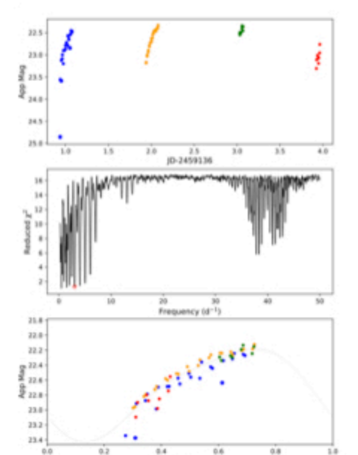
The relation in terms of spin rate, light curve amplitude, and bulk density.
Estimated the bulk density to be about 1.5 g/cm³. This value is similar to that of the C-type asteroids (1.33 g/cm³). This suggests that the Hildas population may contain more C-type asteroids than expected.

Binary candidate in TNOs

- We detected 371 JTs, we could determine the rotation period of 29 TNOs.
- The periodic TNOs have an average rotation period of 11.2 hours, close to the value obtained by Alexandersen et al. (2019)[11].
- We confirmed that smaller TNOs have larger light curve amplitudes, i.e. are more irregular in shape, with a relationship between absolute magnitude and light curve amplitude in a subset of 192 FOSSIL TNOs[3].

The time-averaged absolute magnitude versus lightcurve amplitude of the 192 FOSSIL TNOs that have more than 20 photometric measurements and a baseline of more than 6 hours.





The raw lightcurves (top panels), periodograms (middle panels), and the folded lightcurves (bottom panels) for the candidate compact binary, FSOC01020126.

FOSSIL members

https://fossil-survey.org

Please visit us. You will get more information about FOSSIL.

- The FOSSIL is an international team.

35 members (Japan 8, Taiwan 8, China 7, Korea 5, Canada 4, India 1, NZ 1, USA 2)

Fumi Yoshida[1,2], Mike Alexandersen[3], Edward Ashton[4], Michele Bannister[5], Chan-Kao Chang[4], Ying-Tung Chen[4], Wesley C. Fraser[6], Takashi Ito[7], Youngmin Jeongahn[8], Haibin Zhao[9], JJ Kavelaars[6], Samantha Lawler[10], Matthew Lehner[4], Jian Li[11], Patryk Sofia Lykawka[12], Keiji Ohtsuki[13], Rosemary Pike[3], Tsuyoshi Terai[7], Shiang-Yu Wang[4], Surhud More[15], Young-Jun Choi[8], Dong-Heun Kim[8], Natsuho Maeda[13], Paula Granados[4], Hirohisa Kurosaki[16], Zhong-Yi Lin[17], Peltier Lowell[18], Hong-Kyu Moon[8], Marco Munoz[4], Seitaro Urakawa[19], Jianghui Ji[11], Ji-Lin Zhou[11], Hui Zhang[20], Liyong Zhou[11], Myung-Jin Kim[8], and Jianchun Shi[9]

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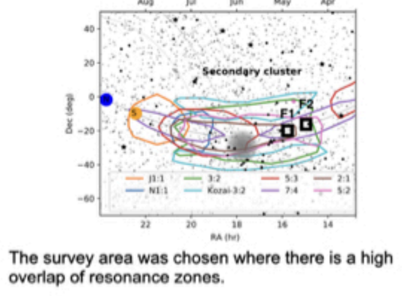
Institutional Partners

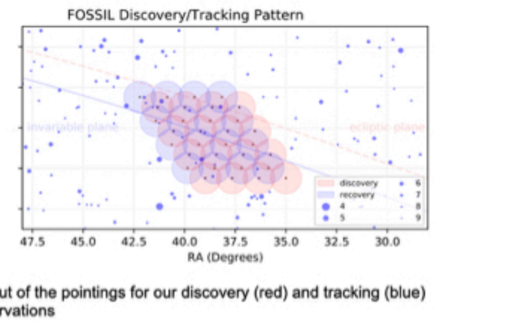
4. FOSSIL II

Finding new TNOs and determining their orbits, identify their dynamical groups.

- This survey began in March 2023.
- Surveys are carried out by dividing into pre-tracking, discovery, tracking and follow-up. The same area will be observed with several visits.
- The weather was very good for the March observations; the weather was not good for the May discovery run; the June observations were cancelled due to HSC problems; we are looking forward to the August observations.



The survey area was chosen where there is a high overlap of resonance zones.



Layout of the pointings for our discovery (red) and tracking (blue) observations

4. FOSSIL II

Finding new TNOs and determining their orbits, identify their dynamical groups.

- **Size distribution of resonant TNOs**

The survey will detect TNOs, determine their orbits from the observational arc over several months (preferably a year), and classify the detected TNOs into dynamical classes. By improving the orbital accuracy with the follow-up observations, the resonance zones to which the TNOs belong are revealed. Since the positions of the resonance zones have not changed since Neptune settled into its current orbit, the size distribution of the primordial Kuiper belt as a function of distance from the Sun will be obtained by studying the size distribution in each resonance zone.

The size distribution of TNOs is a consequence of their formation mechanism and subsequent evolution. In resonance zones located at relatively close perihelion distances, FOSSIL can detect smaller size TNOs (D ~ 35 km) than previous surveys (e.g. OSSOS), allowing precise measurements of the size distribution of small TNOs and signatures of the formation and collision history of resonant TNOs to be sought.

4. FOSSIL II

Finding new TNOs and determining their orbits, identify their dynamical groups.

- **Orbital distribution of High-perihelion Objects**

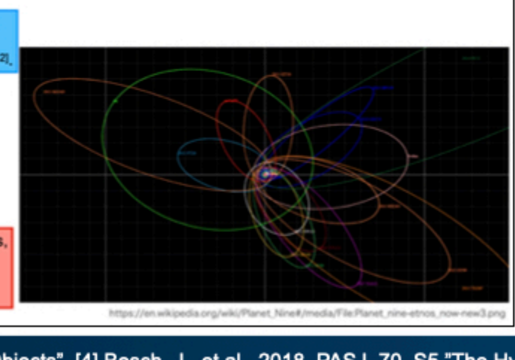
FOSSIL's sensitivity also allows it to detect objects more distant than the Kuiper belt. If FOSSIL can detect more of these objects, it will provide information that could reveal the shape of the outer edge of the Kuiper belt (the so-called Kuiper Cliff), the location of the ninth planet, and the orbital distribution of distant planetesimals.

- **Additional Scientific Results**

We already know how to find TNO binary candidates in the image[12].

- Reveal the binary fraction of small size TNOs.
- Measure the size distribution of small size MBAs, NEAs, Hildas and JTs which will also be in our images.

Prior to the FOSSIL survey, we had examined the size distributions of MBAs, Hildas and JTs and found that the size distributions of Hildas and JTs were almost identical [13][14], and that the size distributions of L4 and L5 of JTs were also identical[15]. These results would be confirmed by FOSSIL.

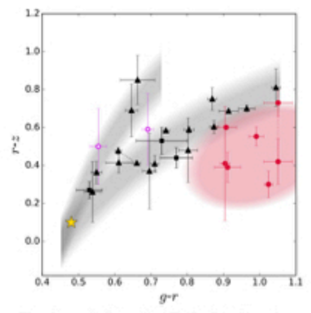


https://en.wikipedia.org/wiki/Planet_Nine#/media/File:Planet_nine-etnos_now-new3.png

5. FOSSIL III

Color (g, r2, z) survey of each dynamical group

- This survey has not yet been started.
- However, a survey of TNO colors should definitely be undertaken. The color distribution of each resonance zone group will provide information that can be linked to the chemical and mineral composition of the icy planetesimal belt at the time the object group was captured in the resonance zone. It is expected to provide fundamental information for understanding the composition and dynamical evolution of the primordial solar nebula.
- The OSSOS found that TNO color classification seems to work well with g, r and z photometry. FOSSIL III detects smaller TNOs than OSSOS, so we will get a color distribution of different TNOs than OSSOS. In addition, if we can make observations of Hilda, JTs and TNOs all at once, as we did with FOSSIL I, we may be able to obtain information by comparing the colors of the TNOs as to whether there are objects in the present Hildas and JTs that have fallen from the primordial Kuiper belt, as predicted by the theory of planetary migration.



The dynamically excited TNOs (black) and blue binaries (agent) occupy two surface types, "red" and "neutral" based on their g-r. The clod classical red surfaces can be identified with g, r, z photometry. The star indicates solar colors.

From Col-OSSOS[16]

We have experience using data from the HSC-Subaru Strategic Program survey to obtain TNO and Centaurs colors and to classify red and non-red objects [17][18]. We will use the same instruments in FOSSIL III, we are sure that we can obtain the TNO colors.
It would also be possible to measure the colors of MBAs [19].

References: [1] Chang, C.-K., et al., 2021, PSJ, 2:191 "FOSSIL. I. The Spin Rate Limit of Jupiter Trojans", [2] Chang, C.-K., et al., 2022, ApJSS, 259:7 "FOSSIL. II. The Rotation Periods of Small-sized Hilda Asteroids", [3] Ashton, E., et al., 2023 submitted. "FOSSIL III: Lightcurves of 371 Trans-Neptunian Objects", [4] Bosch, J., et al., 2018, PASJ, 70, S5 "The Hyper Suprime-Cam software pipeline", [5] Chambers, K. C., et al. 2017, VizieR Online Data Catalog, II/349, [6] Hough, P., 1959 Proc. Int. Conf. High Energy Accelerators and Instrumentation "Machine Analysis of Bubble Chamber Pictures", [7] Duda, R., & Hart, P. 1972, Communications of The ACM-CACM, 15, [8] Lo, K.-J., et al. 2020, AJ, 159, 25 "Asteroid Discovery and Light Curve Extraction Using the Hough Transform: A Rotation Period Study for Subkilometer Main-belt Asteroids", [9] Fraser et al. 2016a, AJ, 151, 158 "TRIPPy: TRAILED IMAGE PHOTOMETRY IN PYTHON", [10] Fraser et al. 2016b http://ascl.net/1605.010 "TRIPPy: Python-based Trailed Source Photometry", [11] Alexandersen, M., et al. 2019, ApJS, 244, 19, "OSSOS. XII. Variability Studies of 65 Trans-Neptunian Objects Using the Hyper Suprime-Cam", [12] Lin, H.-W., et al. 2010, PASP, 122, 1030 "On the Detection of Two New Trans-Neptunian Binaries from the CFEPS Kuiper Belt Survey", [13] Yoshida, F. & Terai, T., 2017, AJ, 154:71 "Small Jupiter Trojans Survey with the Subaru/Hyper Suprime-Cam", [14] Terai ,T. & Yoshida, F., 2018, AJ, 156:30 "Size Distribution of Small Hilda Asteroids", [15] Uehata, K., et al. 2022, AJ, 163:213 "Size Distribution of Small Jupiter Trojans in the L5 Swarm", [16] Pike, R. E., et al., 2017, AJ, 154, 101 "Col-OSSOS: z-Band Photometry Reveals Three Distinct TNO Surface Types", [17] Sakugawa, H., et al. 2018, PASJ, "Colors of Centaurs observed by the Subaru/Hyper Suprime-Cam and implications for their origin", [18] Terai, T., et al., 2018, PASJ, 70, S40 "Multi-band photometry of trans-Neptunian objects in the Subaru Hyper Suprime-Cam survey", [19] Maeda, N., et al. 2021, AJ, 162:280 "Size Distribution of Bluish and Reddish Small Main-belt Asteroids Obtained by Subaru/Hyper Suprime-Cam".