

Polarimetric and Photometric observations of the very close approach NEA “2024 MK” and Hayabusa2# targets NEA “Torifune”



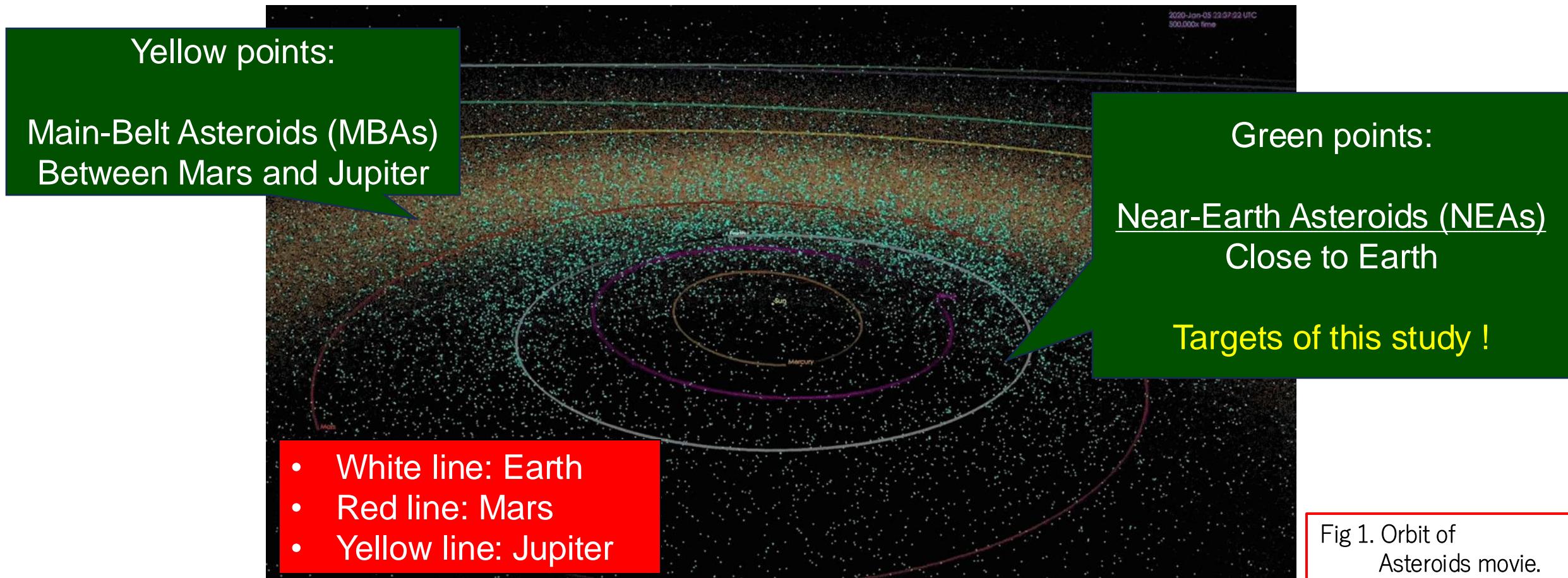
EOU Seminar
2024/12/20 14:45-16:15
M1 Kazuya DOI

Contents

1. Introduction
 - 1-1. Classification of Asteroids
 - 1-2. Origin of NEAs
 - 1-3. Taxonomy
 - 1-4. Number
 - 1-5. Planetary Defense (Space Guard)
 - 1-6. Planetary Defense Missions
 - 1-7. JAXA Hayabusa2# Mission
2. Purpose and Goals
3. Observation methods and can be derived physical properties
 - 3-1. Observation methods
 - 3-2. Identification of target Asteroids
 - 3-3. (A) Polarimetric observations
 - 3-4. (B) Photometric observations
 - 3-5. 1.6 m Pirka Telescope & MSI
 - 3-6. 3.8 m Seimei Telescope & TriCCs
4. 2024 MK
 - 4-1. 2024 MK Information and Observations
 - 4-2. 2024 MK Results
 - 4-3. 2024 MK Discussion
 - 4-4. 2024 MK Future works
5. Torifune
 - 5-1. Torifune Information and Observations
 - 5-2. Torifune Future works
6. Summary
7. References

1-1. Classification of Asteroids

Classification by Orbit



1-1. Classification of Asteroids

Potentially-Hazardous Asteroids (PHAs)

- Specifically, minimum orbit intersection distance is within 0.05 au, and diameter exceeds 140 m NEAs.
- PHAs have a high probability of collision, and cause significant potential hazards.
e.g., Itokawa, Ryugu

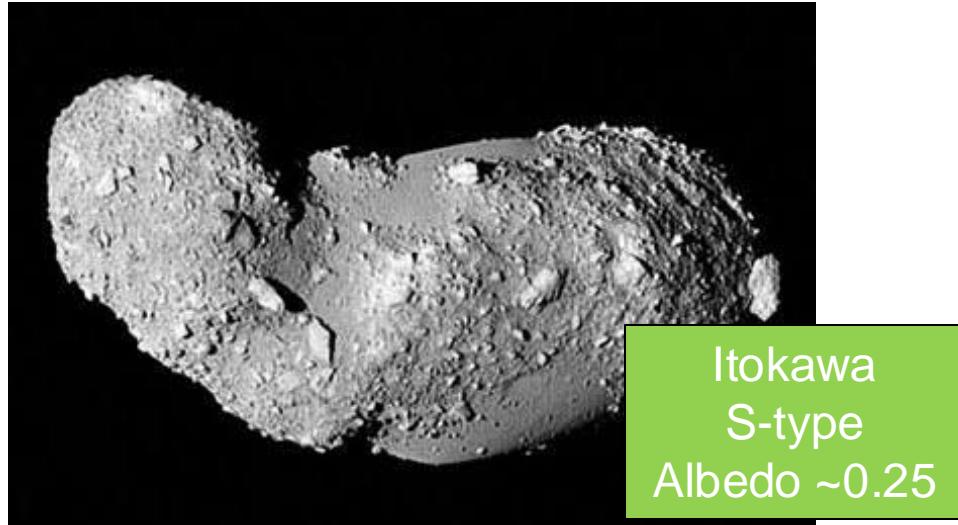


Fig 2, 3, 4. Image of asteroid impact, S-type PHA Itokawa, C-type PHA Ryugu.

1-2. Origin of NEAs

Asteroids as survivors of planetesimals

- Asteroids retain primordial information from before the formation of planets.

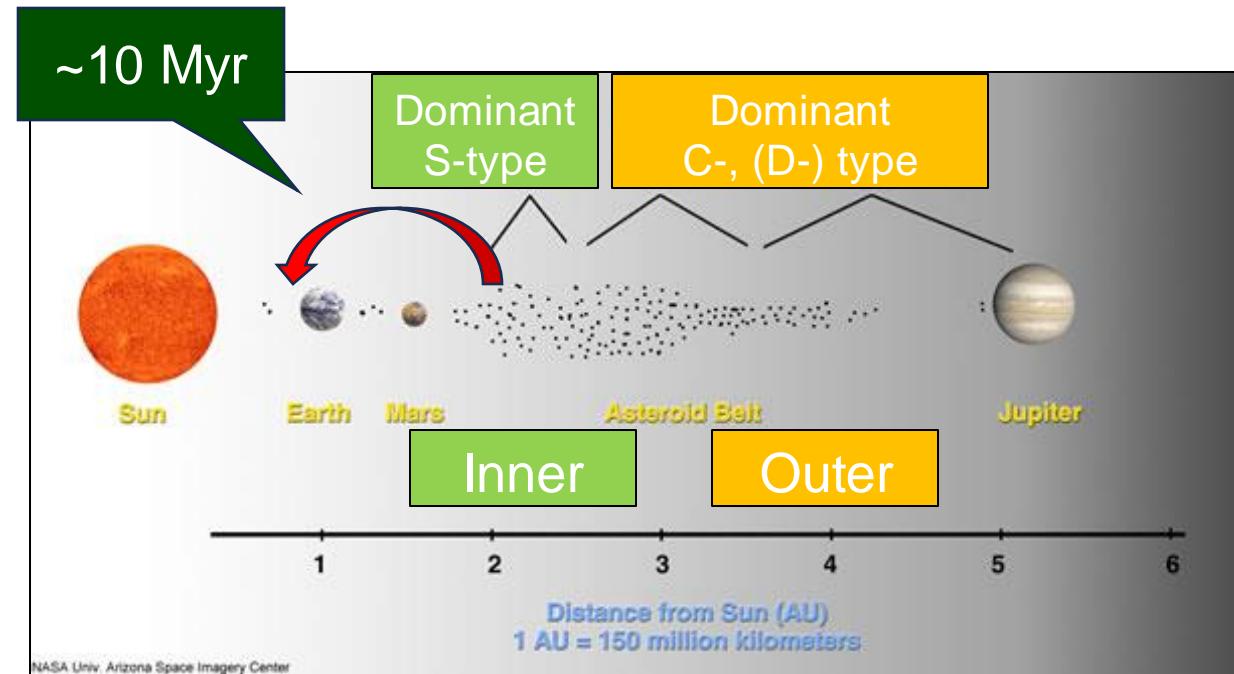


Fig 5. Simple model of distribution of asteroids in the Solar System.

Most NEAs originate from the Inner Main-belt

- Scattered by Jupiter's gravity, many S-types (stony) come from the inner Main-belt. In contrast, C-types (carbonaceous) are primarily located in the outer Main-belt. Due to their fragile composition, some cases collapse instead of being scattered. So that C-type NEAs are rare ~10 % (including dark observational bias).

1-2. Origin of NEAs

Origin of life (water) have been brought by Asteroids (and/or Comets) ?

- Considering the origin of meteorites means considering the origin of NEAs.
- NEAs come from the Main-belt (~10 Myr).
- The presence of water, minerals and amino acids has been confirmed.
e.g., C-type NEA Ryugu
- Material transportation by Asteroids (and/or Comets) ?
- Brought to Earth through collisions (like C-type NEAs) ?



Study of NEAs is important !

1-3. Taxonomy

5 major Types: Classification by surface composition

“Taxonomy”

1. S-type

Stony, silicate and olivine-rich.

2. C-type

Carbonaceous.

3. D-type

Tagish Lake meteorites.

4. V-type

Basaltic, fragments of Vesta.

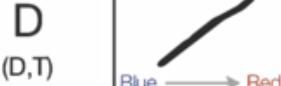
5. X-type

Various metallic meteorites.



Fig 6, 7. S-type Asteroid Itokawa, C-type Asteroid Ryugu.

Tab 1. Characteristics of the five major types.

Major Taxonomic Types	Reflectance Spectrum (0.4-0.9 um)	Spectral Features	Visible Albedo	Suspected Composition
D (D,T)		Relatively featureless spectrum Steep red slope	0.02-0.06	Primitive carbonaceous Organic-rich compounds Hydrated minerals
C (C,B,F,G)		Slight bluish to slight reddish slope Shallow to deep absorption blueward of 0.5 μm Hydrated asteroids with absorption at 0.7 and 3.0 μm	0.03-0.10	Hydrated minerals Silicates Organics
X (E,M,P)		Slightly reddish spectrum E: absorption features at 0.5 and 0.6 μm	E: 0.18-0.4 M: 0.10-0.18 P: 0.03-0.10	
S (S,Q,A,K,L)		Moderately steep red slope ($\lambda < 0.7 \mu\text{m}$) Shallow to deep absorption at 1.0 and 2.0 μm	0.10-0.22	Stony composition Magnesium Iron silicates
V		Moderate to steep red slope Very deep absorption at 1.0 μm	0.60	Volcanic basalts Plutonic rocks

S-type
High albedo

C-type
Low albedo

1-3. Taxonomy

Most NEAs are S-type, while C-type are rare.

- They are supplied from the inner Main-belt due to gravitational perturbations by Jupiter (again).

C-type asteroids are dark

- Dark (low albedo) observational bias makes them harder to discover.

Observation Opportunities

- There is an (only) opportunity to observe during close approaches (brighten!).
- Opportunities for **Polarimetric observations** at wide phase angles are rare.

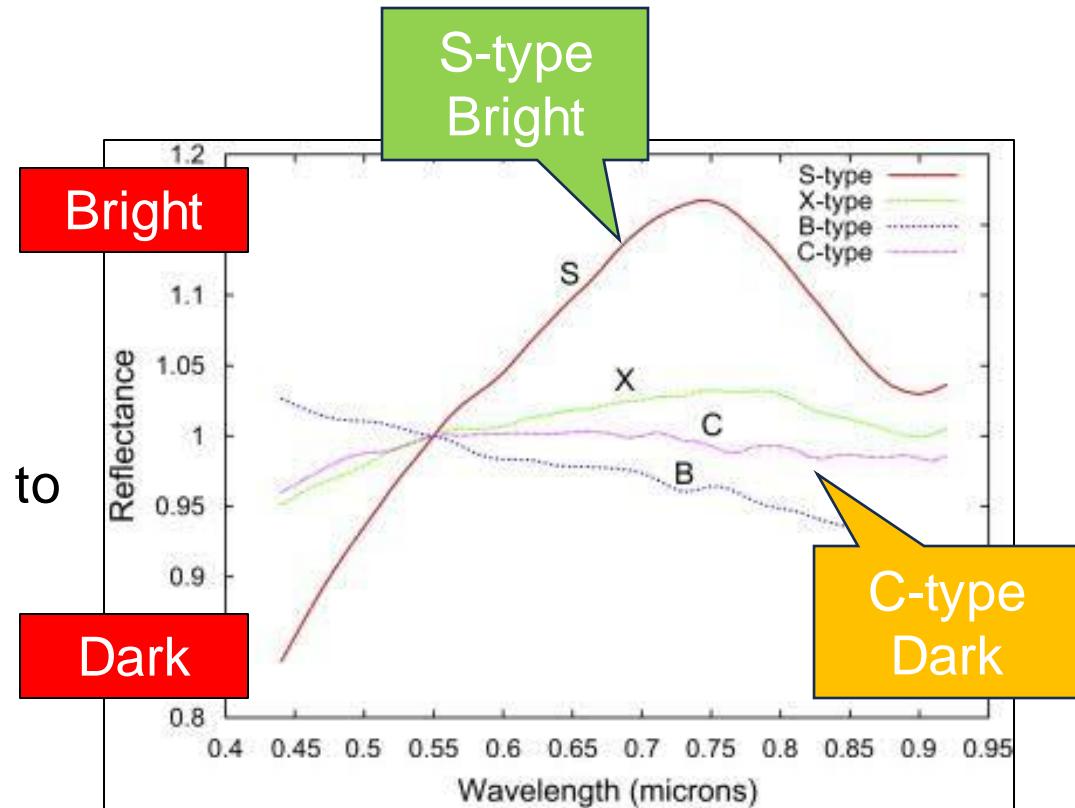


Fig 8. Relative reflectance of each type asteroids (visible range).

What if, in the future, it is identified that a C-type NEA will collide ?

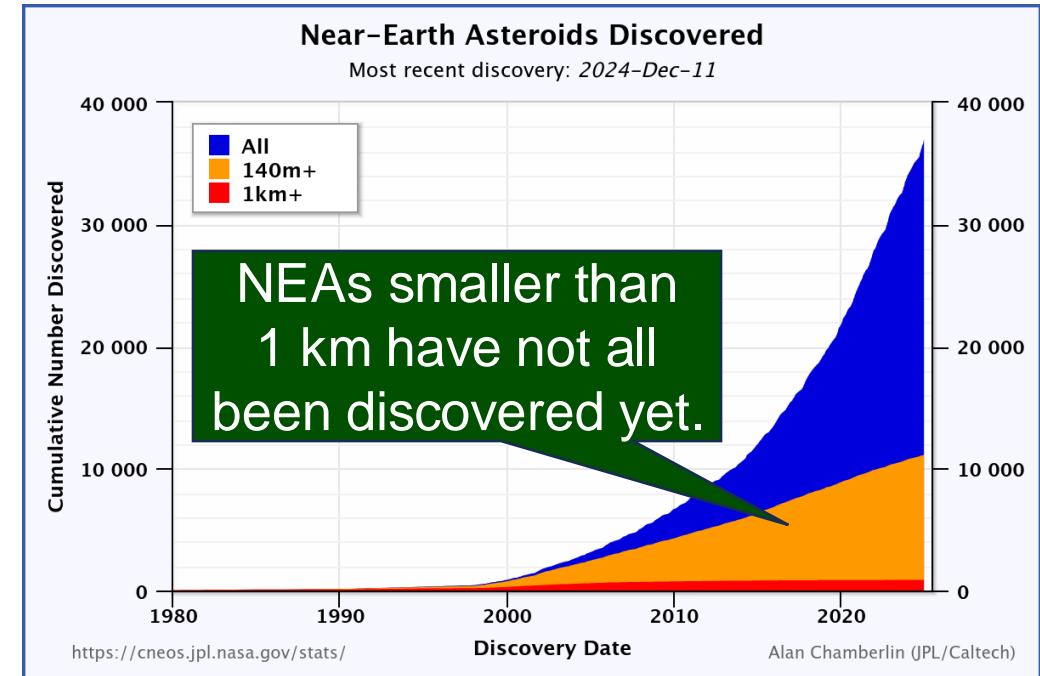
From a Planetary Defense perspective, it is important to clarify **in advance** the behavior of C-type NEAs to **prepare**.

1-4. Number

1.4 million discovered (as of December, 2024)

- The number of discoveries is increasing steeply.

Due to improvements of observational instruments and skills.



Number of NEAs (as of December, 2024)

- ~36,000 have been discovered, but the **physical properties of many newly discovered NEAs are unknown**.
- Most NEAs larger than 1 km have been discovered because they are bright, but many NEAs smaller than 1 km remain undiscovered because they are dark.

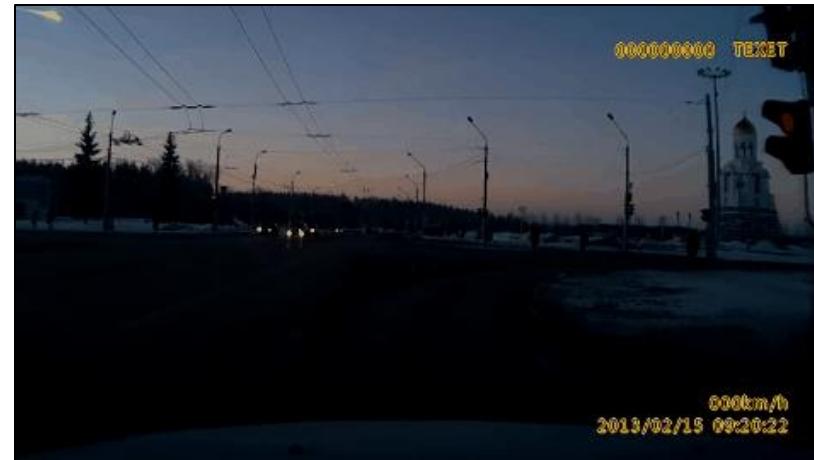
We can not deal with the unknown !

Fig 9. Number of NEAs discovered as of December, 2024.

1-5. Planetary Defense (Space Guard)

Protecting the Earth from Asteroids (and Comets) collisions

- 66 million years ago, Dinosaurs extinction was caused by collision of ~20 km Asteroid or Comet.
- In 2013, ~20 m Asteroid exploded over Chelyabinsk, injuring 1,500 people.
- In 1994, Comet Shoemaker-Levy 9 collided with Jupiter. etc.

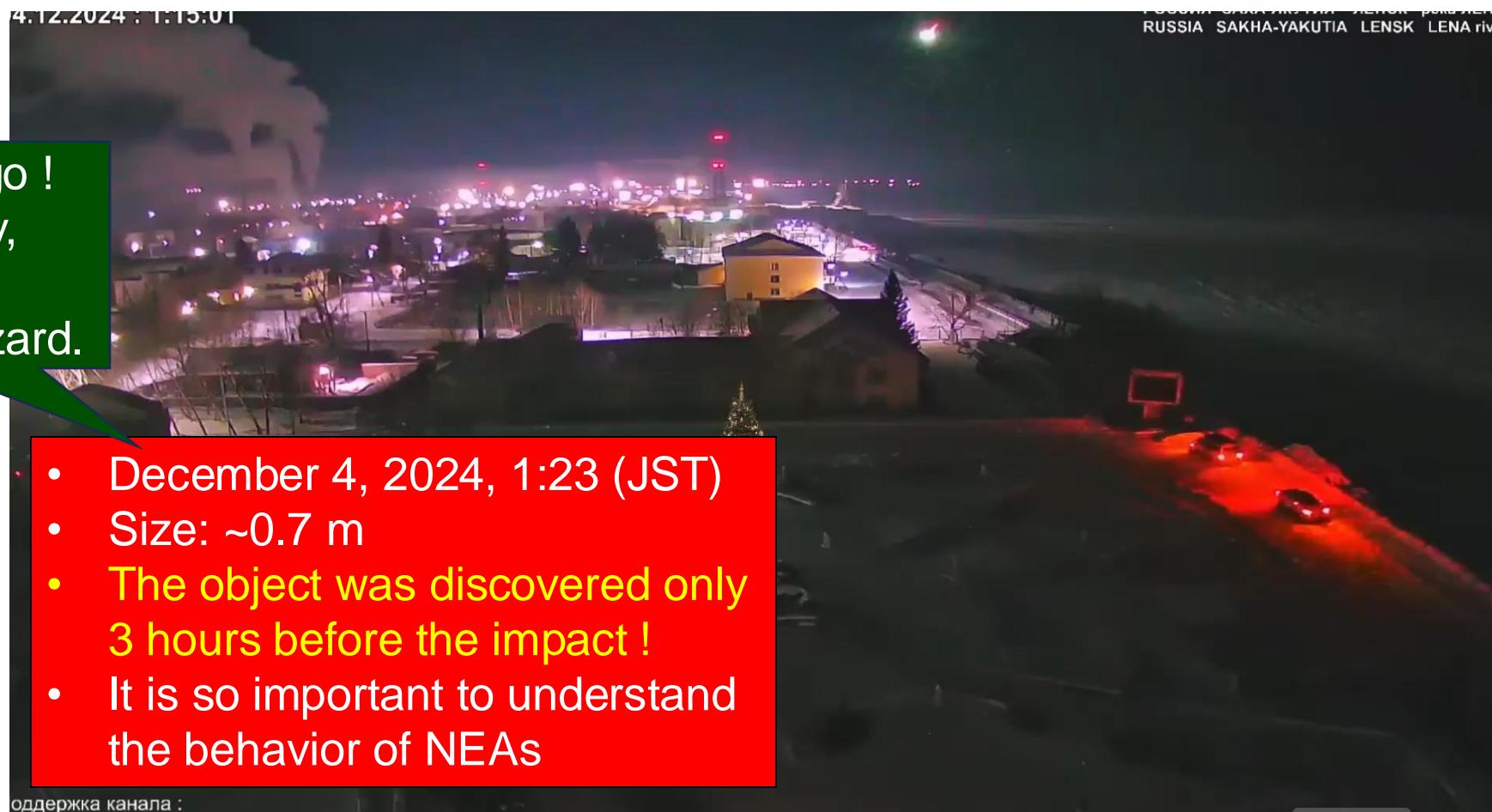


- So now, multiple missions are being conducted to achieve and contribute Planetary Defense.

Fig 10, 11, 12. Chicxulub meteor, Chelyabinsk meteor explosion movie, The collision of Comet Shoemaker-Levy 9 with Jupiter.

1-5. Planetary Defense (Space Guard)

Recent impact on Earth !

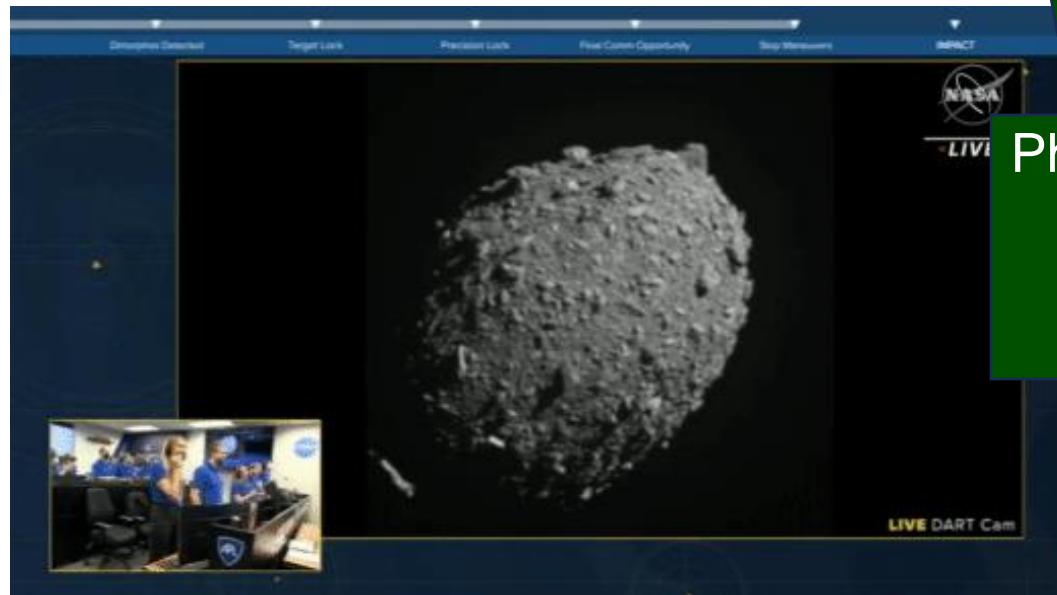


1-6. Planetary Defense Missions

Avoiding collisions
Predicting hazard

NASA DART & ESA HERA Missions

- Target: Binary NEAs, Didymos-Dimorphos
- Change the orbit of Dimorphos (satellite) by impacting it with a DART spacecraft. Investigate details by HERA.



Physical properties
Crater size,
Composition,
Mass, etc.

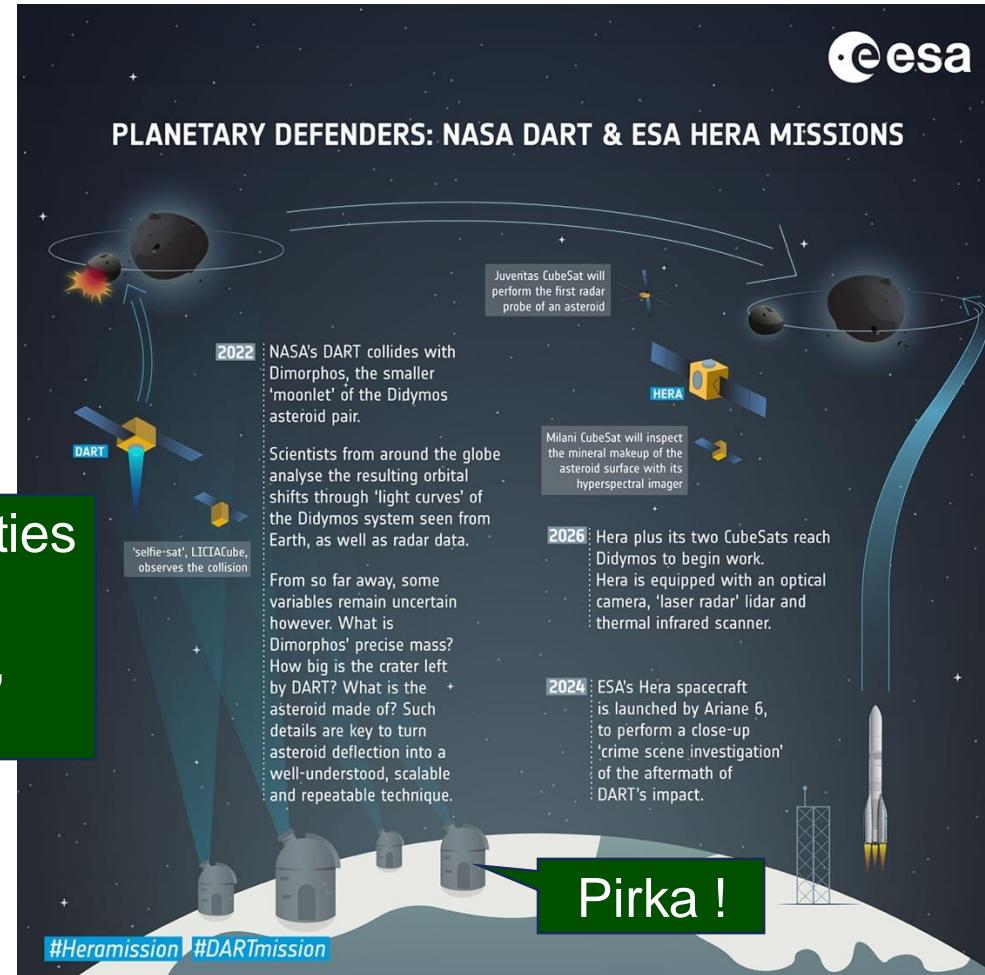


Fig 14, 15. Impact of DART spacecraft movie, DART Mission & HERA Mission outline.

1-7. JAXA Hayabusa2# Mission

Mission objectives

1. Advancement of long-term solar system navigation technology.
2. Realization of exploration of small and fast rotating Asteroids.
3. Acquisition of science and technology contributing to
Planetary Defense.

Targets Asteroids

1. **Torifune**, Flyby in July 2026.
PHA, Itokawa like ?
2. **1998 KY26**, Rendezvous in July 2031.
Size: 20-40 m (tiny), Rot. Period: 10 min. (so fast) Monolith ?

I observed with
Seimei & Pirka.

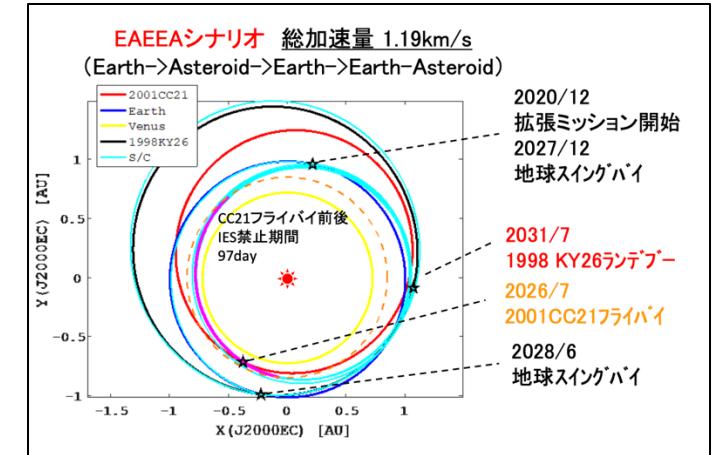


Fig 16, 17. JAXA EAEAA Flyby scenario, Hayabusa2 Flyby image.

Not public information !
I will delete from the
PDF after this seminar.

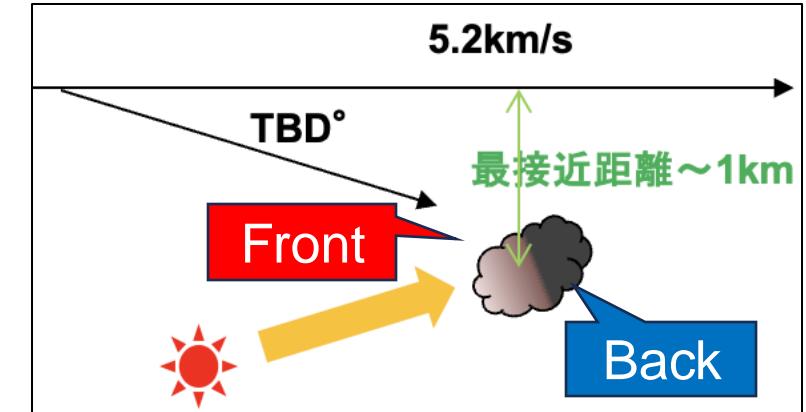
1-7. JAXA Hayabusa2# Mission

Importance of ground-based observations before the Flyby

- The Flyby speed is ~5 km/s (so fast !)
- The planned closest distance ~1 km (called “Kamihitoe”)
- Preliminary derivation of **Brightness** is important to set the shutter speed of the onboard camera.

Brightness information: Albedo and **Local surface composition**

- Local surface composition has not been derived, so **Color Light Curve observation** is necessary.
- To determine whether the surface is **uniform or varies** between the front and back sides.
(details in chapter 5)



Spatially resolvable time is only 2~3 s !!!

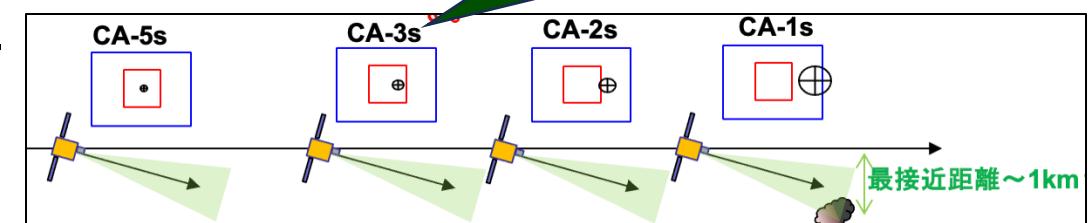


Fig 18, 19. Hayabusa2 Flyby plan.

Tab 2. The hazard based on physical properties.

2. Purpose and Goals

Introduction Summary

- Clarifying NEAs, especially study of C-type NEAs is so important:
Origin of materials, Rarity of observation opportunities, Planetary Defense
- Ground-based observations before the “in-situ” observations are essential.

	Size	Composition	Porosity
Major	Large	Stony, Metallic	Low
Minor	Small	Carbonaceous	High

Goals

- Obtaining information necessary to understand NEAs.
- Contributing to Planetary Defense, especially Hayabusa2# mission.

I conducted Polarimetric and Photometric observations.

Purpose

- Deriving the **physical properties of unique NEAs** through ground-based observations.
Surface composition, albedo, regolith, etc. (Representative NEA)

3-1. Observation methods

Physical properties of Asteroids

- Orbit
- Size
- Shape
- Rotation Period
- Surface composition
- Albedo
- Grain size / Porosity
- etc.

(A) Polarimetric observations

- Surface composition (rough)
- Albedo
- Grain size / Porosity

(B) Photometric observations

- Size
- Rotation Period
- (Local) Surface composition
- etc.

Pirka

Other observations

(Thermal infrared, Radar, Survey, Occultation, In situ, Spectroscopy, Astrometry etc.)

- Orbit • Size • Shape
- Albedo • Rotation Period
- Surface composition (precise) • Albedo etc.

Seimei

3-2. Identification of target Asteroids

Identification method

- ‘Blink’ 2 fits data (images taken 5-10 min apart), while tracking in Asteroid mode, so that the moving objects are stars, and the stationary object is the target Asteroids.

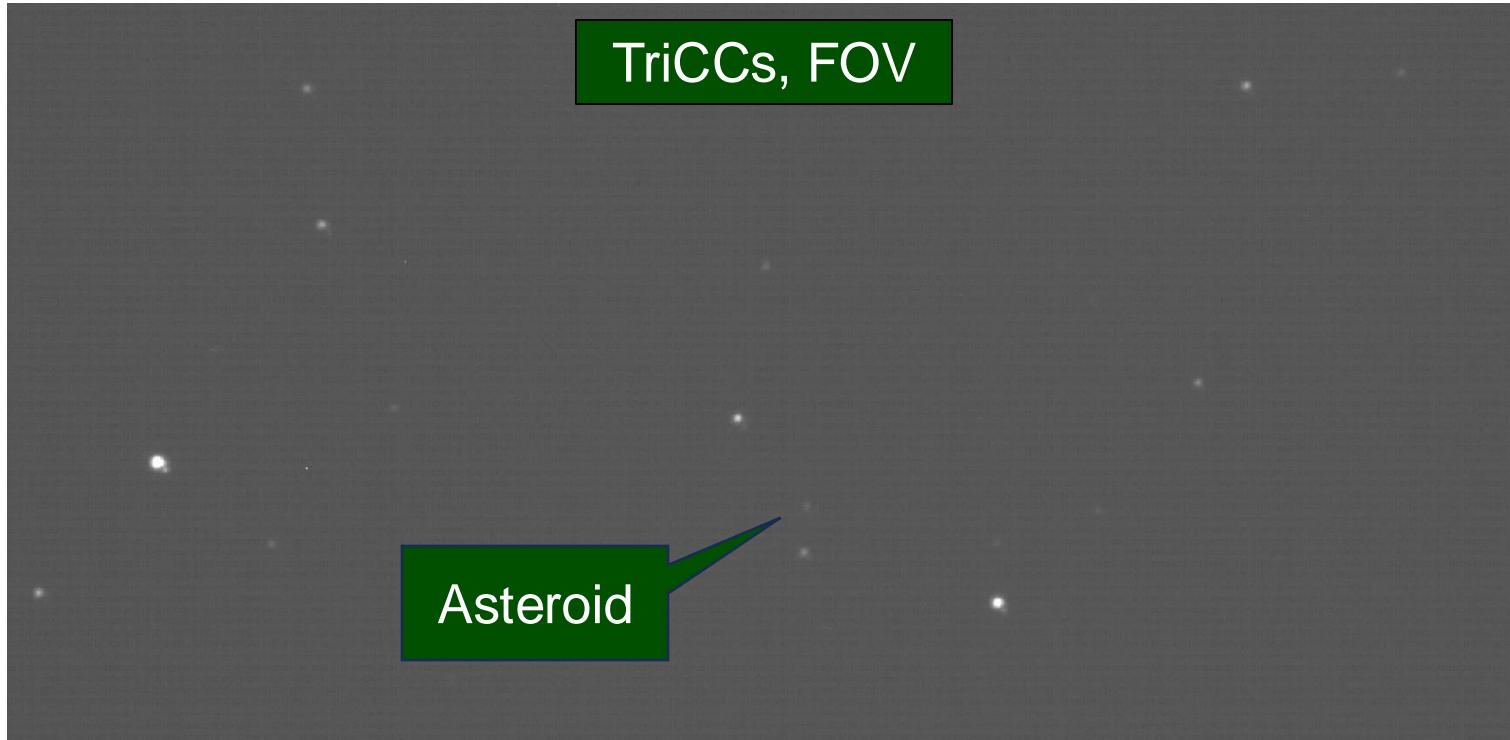


Fig 20. 2 fits data of
target Asteroids
blink movie.

3-3. (A) Polarimetric observations

Polarization

- Light that vibrates in various directions, with only certain directions of vibration being selected.

Asteroids reflect sunlight (unpolarized light) and polarization occurs depending on the surface properties.



Unpolarized & Polarized light

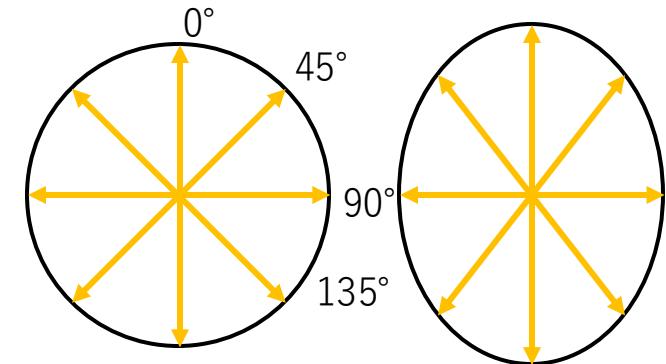


Fig 21, 22, 23. Polarization filter movie, Polarization of Asteroid, Unpolarized and polarized light.

3-3. (A) Polarimetric observations

Polarization degree

- Linear Polarization: $P_r = \frac{I_{\perp} - I_{\parallel}}{I_{\perp} + I_{\parallel}} \%$
- Polarizer: Wollaston Prism
separate into Ordinary-ray (O-ray: I_{\perp}) and Extraordinary-ray (E-ray: I_{\parallel})

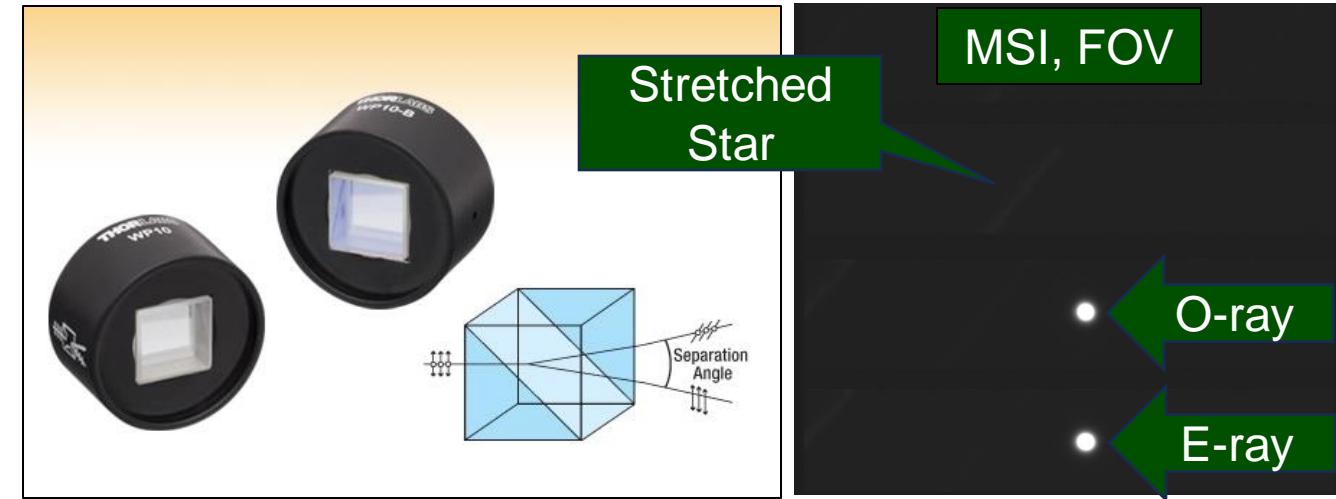
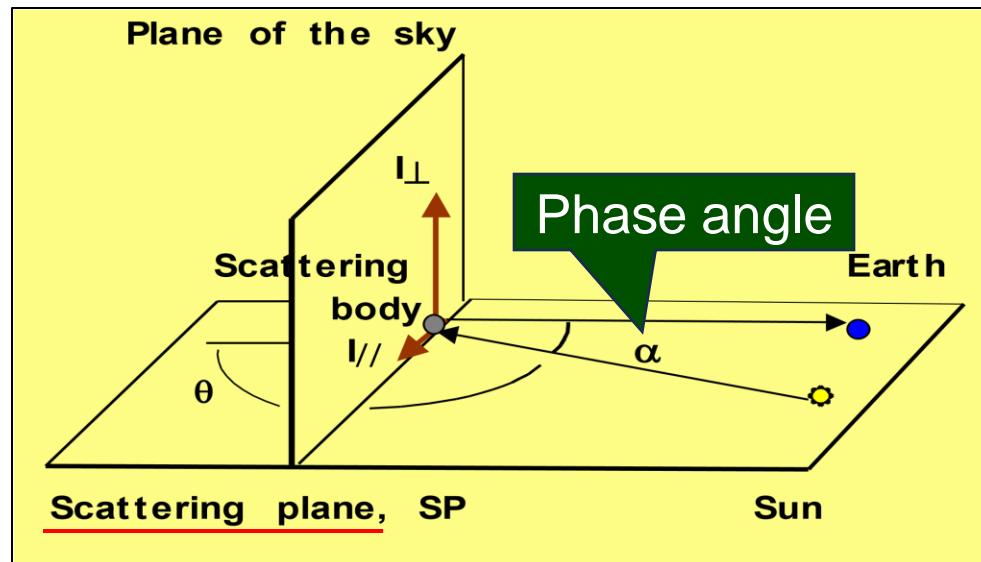


Fig 24, 25, 26. Basic information of Polarization, Wollaston Prism, MSI FOV.

3-3. (A) Polarimetric observations

- Linear Polarization: P_r depends on the phase angle (α)
- Phase angle: Sun-Target-Observer (S-T-O) angle

Tab 3. Comparison of MBAs and NEAs.

	MBAs	NEAs
Distance from the Earth	Far	Close
Change in phase angle over a few days	Small	Large (wide range) <i>Obtain various data !</i>

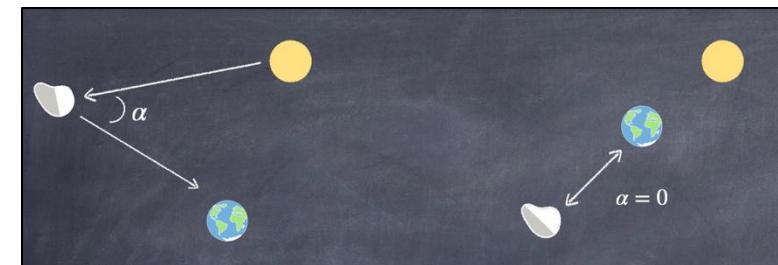
- Polarization curve and detect polarization parameters.

α_{inv} : inversion angle

$h = \frac{dP_r}{d\alpha}$: slope at α_{inv} (when $P_r = 0$)

$P_{\min}(\alpha_{\min})$: Minimum polarization degree

$P_{\max}(\alpha_{\max})$: Maximum polarization degree



P_r vs α linear polarization curve

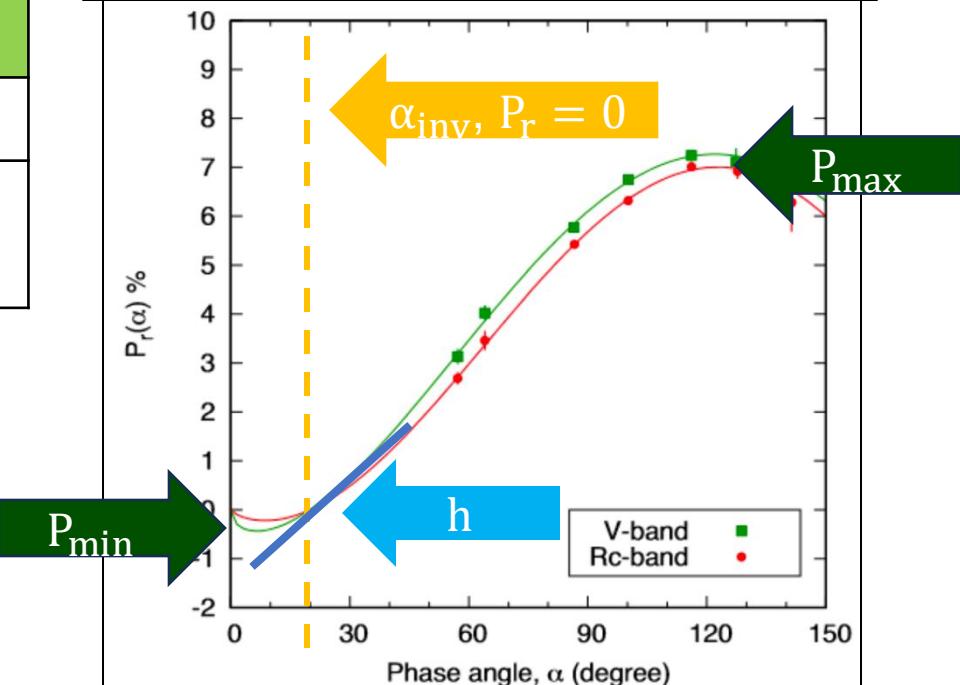


Fig 27. NEA 1566 Icarus. [Ishiguro et al., 2017]

3-3. (A) Polarimetric observations

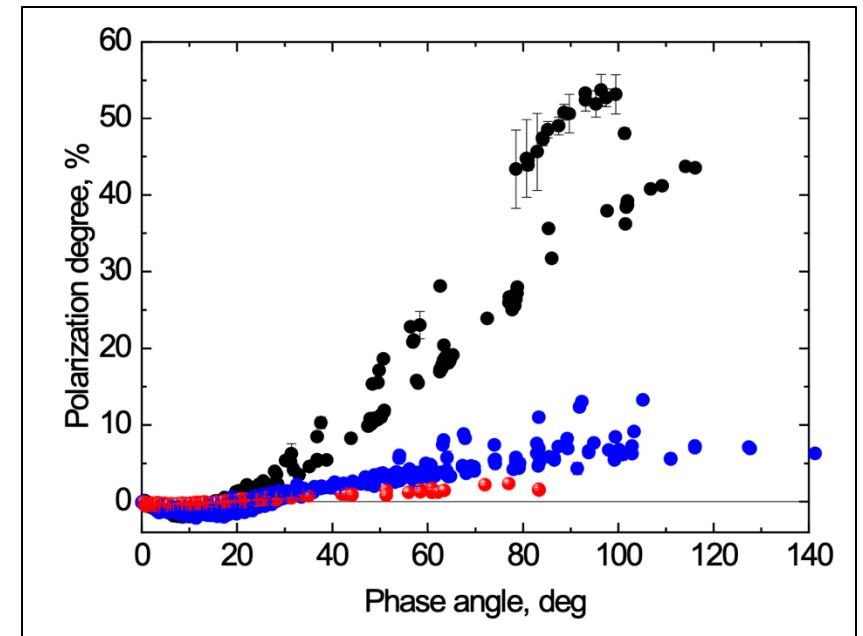
Surface composition (Empirically)

- Polarization curve shape (visually)
- Slope: h , P_{\min} & α_{inv}
estimate Taxonomy Type (C or S or E(X))

Tab 4. Polarization parameter characteristics of C-type and S-type.

Polarization parameters	α_{inv}	h	P_{\max}	P_{\min}
C Type	Small	Steep	High	Deep
S Type	Large	Mild	Low	Shallow

- It is certain that the polarization degree of Asteroids depends on surface properties, but the detail remain unclear.



C-complex ($p \sim 0.07$) $P_{\max} \sim 40\text{-}50\%$
S-complex ($p \sim 0.2$) $P_{\max} \sim 6\text{-}12\%$
E-type ($p \sim 0.4$) $P_{\max} \sim 2\%$

Fig 28. Polarization of typical C-, S-, E-Type Asteroids include NEAs. [Belskaya, 2024]

3-3. (A) Polarimetric observations

Albedo (Empirically)

- Slope: h

$$\log_{10} A = C_1 \log_{10} h + C_2$$

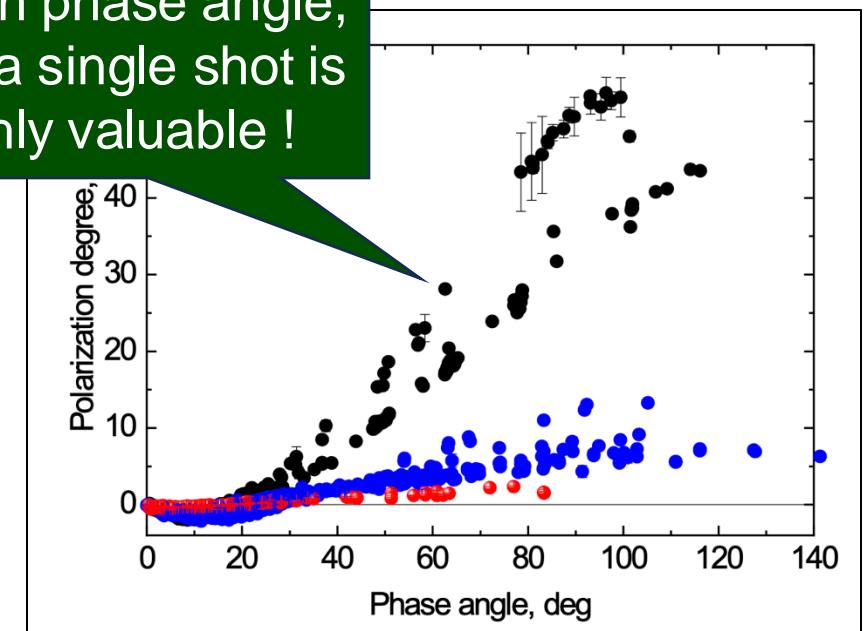
A: albedo, C_1 , C_2 : constant [Cellino et al., 1999]

(The values of C_1 and C_2 vary across different studies.)

Tab 4. Polarization parameter characteristics of C-type and S-type.

Polarization parameters	α_{inv}	h	P_{\max}	P_{\min}
C Type	Small	Steep	High	Deep
S Type	Large	Mild	Low	Shallow

At high phase angle,
even a single shot is
highly valuable !



C-complex ($p \sim 0.07$) $P_{\max} \sim 40\text{-}50\%$

S-complex ($p \sim 0.2$) $P_{\max} \sim 6\text{-}12\%$

E-type ($p \sim 0.4$) $P_{\max} \sim 2\%$

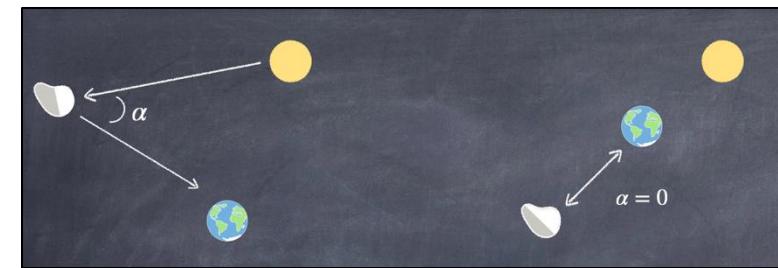
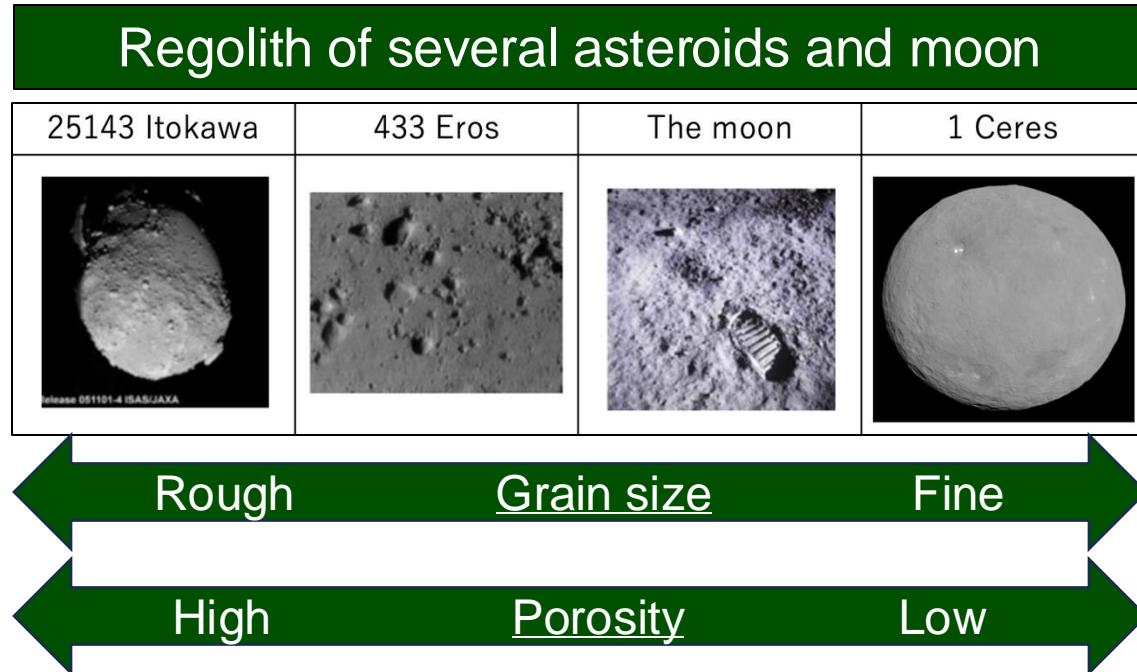
Fig 28. Polarization of typical C-, S-, E-Type Asteroids include NEAs. [Belskaya, 2024]

3-3. (A) Polarimetric observations

Regolith: Grain size & Porosity (Empirically)

- Grain size: P_{\max} & Albedo
- Porosity: P_{\max}

Tab 5. Grain size and Porosity relationship.



P_r vs α linear polarization curve

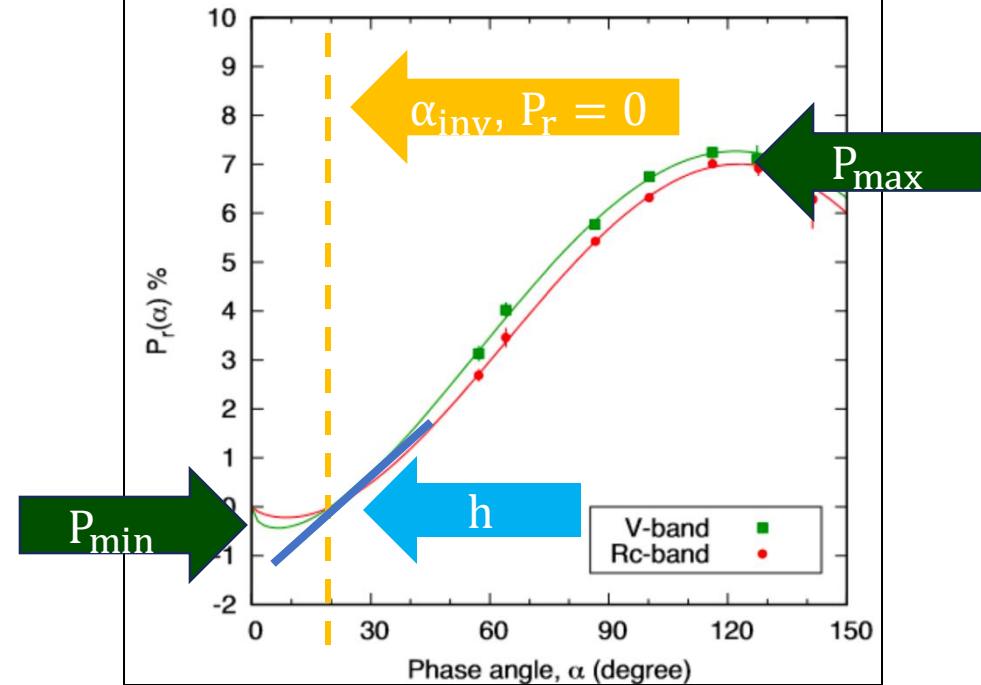


Fig 27. NEA 1566 Icarus. [Ishiguro et al., 2017]

3-4. (B) Photometric observations

Local surface composition

- Color light curve: Light curve + g-, r-, i-filter color photometry.

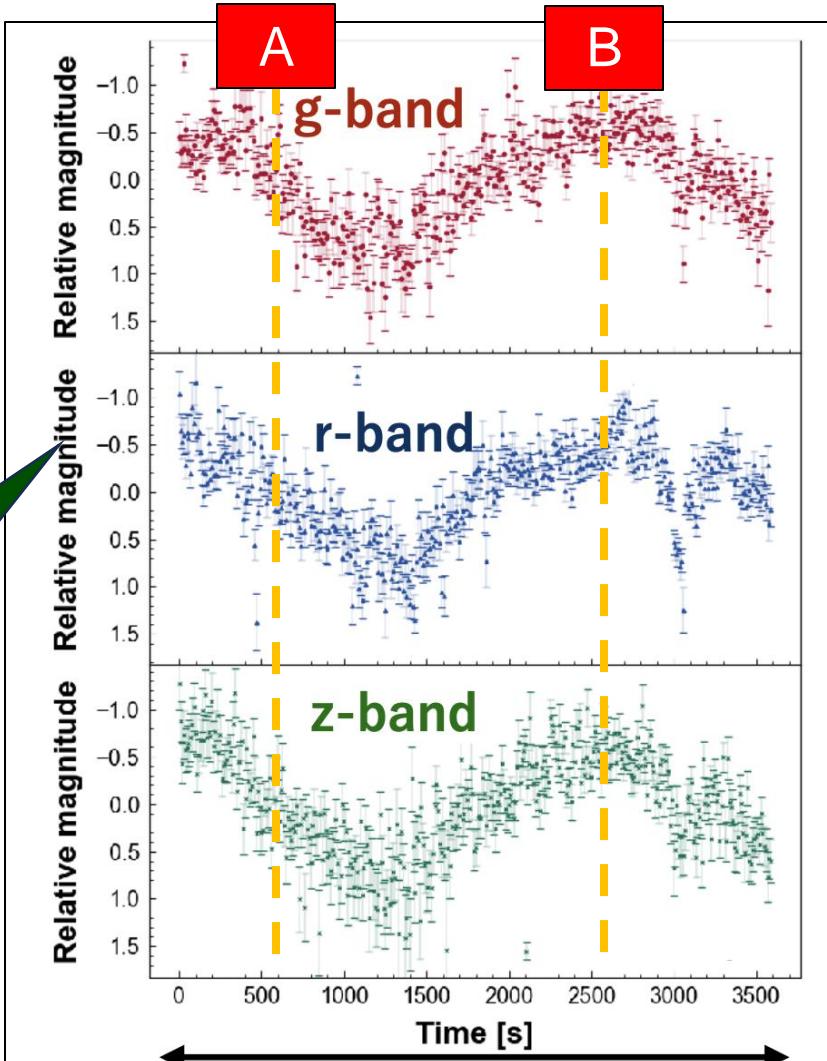
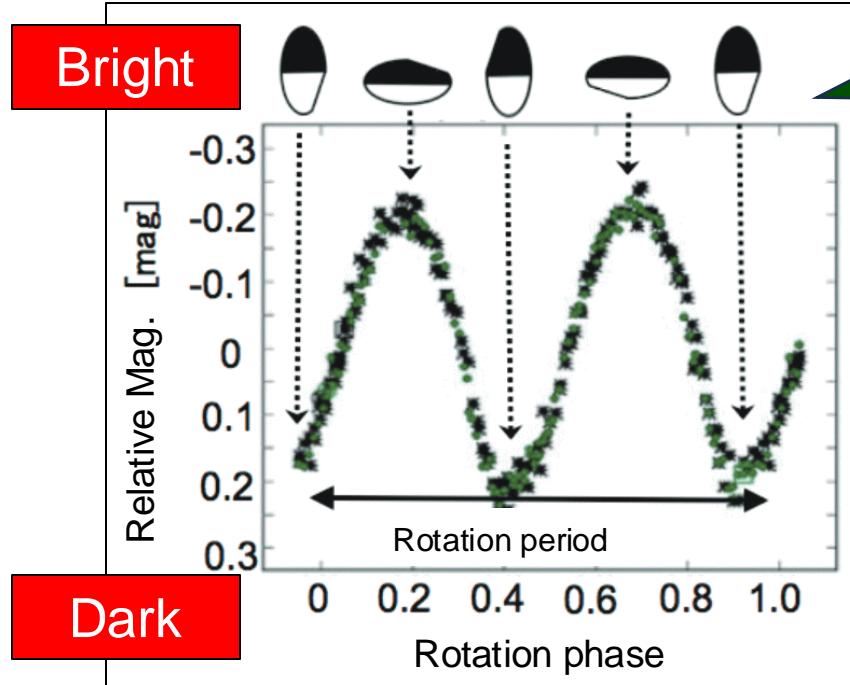


Fig 29, 30. Rotation period of asteroid,
TriCCs color light curve of tiny NEA. [Beniyama et al., 2021]

3-5. 1.6 m Pirka Telescope & MSI

Pirka Telescope

- Location: Nayoro Observatory
- Own: Hokkaido Univ.

MSI (Multi-Spectral Imager)

- Wavelength: 0.36-1.05 μm
- Field of view (FOV): $3.3' \times 3.3'$
- Array format: 512×512 pixels
- Filter: Johnson-Cousins U, B, V, Rc, Ic
- Polarizer: Wollaston Prism

Can conduct polarimetry

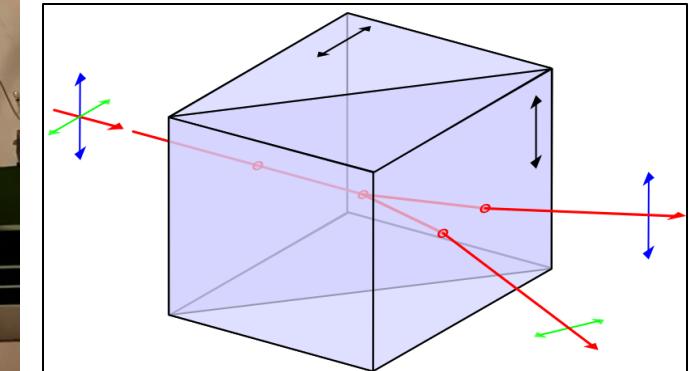
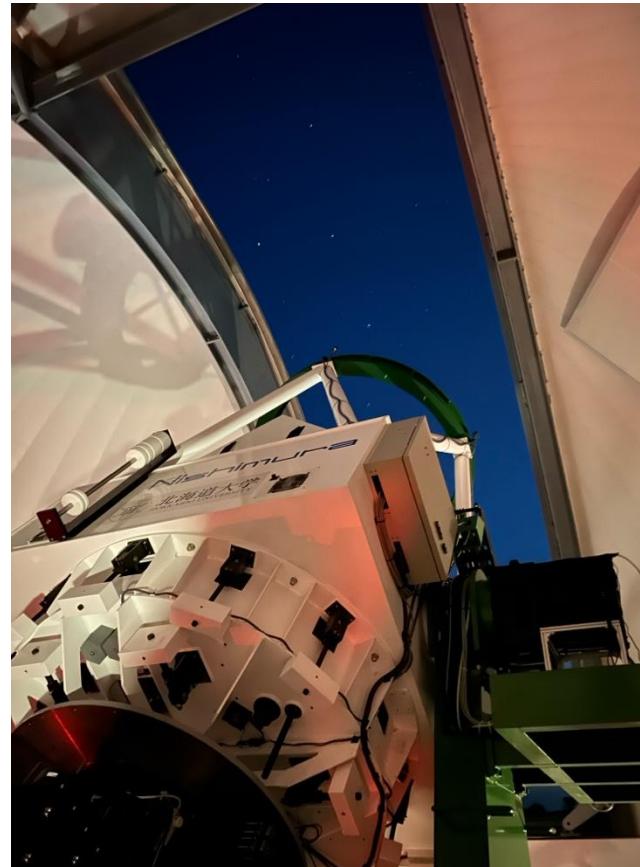
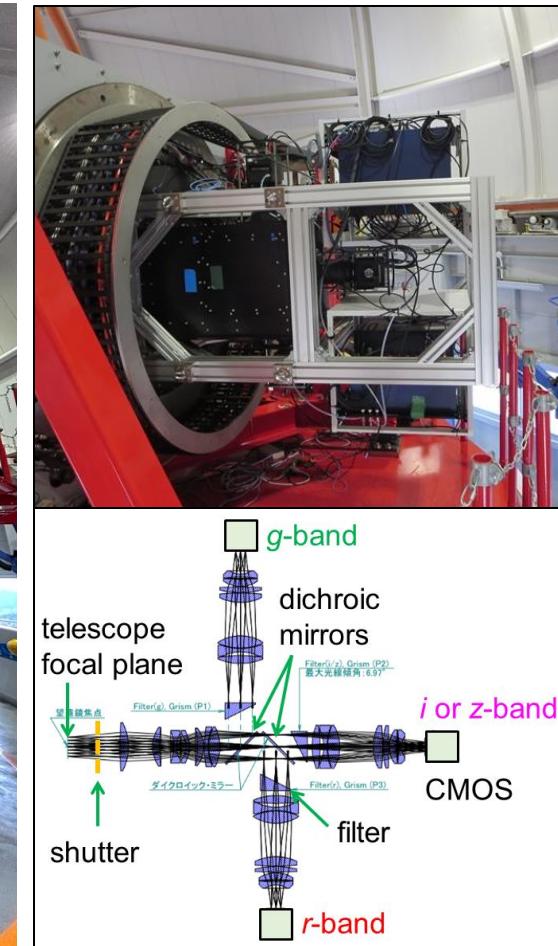


Fig 31, 32, 33. Pirka Telescope, MSI, Wollaston prism.

3-6. 3.8 m Seimei Telescope & TriCCCs

Seimei Telescope

- Location: Okayama Observatory
 - Own: Kyoto Univ., and open use by NAOJ
- The largest optical telescope in East Asia



TriCCCs (Tricolor CMOS Cameras)

Imaging mode:

Tri-colors simultaneous photometry

- FOV: $12.6' \times 7.5'$
- Array format: $2,220 \times 1,360$ pixels
- Filter: g2 (or g), r2 (or r), i2, and z band

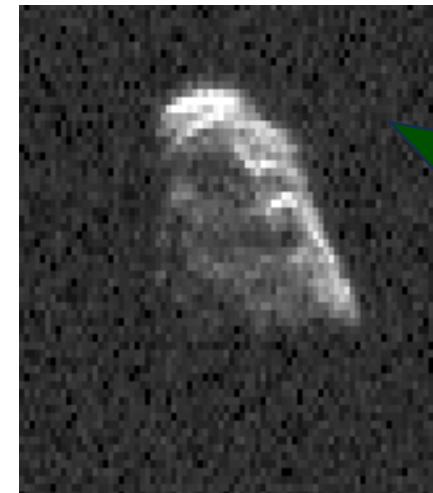
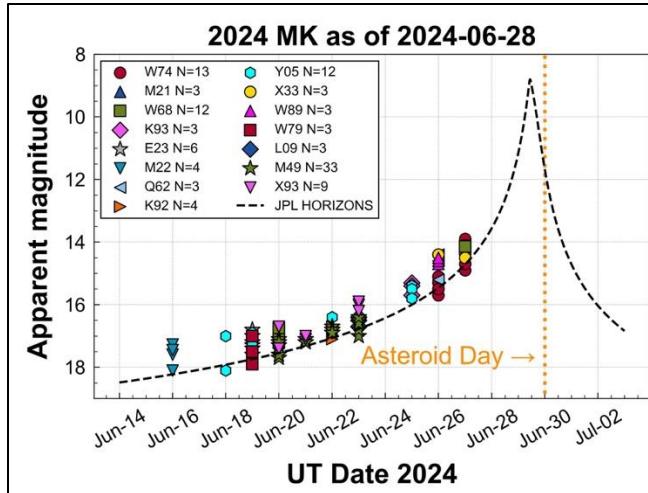
Color light curve

Fig 34, 35, 36. Seimei Telescope, TriCCCs, Imaging mode details of TriCCCs.

4-1. 2024 MK Information and Observations

Information

- Approaching closer to Earth than the Moon, discovered only two weeks before closest approach.
- Tracked by NASA's Goldstone Solar System Radar, derived its shape and size: ~150 m.
Other physical properties can't be derived. **This study derived.**



This **large size NEA** approaching closer than Moon occurs only once in several decades !

Fig 37, 38, 39. Orbit of 2024 MK, Apparent magnitude of 2024 MK, NASA Goldstone radar images of 2024 MK.

4-1. 2024 MK Information and Observations

Observations

- Polarimetric observations with the Pirka telescope

Tab 6. Observation condition of 2024 MK.

Date	Phase angle	Filter	Notes
1. 6/29	26-28°	V, Rc	Closest approach night, S/N: ~2000 !
2. 7/2	101°	V, Rc	Maximum phase angle, can not be observable after (dark)

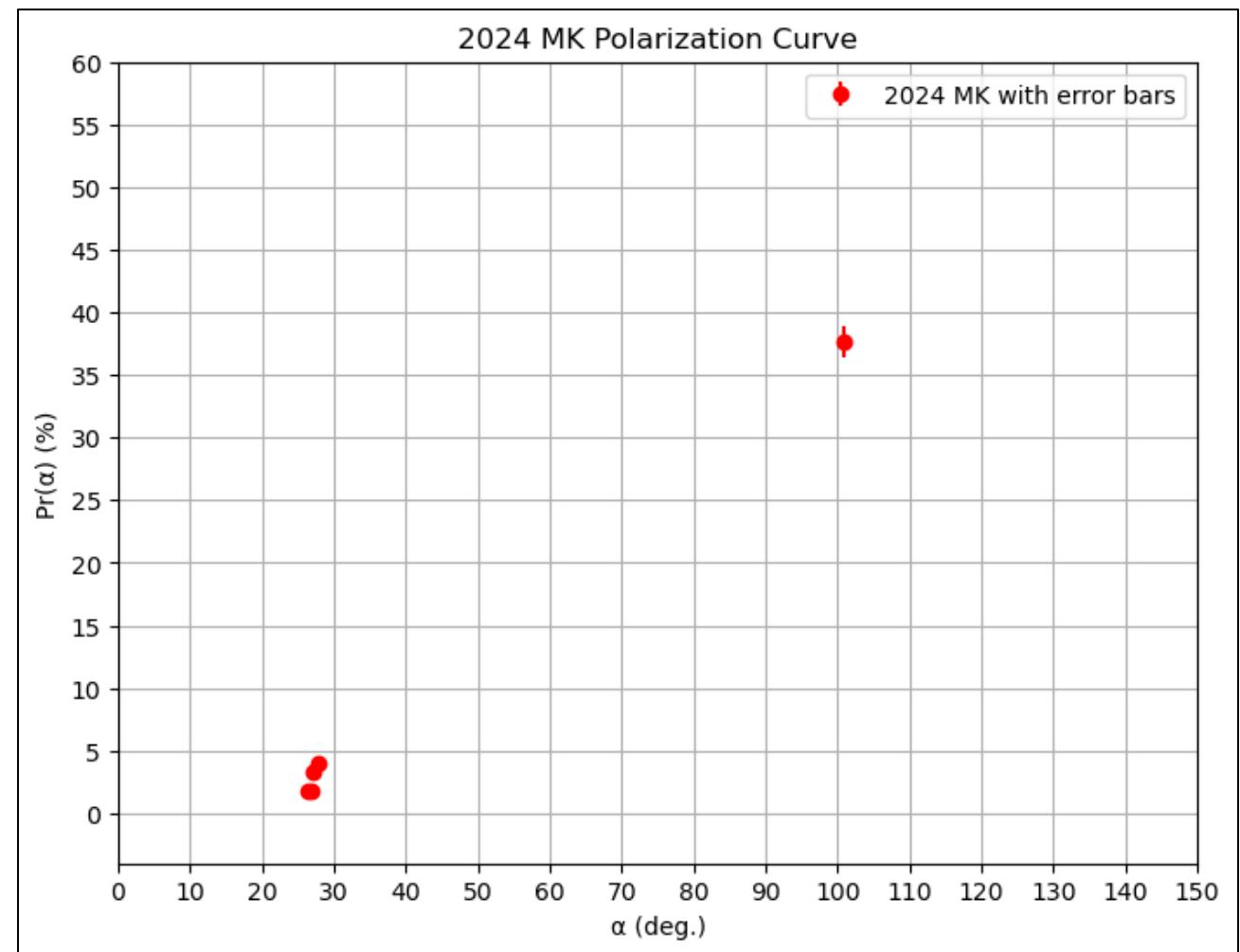
4-2. 2024 MK Results

- Plot of P_r vs α

Tab 7. Polarization degree of 2024 MK.

	Phase angle	P_r
1. 6/29	26.3°	$1.84 \pm 0.03 \%$
	26.8°	$1.84 \pm 0.04 \%$
	27.1°	$3.33 \pm 0.04 \%$
	27.7°	$3.96 \pm 0.04 \%$
2. 7/2	101.0°	$37.63 \pm 1.22 \%$

Fig 40. Polarization degree of 2024 MK.



4-3. 2024 MK Discussion

- Comparison with previous Polarimetric observation results of NEAs.

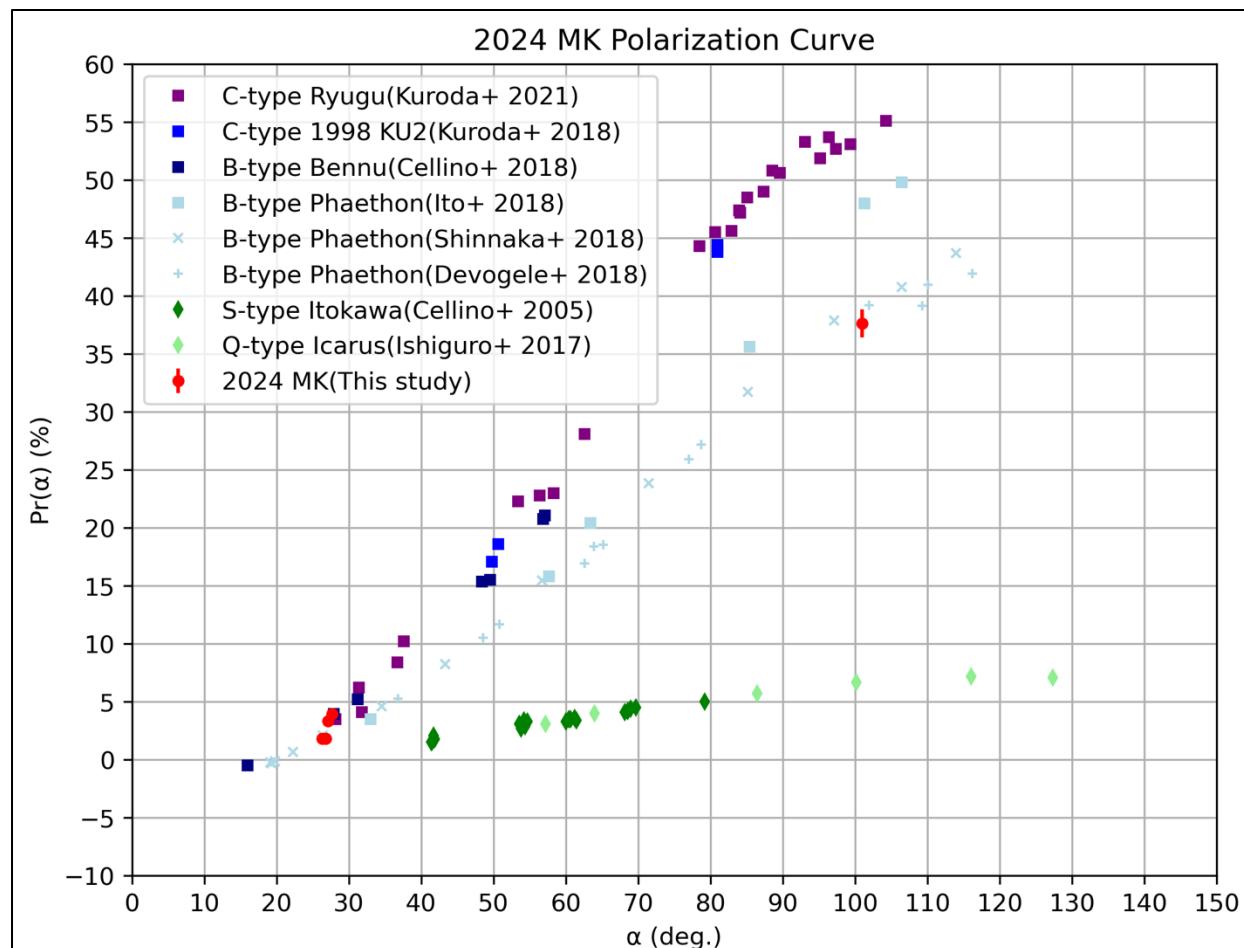
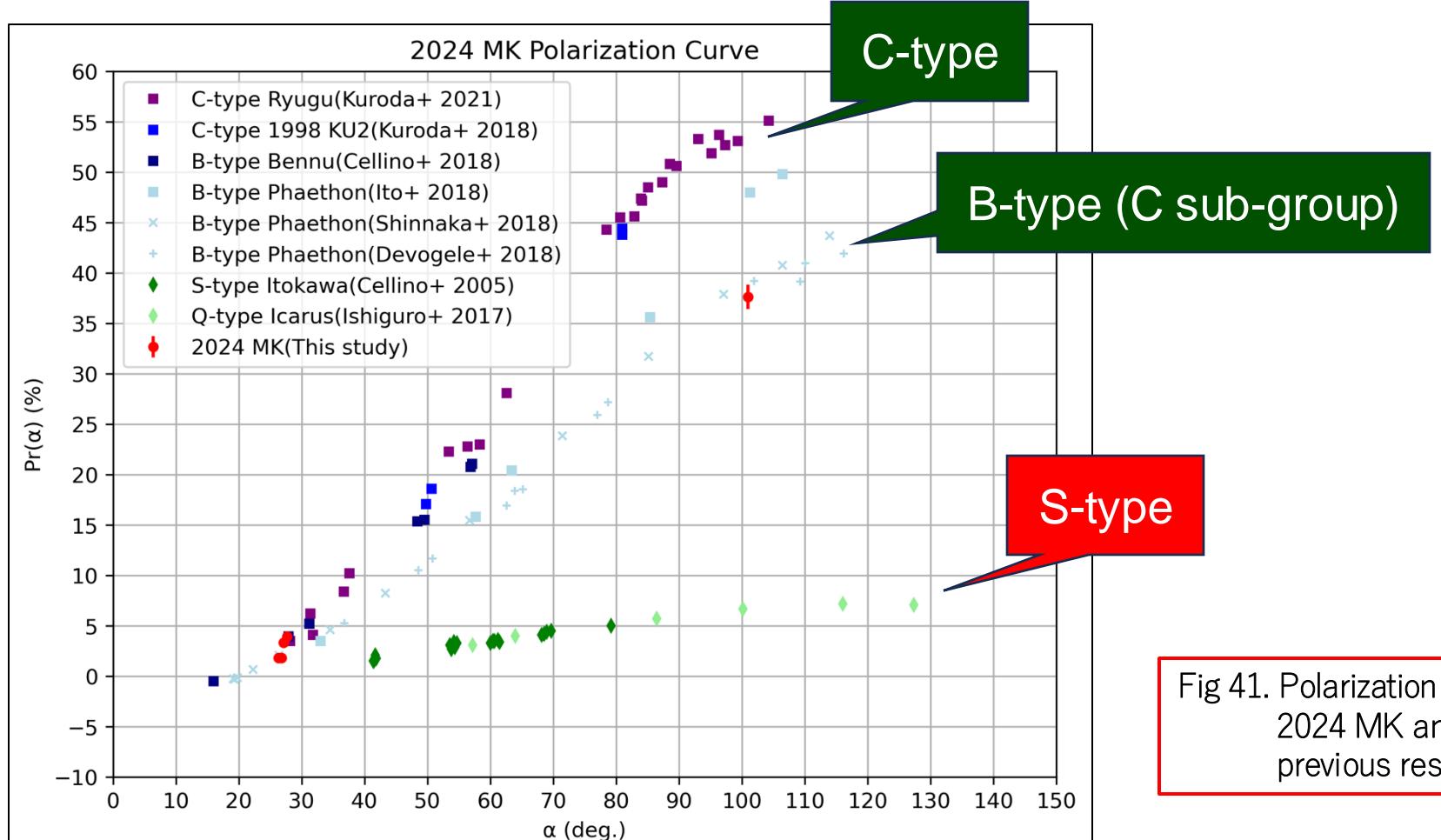


Fig 41. Polarization degree of 2024 MK and Several previous results.

4-3. 2024 MK Discussion

- Comparison with previous Polarimetric observation results of NEAs.



4-3. 2024 MK Discussion

C-type, especially sub-group B-type

- Similar to unique NEAs
e.g., Phaethon, JAXA DESTINY+ targets NEA
- Compare with these NEAs ?
- What is the origin ?
B-types formed outer (colder) than C-types.
- Examples of polarimetric observations at high phase angles for C- (B-) type asteroids are rare.
- This is the first Polarimetric observational example
(Such as large size NEA: ~150 m) to approach closer to Earth than the Moon (My research) ?

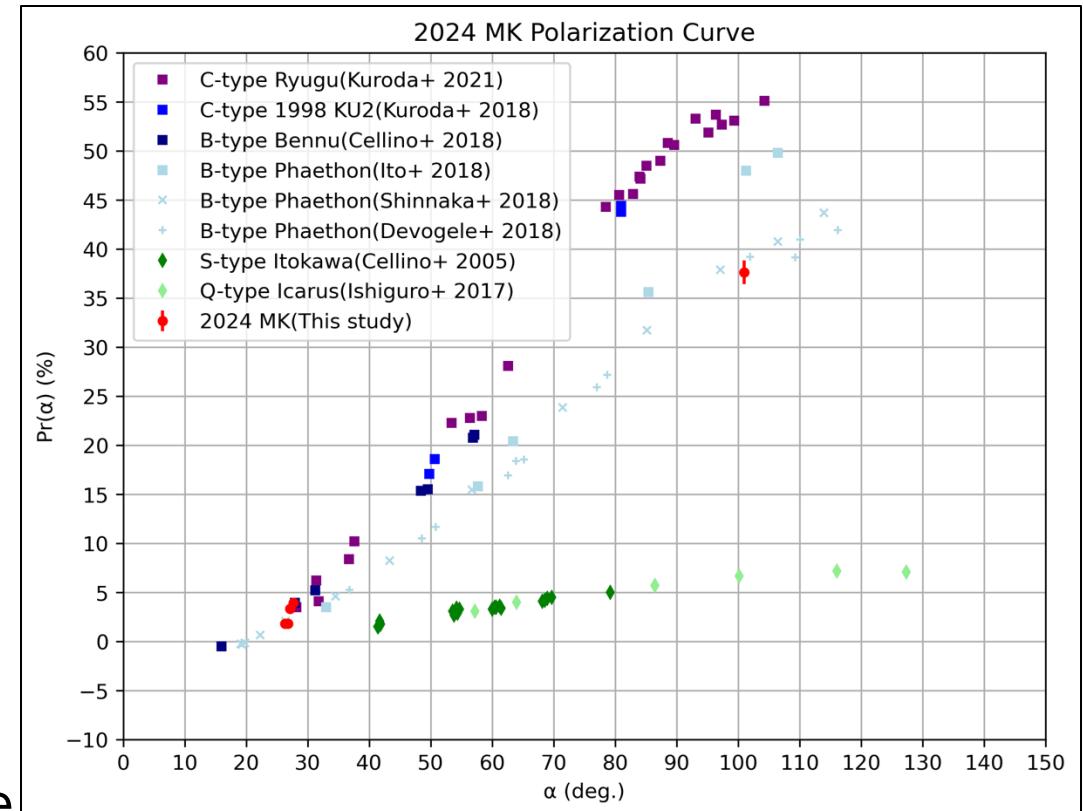


Fig 41. Polarization degree of 2024 MK and Several previous results.

4-4. 2024 MK Future works

Future works

- Draw the Polarization curve (possible ?)

Lumme-Muinonen function

$$P_r(\alpha) = b(\sin\alpha)^{C_1}(\cos\frac{\alpha}{2})^{C_2}\sin(\alpha - \alpha_{\text{inv}})$$

b, C₁, C₂: free parameter [Muinonen et al, 1993]

- Derivation of h: slope parameter to albedo
- Derivation of P_{max} to grain size and porosity
- There is sufficient value in reporting.
(only surface composition information)
We planned to be published as a letter paper.

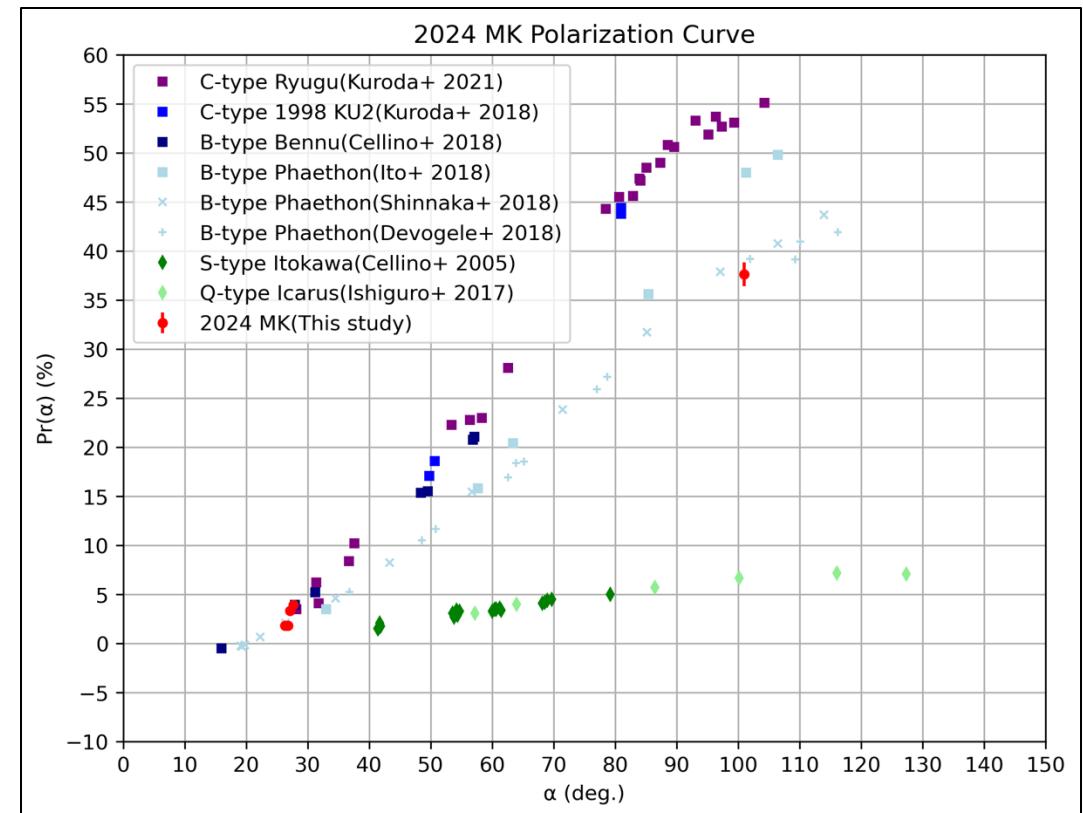


Fig 41. Polarization degree of 2024 MK and Several previous results.

5-1. Torifune information and observations

Information

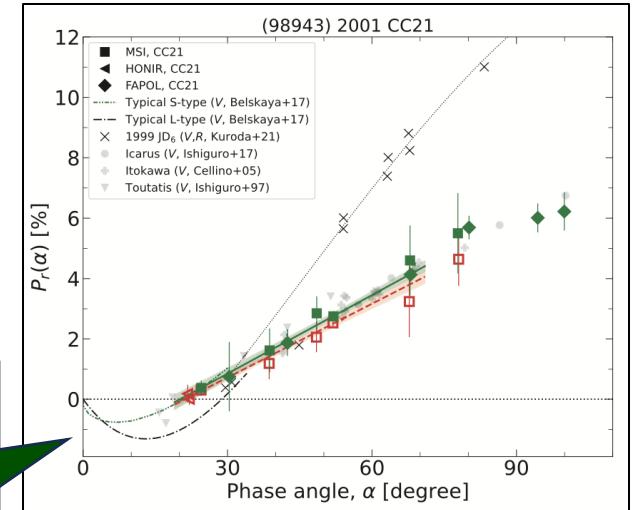
- Hayabusa2# next targets asteroid (PHA), Named this year by JAXA.
- Similar to (Hayabusa targets Asteroid) Itokawa ?

Tab 8. Comparison of Itokawa and Torifune.

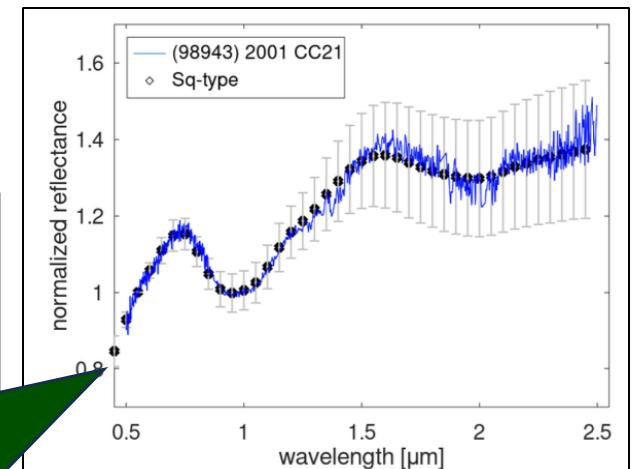
	Itokawa	Torifune
Taxonomy	S Type	S (Sq) Type
Size, Shape	$535 \times 294 \times 209$ m	~ 500 m
Surface	Rubble pile	?

Fig 42, 43. Polarization curve of Torifune.
[Geem et al., 2023],
Reflectance spectral of Torifune
[Popescu et al, 2024 (not published)]

Polarimetry
S-type



Spectroscopy
Sq-type
(overall or mean (not local !))
New result by
10.4 m Telescope !



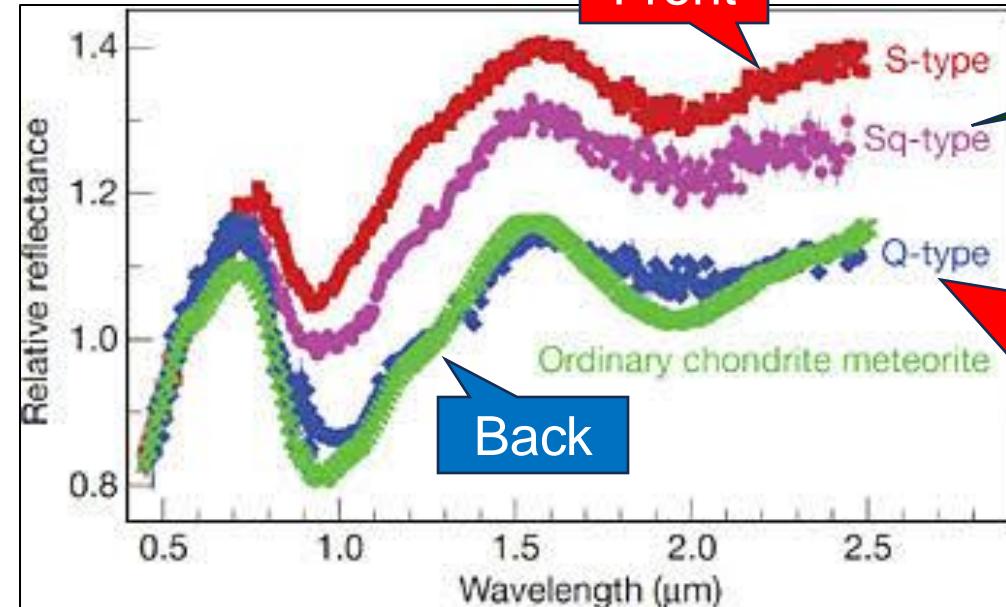
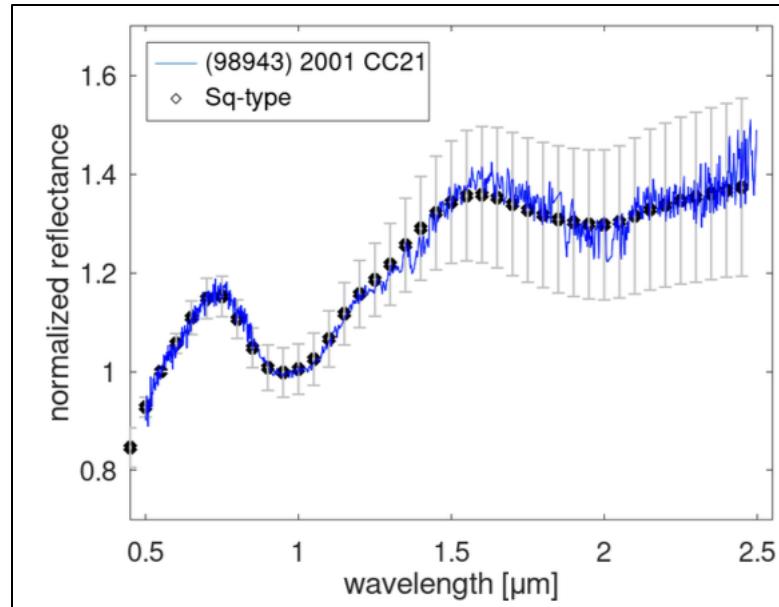
5-1. Torifune information and observations

Information

- Spectroscopic observation result: Sq-type (S sub-group)

Overall or Mean surface information, not Local surface information

Local surface information is necessary for Flyby !



1. Both case
Front and back
sides are Sq-type

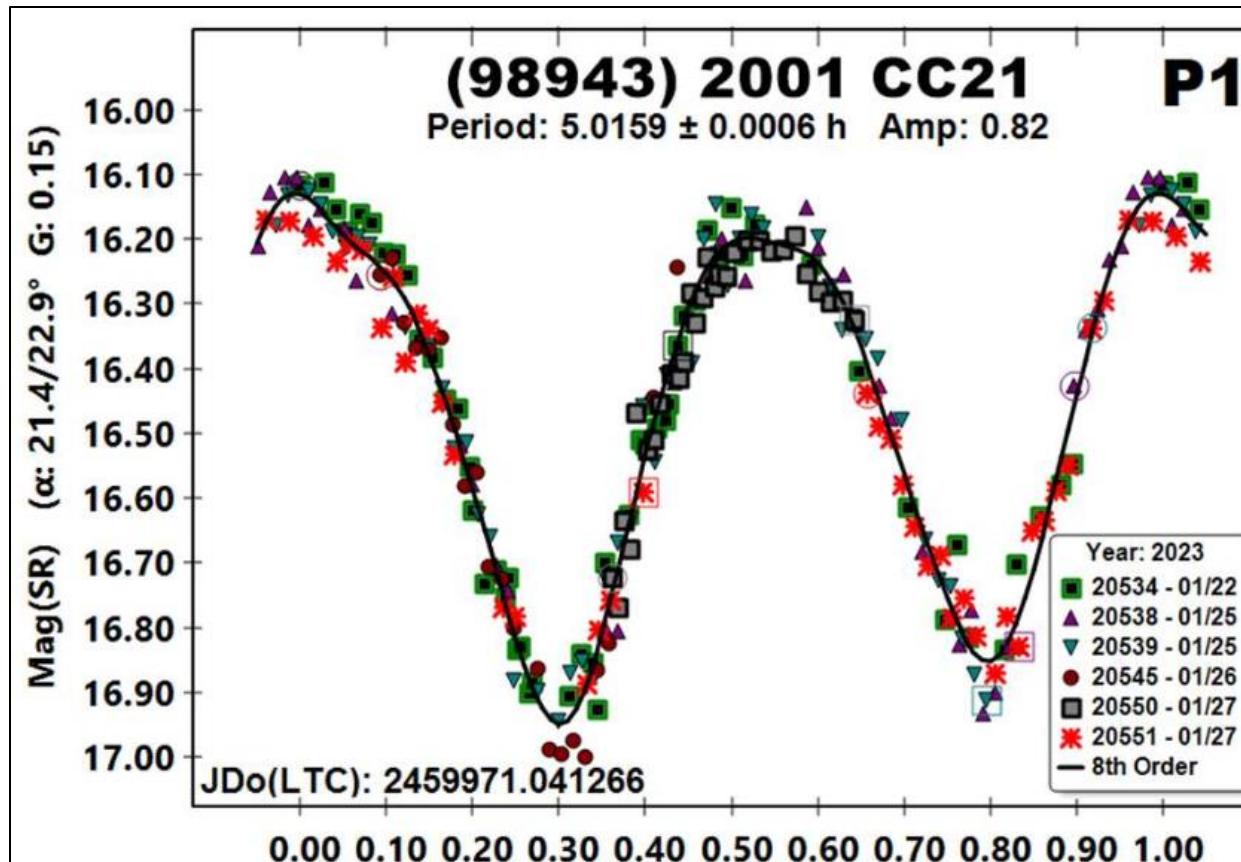
2. Mean case
Front side is S-type,
back side is Q-type
Mean is Sq-type.

Fig 43, 44. Reflectance spectral of Torifune. [Popescu et al, 2024 (not published)], Reflectance of S-, Sq- and Q-type.

5-1. Torifune information and observations

Information

- Rotation period: ~5 hours



Normal light Curve
(no filter)

Not Color Light Curve !
(g, r, i filter)

Fig 45. Light curve of
Torifune(2001 CC21).
[B.D. Warner 2024]

5-1. Torifune information and observations

Torifune
(Opposition)

Observations

- Polarimetric observations with the Pirka telescope
- Photometric observations with the Seimei telescope
We aimed opposition surge (brighten).

Tab 9. Observation condition of Torifune.

Date	Phase angle	Filter	Notes
1. 11/11	19°	V	
2. 11/25	6°	V	Around P _{min}
3. 11/27, 28	6°	g, r, i	Photometry, ~4 hours
4. 12/3	12°	V	

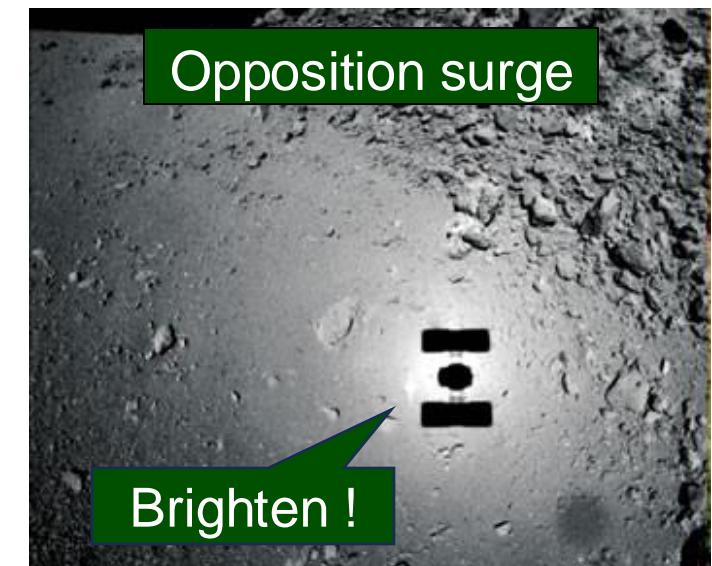


Fig 46, 47. Torifune's position at 11/27, 28, Opposition surge of Itokawa and Hayabusa.

5-2. Torifune Future works

Future works

- Analysis of Seimei's 3 color simultaneous photometry data. As soon as the twilight frames arrive from Okayama (We could not obtain due to cloudy sky conditions).
- Analysis of Pirka's low phase angle polarimetry data.
Size of the regolith be derived ?
- Observe again with Seimei in August 2025 ?
Reaches around 16 magnitude.
This time: ~4 hours of the 5 hours rotation period.
Maybe more data is necessary.
- Preparing for publication in the
'Hayabusa2# special issue' in Space Science Reviews.

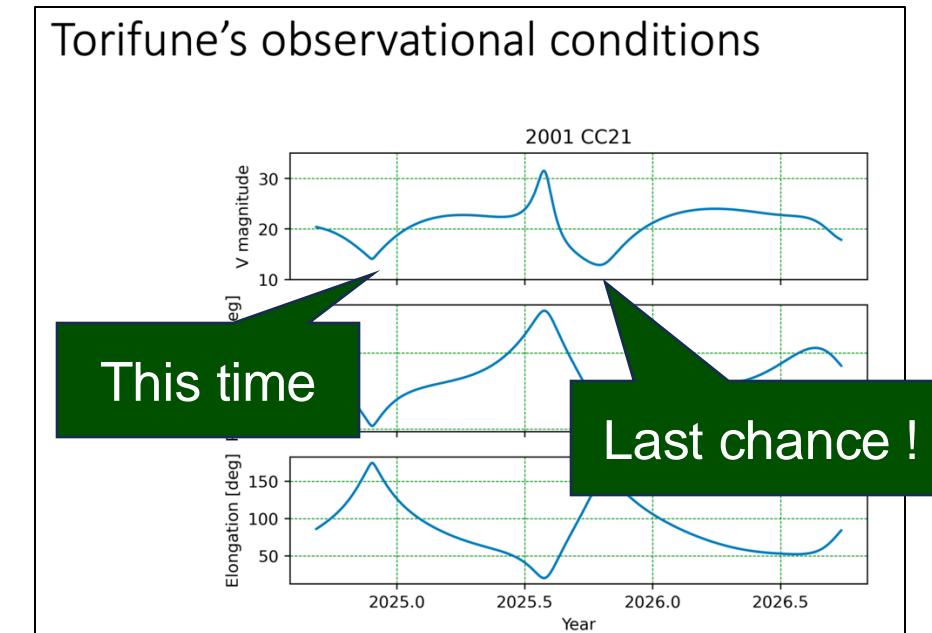


Fig 48. Observational conditions of Torifune.

6. Summary

1. 2024 MK
 - **B-(C-) type, Carbonaceous and Hydrated minerals** from polarimetry observations
 - I will try to derive polarization parameters
 - We are planning to be published as a letter paper
2. Torifune
 - We conducted polarimetric and photometric observations
 - Photometric observations data will be derived **local surface composition**
 - Polarimetric observations data will be derived **regolith size**
Analysis is not yet
 - We are planning to observe again with Seimei telescope in August 2025
 - We are planning to be published as a paper and
'Hayabusa2# special issue' in Space Science Reviews

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