Solar system science from **FOSSIL I** [S20A-096I]

Formation of the Outer Solar System - an Icy Legacy

Explore the icy world.

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

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FOSSIL members

- The FOSSIL is an international team.
- Zoom meetings are held regularly to provide an opportunity for members to communicate with each other and discuss the progress of their research.
- We also launched a website. You can see the research purpose and results from FOSSIL I. Data sharing is also done on this site.

https://fossil-survey.org

- Data reduction and identification of moving objects have been carried out at ASIAA and members in each country can download the moving object catalogue from, the website for use in their own research.

- The dataset of moving objects detected by FOSSIL I is not available to the public at the moment. But the objects detected by FOSSIL I will be reported to the MPC. Such reports, together with previous detections from other surveys in the MPC database, will help to determine the exact orbit of our detected moving objects.

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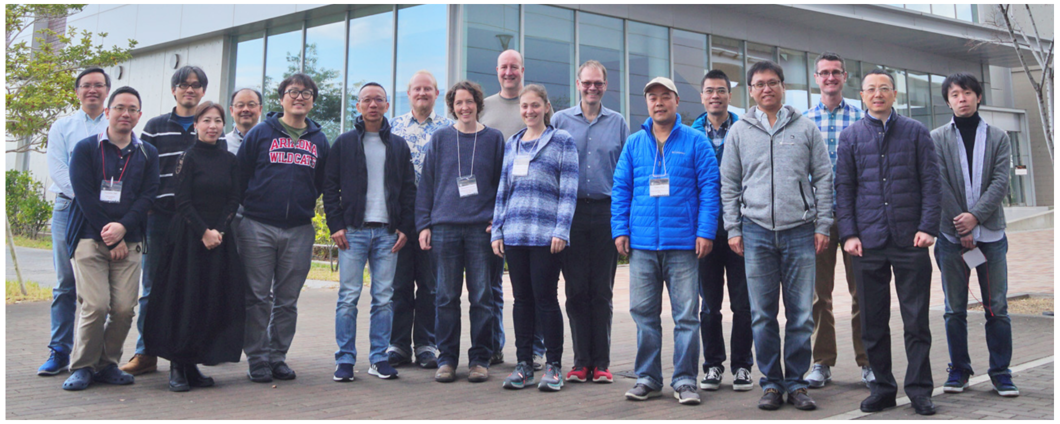
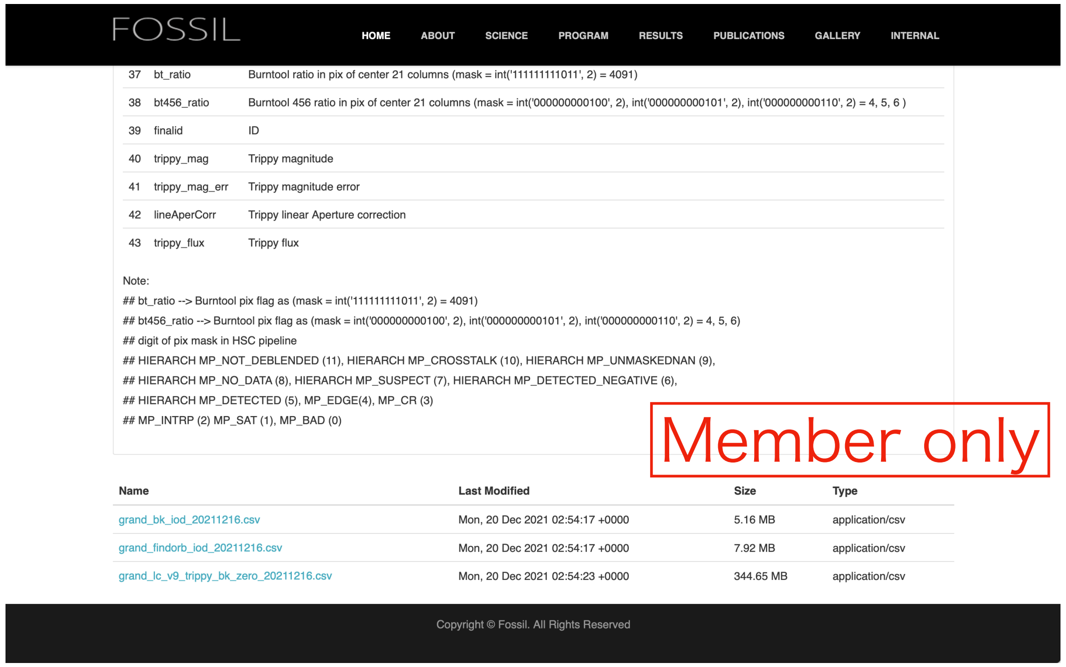
35 members (Japan 8, Taiwan 7 , China 6, Korea 5, Canada 5, India 1, NZ 1, USA 2)





Scientific Goals of FOSSIL

The FOSSIL Survey is an intensive program of the Subaru Telescope using the Hyper Suprime-Cam (HSC) to investigate the formation and evolution of our Solar System. FOSSIL will probe the populations of the Jupiter Trojans (JTs) and Trans-Neptunian Objects in order to learn about their formation histories and dynamical evolution.

FOSSIL was designed to detect efficiently from small JTs to distant/small TNOs, in order to answer specific questions about Solar System formation and evolution which have been left unanswered by earlier observations and will not be well addressed by future surveys (such as LSST).

The main scientific goals of the survey are:

Colors and Rotation Periods of Jovian Trojans

Where were the JTs formed and how did they become co-orbitals? FOSSIL aims to target both the L4 and L5 JT cloud to measure the size distribution, colors, and light-curves of a large sample of JTs. This will constrain the origin and evolution of JTs and the role of Jupiter's migration in the early Solar System.

High-Perihelion Objects

What are the population size and orbital distribution of high-q objects? FOSSIL will use a large and deep survey to detect these objects. Their orbital distribution is indicative of the migration of the giant planets and the presence of any undiscovered planets.

Colors of Resonant TNOs

Which surface types are most common in the resonances, and does this vary depending on the resonance location? FOSSIL aims to specifically target the 3:2, 5:3, 7:4, 2:1, and 5:2 which trapped objects from different formation locations during planetary migration. The color distribution within the resonances constrains the composition of the proto-planetesimal disk.

Plutino Size Distribution

How does the size distribution of Plutinos (3:2) change at small sizes? FOSSIL aims to robustly measure the number of smaller Plutinos by targeting the regions where they are most detectable. The number of small Plutinos probes their collisional history, formation density, and formation conditions.

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FOSSIL I (S20A and S20B) dealt with only this part.
The reasons : most of observations of S20A were cancelled because of COVID-19, and our observations allocated in September (S20B) were separated to August and October due to sudden change of Subaru schedule (maintenance work).

Due to the visibility of the field of view, we could only observe half a night at a time and there was no time to change the filters, so we gave up on color observations.

However, the color is essential for the characterization of Jupiter Trojans, we are trying to apply for the observation again.

For other science cases it is necessary to determine the orbits of the detected moving objects, because without an accurate orbit determination it is not possible to classify the dynamical groups of TNOs.
For these purposes, and to obtain color information, we are planning a survey of FOSSIL II.

FOSSIL I observations in S20A &S20B

S20A-096I

8 nights in 20A and 20B

May 15-18 4 nights for L5 of Jupiter Trojans region

September 4 nights for L4 of Jupiter Trojans region

COVID19 forced us to change our observation plan.

May 18, 19 2 half nights for L5 of Jupiter Trojans region. *Survey area: ~3*deg^2

August 19-22 4 half nights for L4 of Jupiter Trojans region. *Survey area: ~4.5*deg^2

October 13-26 4 half nights for L4 of Jupiter Trojans region. *Survey area: ~4.5*deg^2

February 9-12 3 full nights and 2 half nights for TNO detection and g,r,z colors. *Survey area: ~7.5*deg^2

Compensation for the first 3 night in May 2020.
However, the Jupiter Trojan group stay in a completely different direction at this time and could no longer be observed.

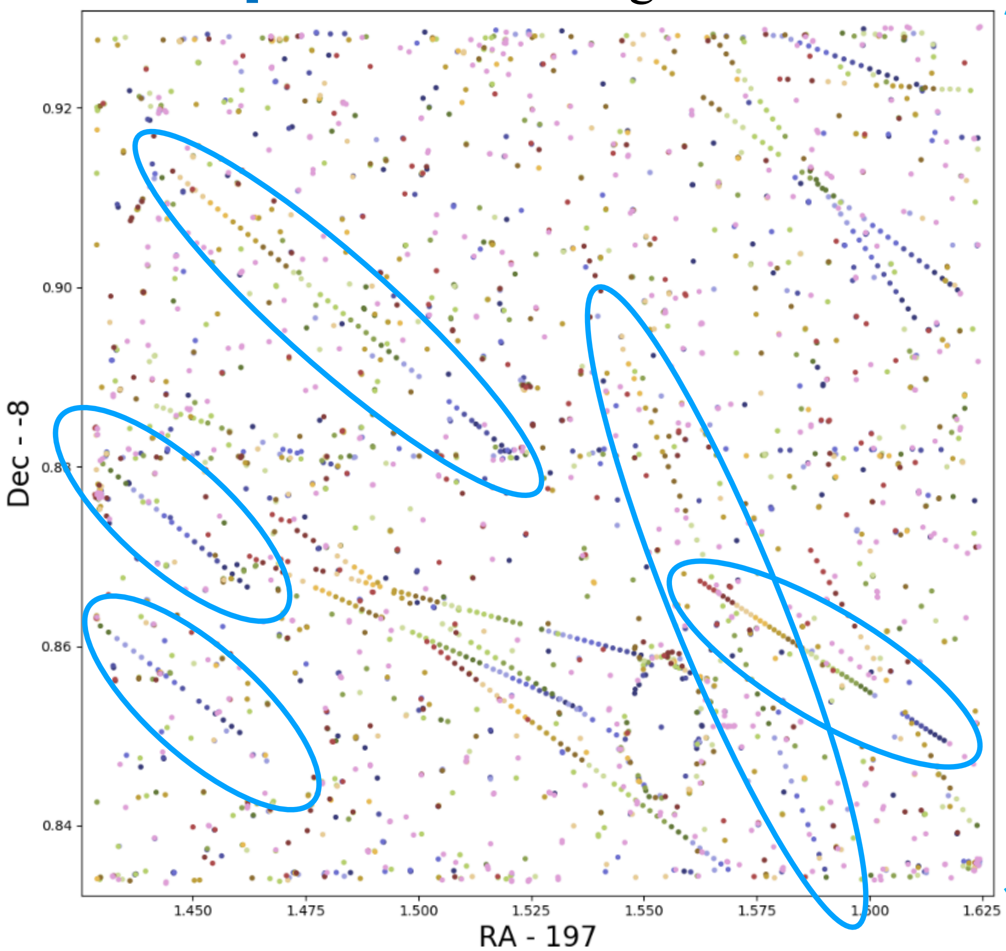
The weather of February run was very unstable.

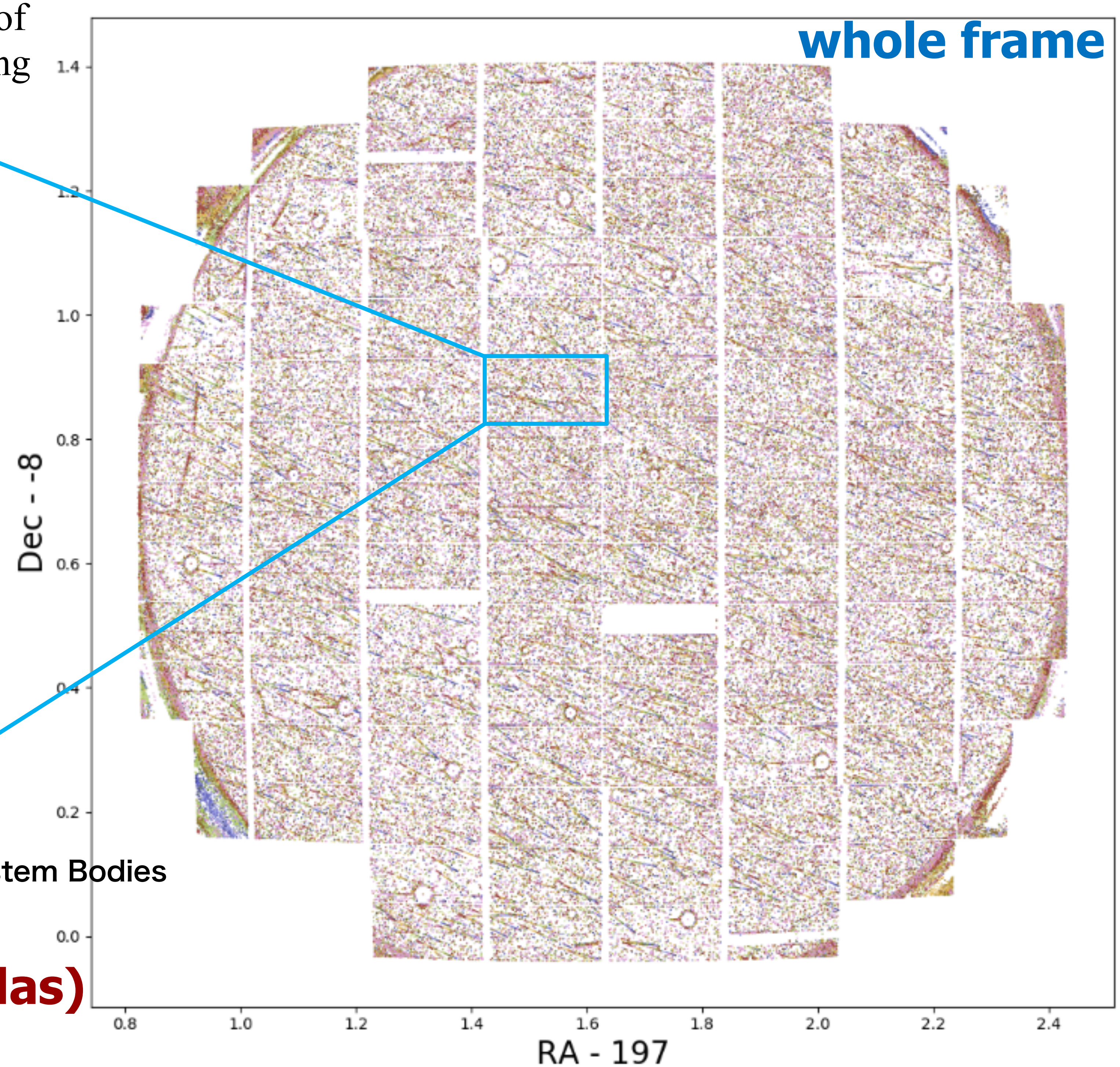
Moving object detection

All data from May, August and October, 2020 have been reduced, and analyzed.

The moving object appears a group of points aligned in a straight line among the detected light sources.

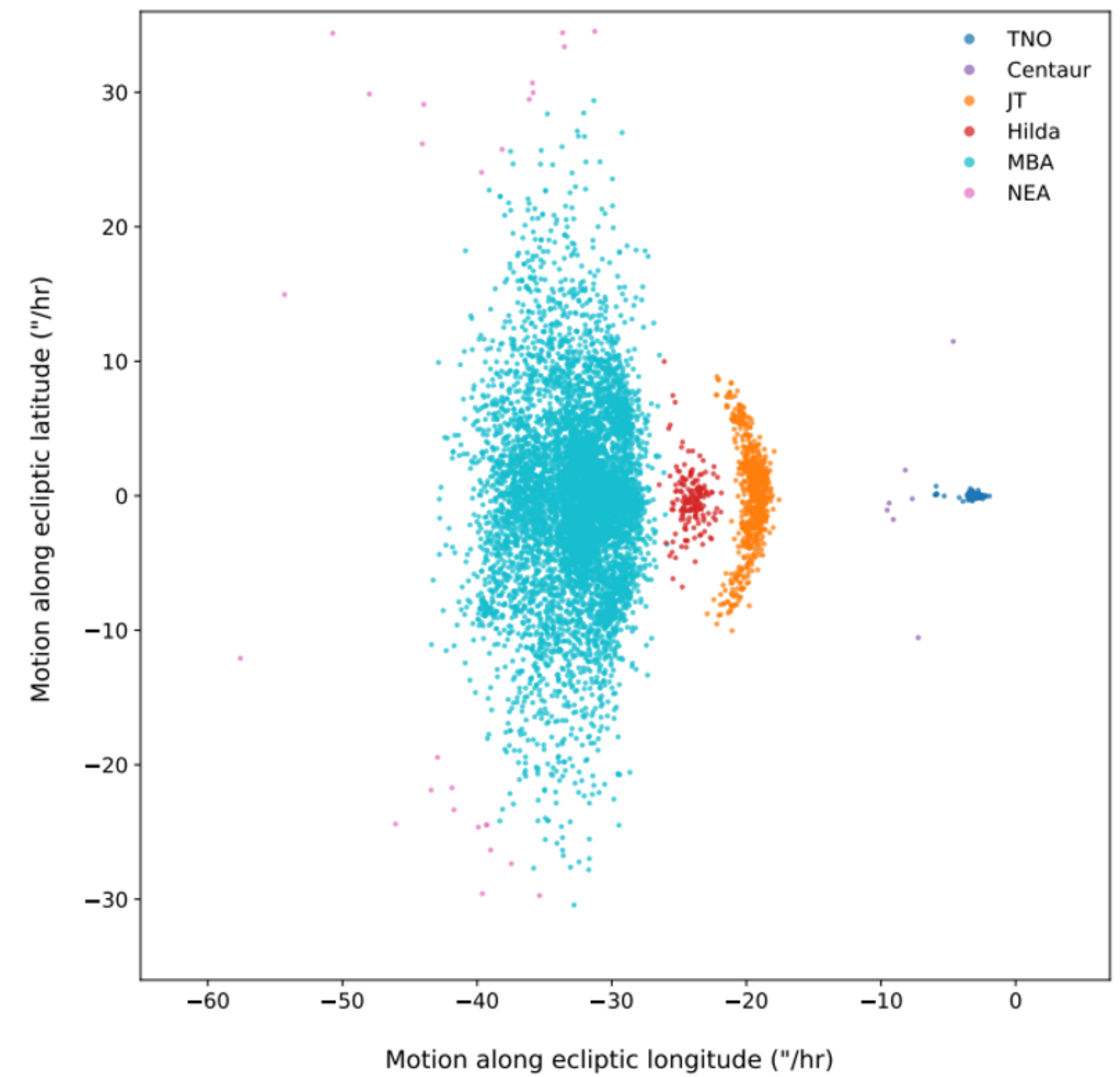
1 chip

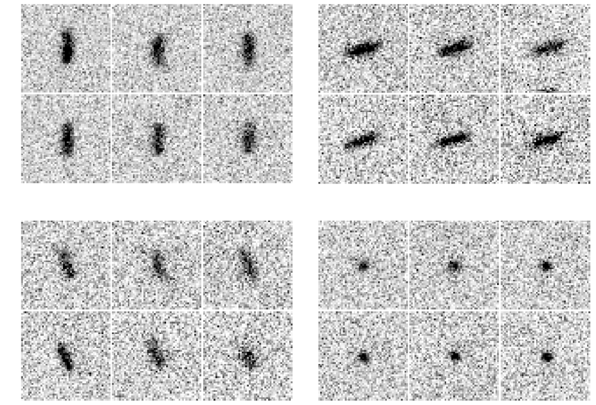




Small Solar System Bodies

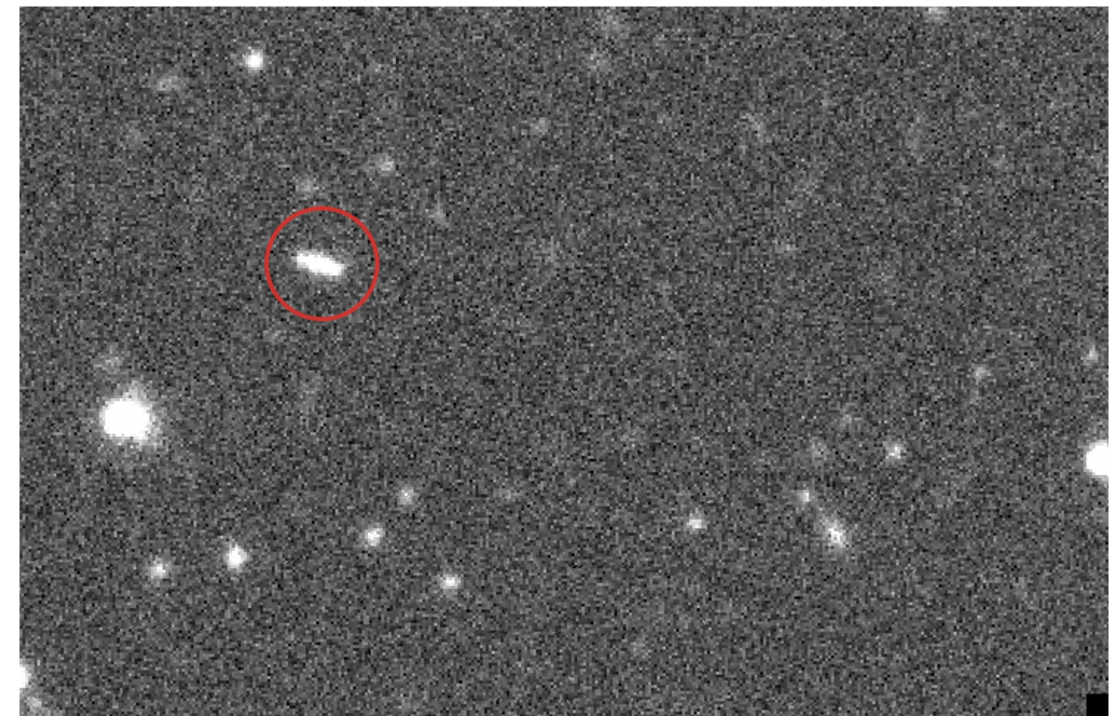
One field, ~1,000 SSSBs (including ~100 JTs and ~30 Hildas)





Cut-out image

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

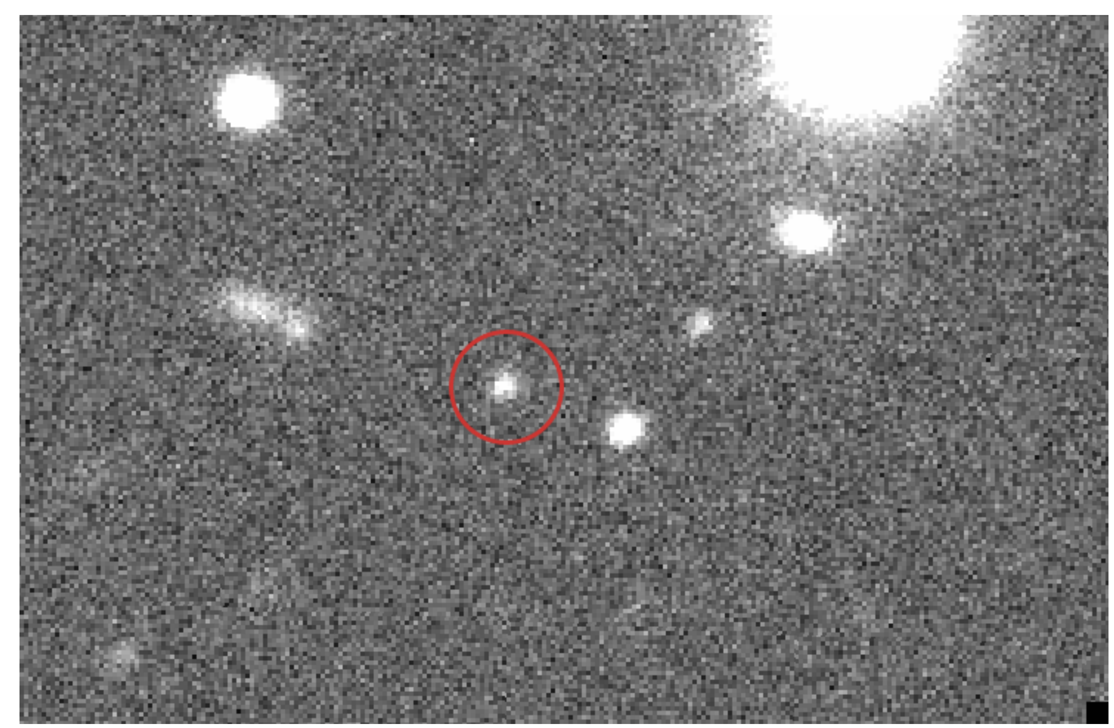


A Jupiter Trojan discovered by FOSSIL on 21 August 2020.

Classifies moving objects according to their moving speed.

They can be classified into NEAs, MBAs, Hildas, JTs, Centaurs, and TNOs.

Populations	Number
TNOs	447
Centaurs	617
Jupiter Trojans	1241
Hildas	315
Main-belt	13510
Near-Earth	188

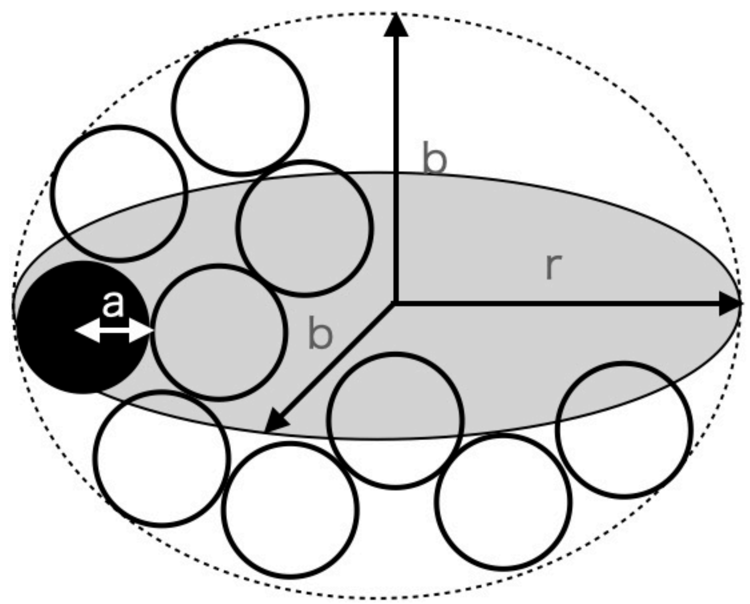


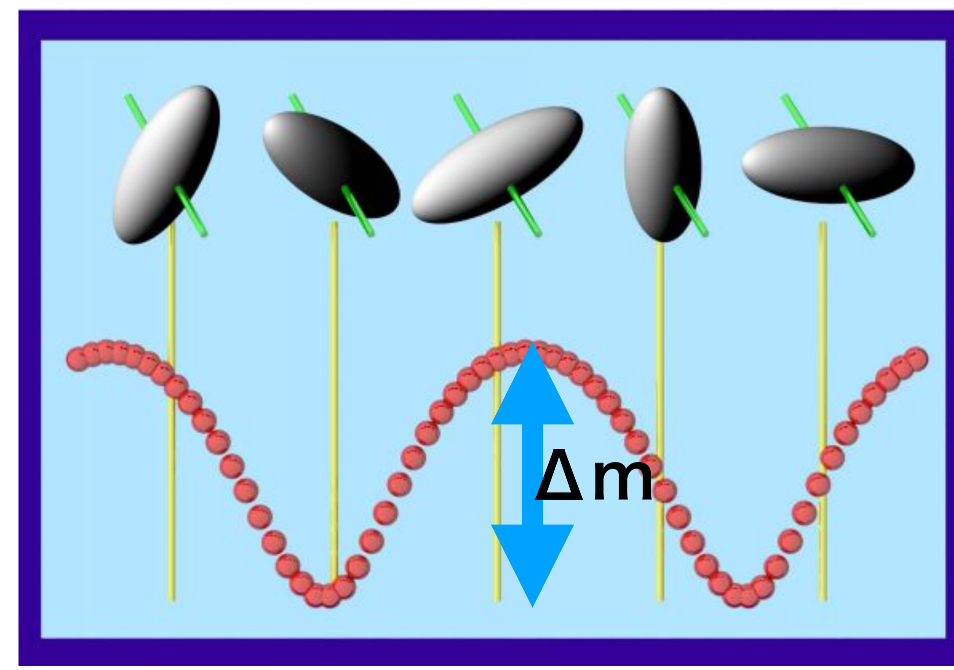
A TNO discovered by FOSSIL on 21 August 2020.

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 planet formation period, collisions and mergers of planetesimals occur in the protoplanetary disk.
It is believed that the interior of small bodies still retains the information from the period of planetesimal collision and merge. Since small bodies are the products of collision and merge 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)

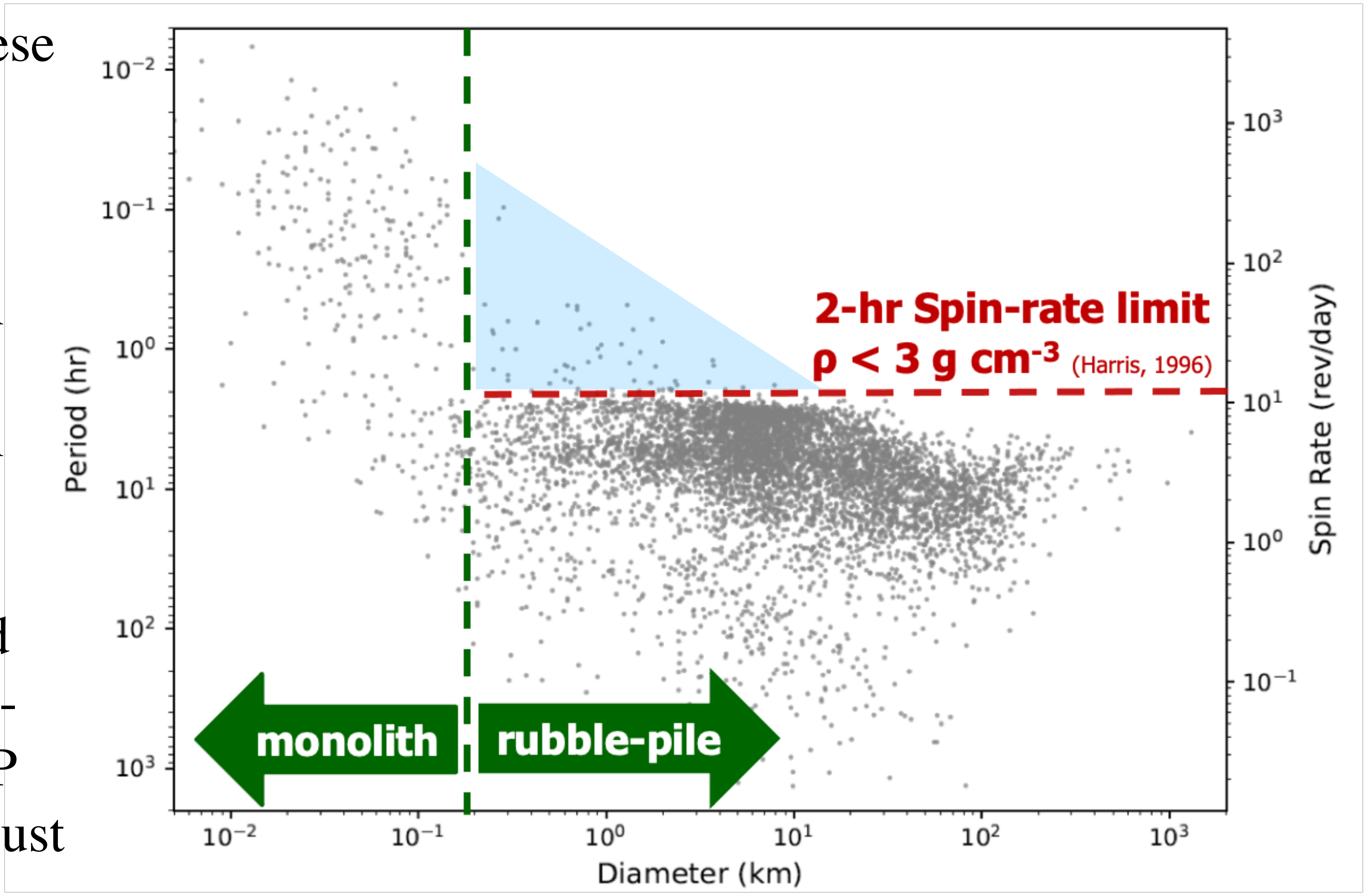
$$P_{lim} \sim 3.3\sqrt{\frac{1+\Delta m}{\rho}}\ \text{(hr)}$$

↓↓↓↓

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/cm^3, which is consistent with the idea that rocky planetesimals are loosely assembled to form a single body (rubble-pile structure).

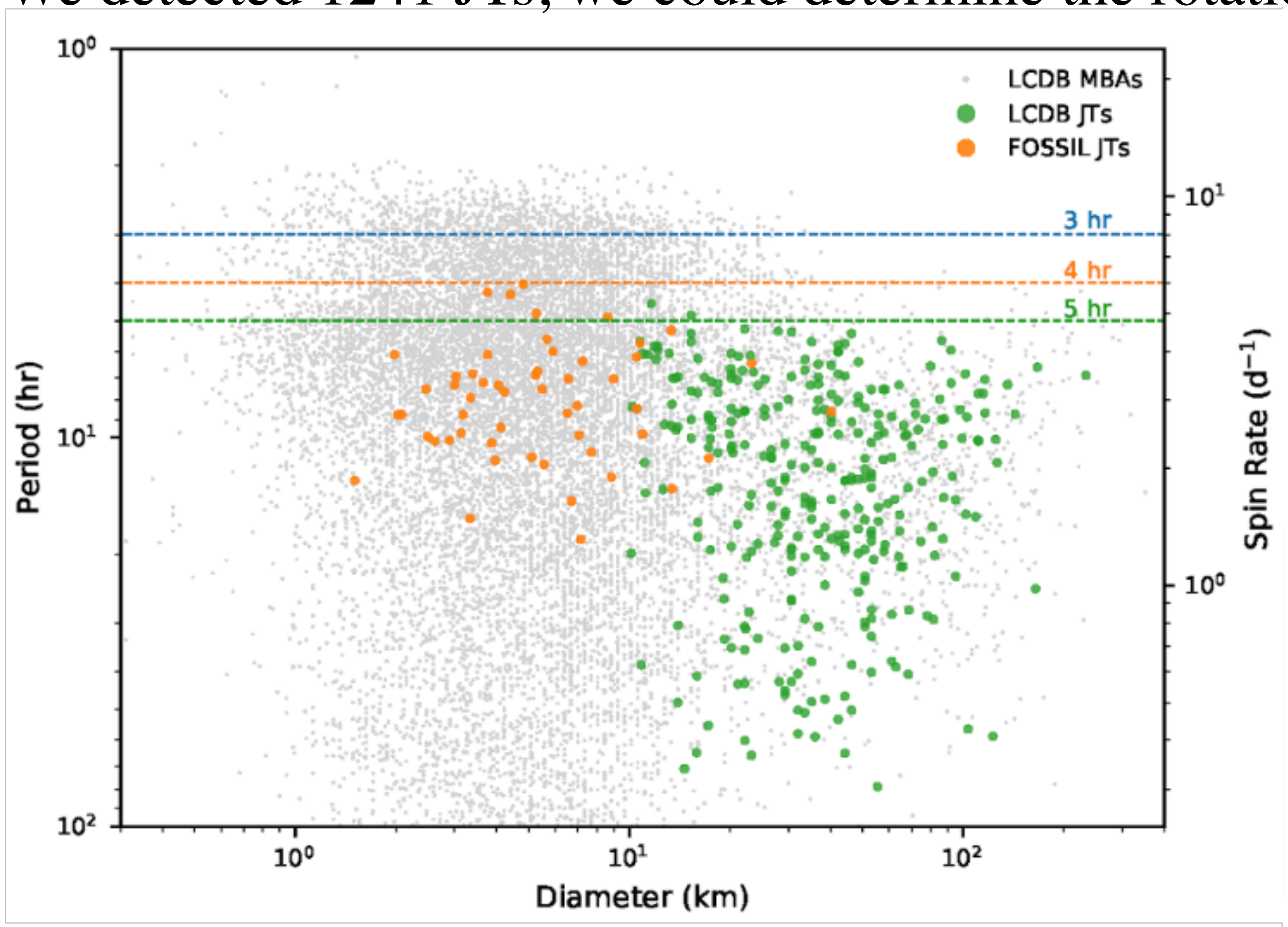


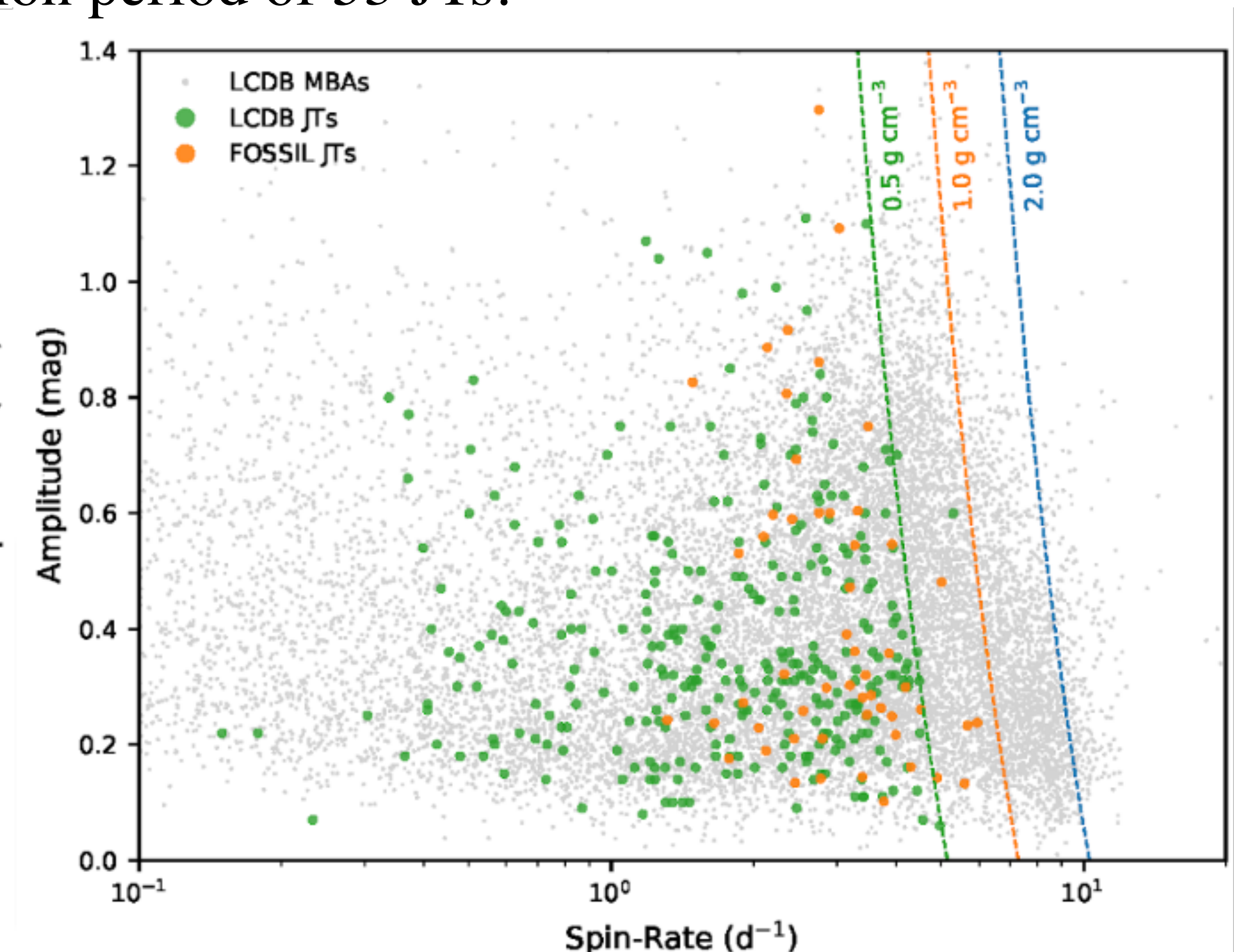
Internal Structure/Bulk Density of Jupiter Trojans (JTs)

FOSSIL work

Chang et al. the Planetary Science Journal, 2:191 (11pp), 2021

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





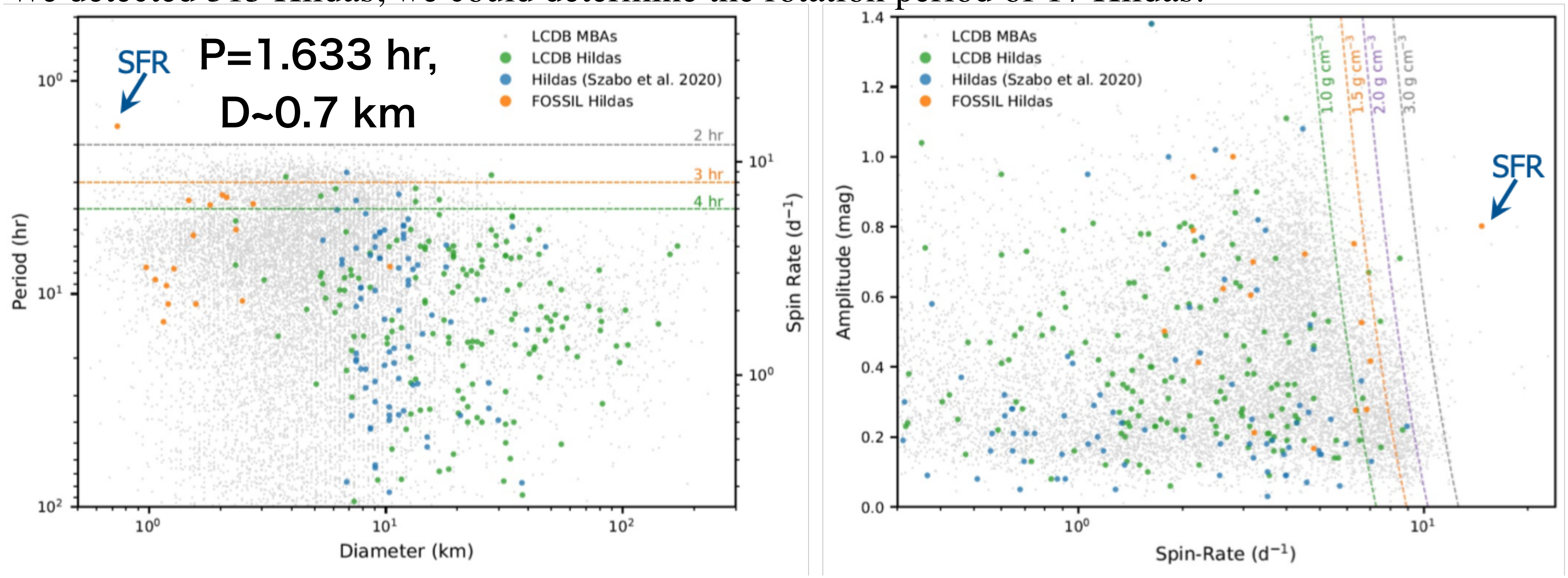
- MBAs and known JTs are also plotted together for comparison.
- In the left panel, gray is MBAs, green is known JTs, and orange is the result from the FOSSIL survey. Clearly, the FOSSIL survey was able to detect smaller JTs and determine the rotation period.
- The spin limited looks about 4 hours for 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/cm^3 — good agreement with ~0.8-1.0 g/cm^3 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

FOSSIL work

Chang et al. submitted to the Planetary Science Journal

We detected 315 Hildas, we could determine the rotation period of 17 Hildas.



- As in the case of JTs, MBAs and known Hildas are also plotted together for comparison. The FOSSIL survey (orange ones) clearly detects the smaller Hildas.
- We estimated <u>the spin limited of Hildas is about 3 hours.</u>
- We estimated <u>the bulk density to be about 1.5 g/cm^3.</u> This value is similar to that of the C-type asteroids (1.33 g/cm^3). This suggests that the Hildas population may contain more C-type asteroids than expected.

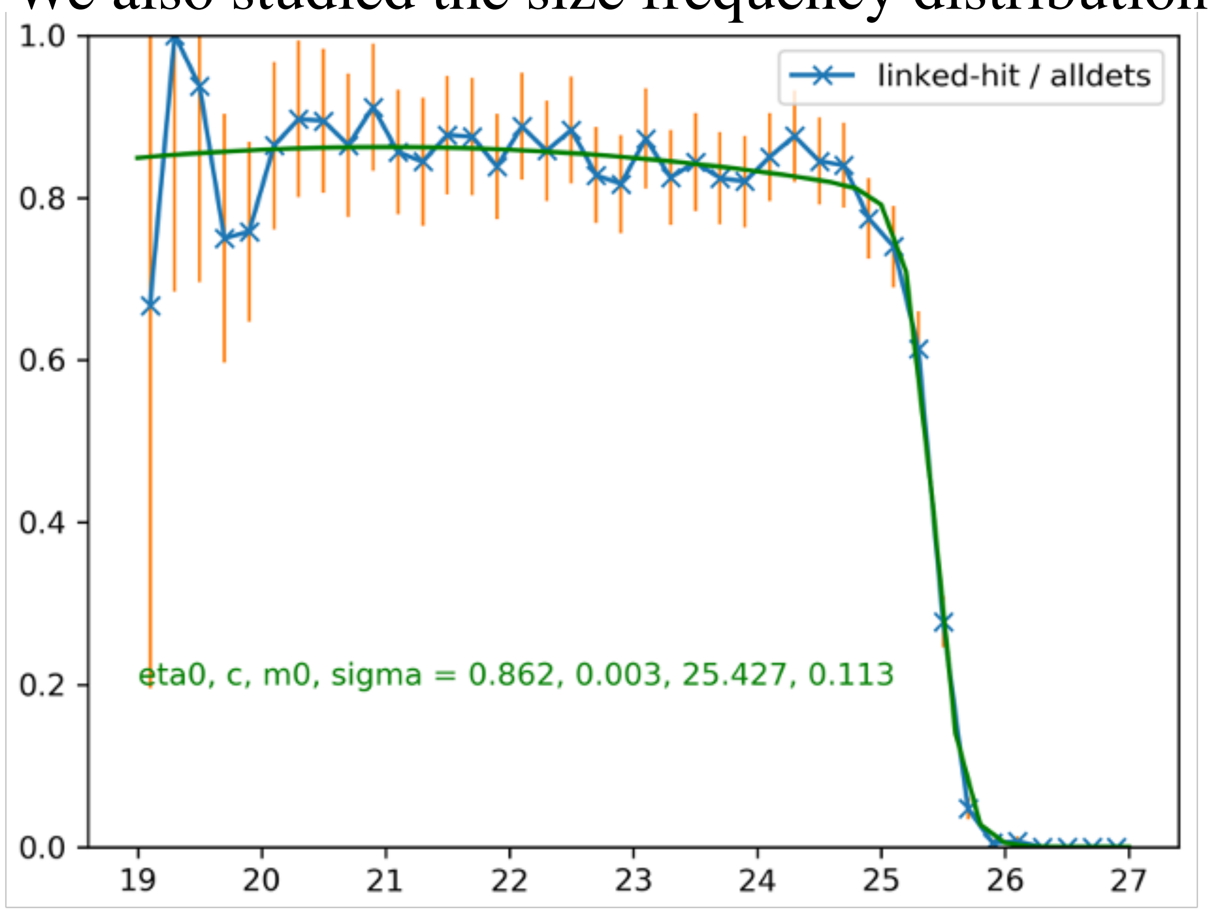
- In addition, we found one fast rotator in Hildas. This is the first discovery of a fast rotator in the Hilda group. The Hilda group may be experiencing spin-up due to the YORP effect as well as MBAs or NEAs.

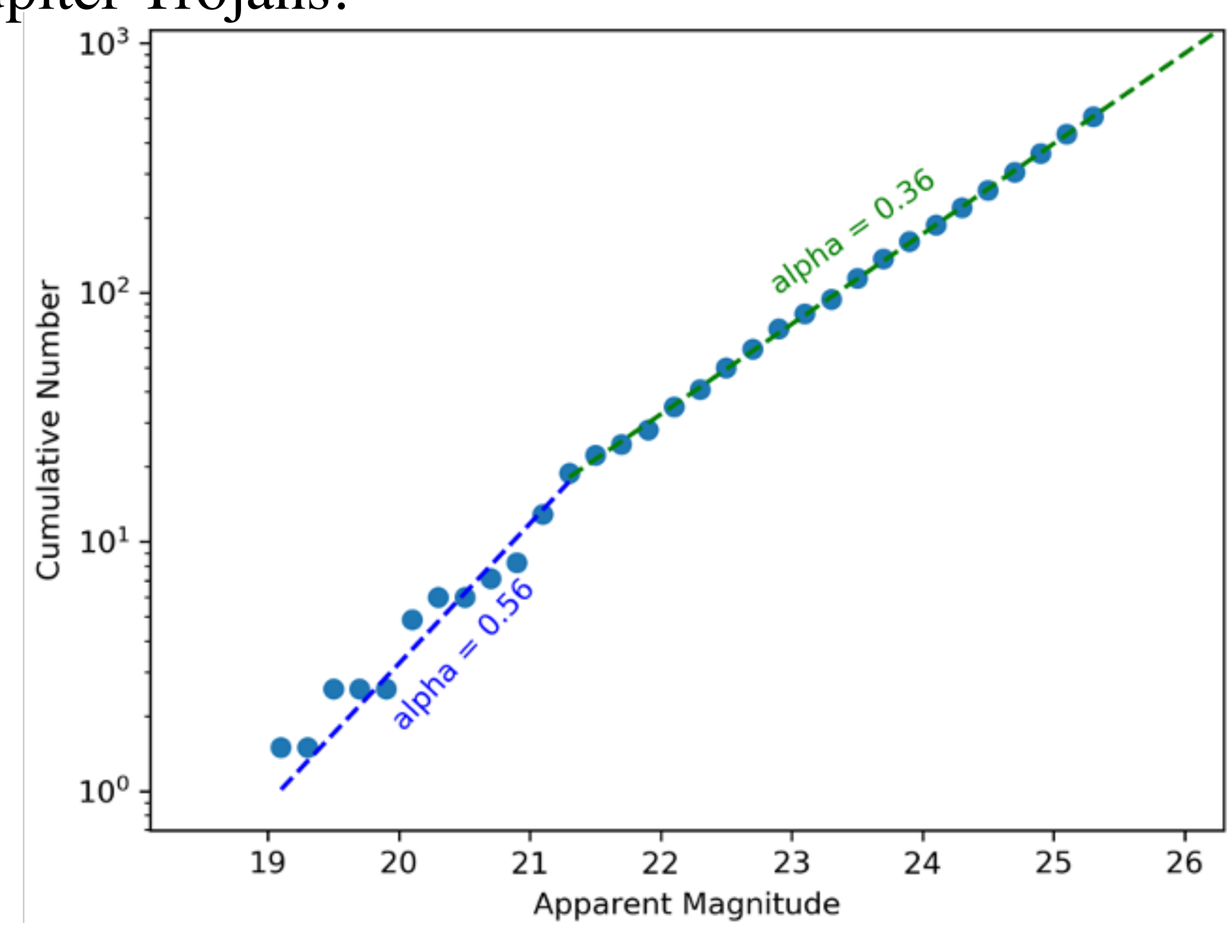
Size frequency distribution of JTs

FOSSIL work

Chen et al. in preparation

We also studied the size frequency distribution of Jupiter Trojans.





- The results are the same as the previous study: Yoshida & Terai 2017, Small Jupiter Trojans Survey with Subaru/Hyper Suprime-Cam. AJ, 154, 71.
- FOSSIL had better observational conditions and longer exposure time than this previous study, so we were able to do a deeper survey.

Detection limit : 25.4 mag@ FOSSIL, 24.4 mag@Yoshida&Terai (2017)

- FOSSIL survey confirmed that the same slope of the size frequency distribution continues down to smaller sizes.

Summary and future prospects

The following three results have been obtained by FOSSL I to date.

- Rotation period distribution and bulk density of Jupiter's Trojan group
- Rotation period distribution and bulk density of Hilda asteroids
- Size distribution of Jupiter's Trojan group

We will investigate

- Rotation period distribution of MBAs, which are smaller than the known MBAs.
- Discovery of Main belt comets.
- Rotation period distribution and bulk density of TNO group

Since we know that there are four dynamical groups with different histories of orbital and collisional evolution in TNOs, we need to study the characteristics of each of these dynamical groups. To do this, we need to determine the orbits more precisely and classify the detected TNOs into dynamical groups.

As FOSSIL II, we have twice proposed a survey to characterize the dynamical groups of TNOs. Although the science is highly appreciated, we have been denied by the TAC because The Subaru schedule in S22A does not match the timing requirements of the FOSSIL II survey. The FOSSIL II requirements are a set by both RA/Dec requirements and timing to measure orbits (3 observations with one or two month intervals + additional observation at 1 year later from the first-observation). We hope that Subaru observatory will cooperate so that the proposals whose science is highly evaluated will be realized.