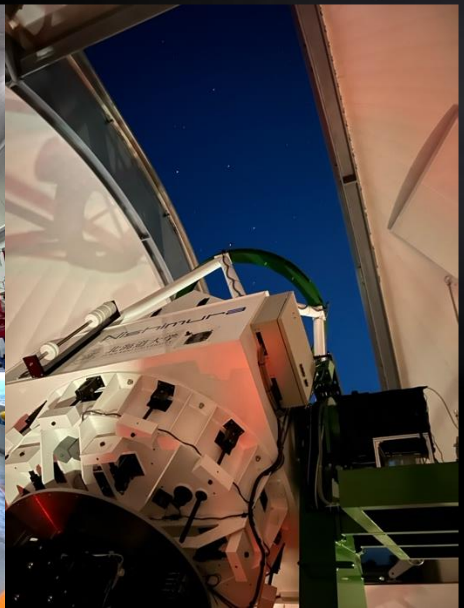
Polarimetric and Photometric observations of the very close approach NEA “2024 MK” and Hayabusa2# targets NEA “Torifune”

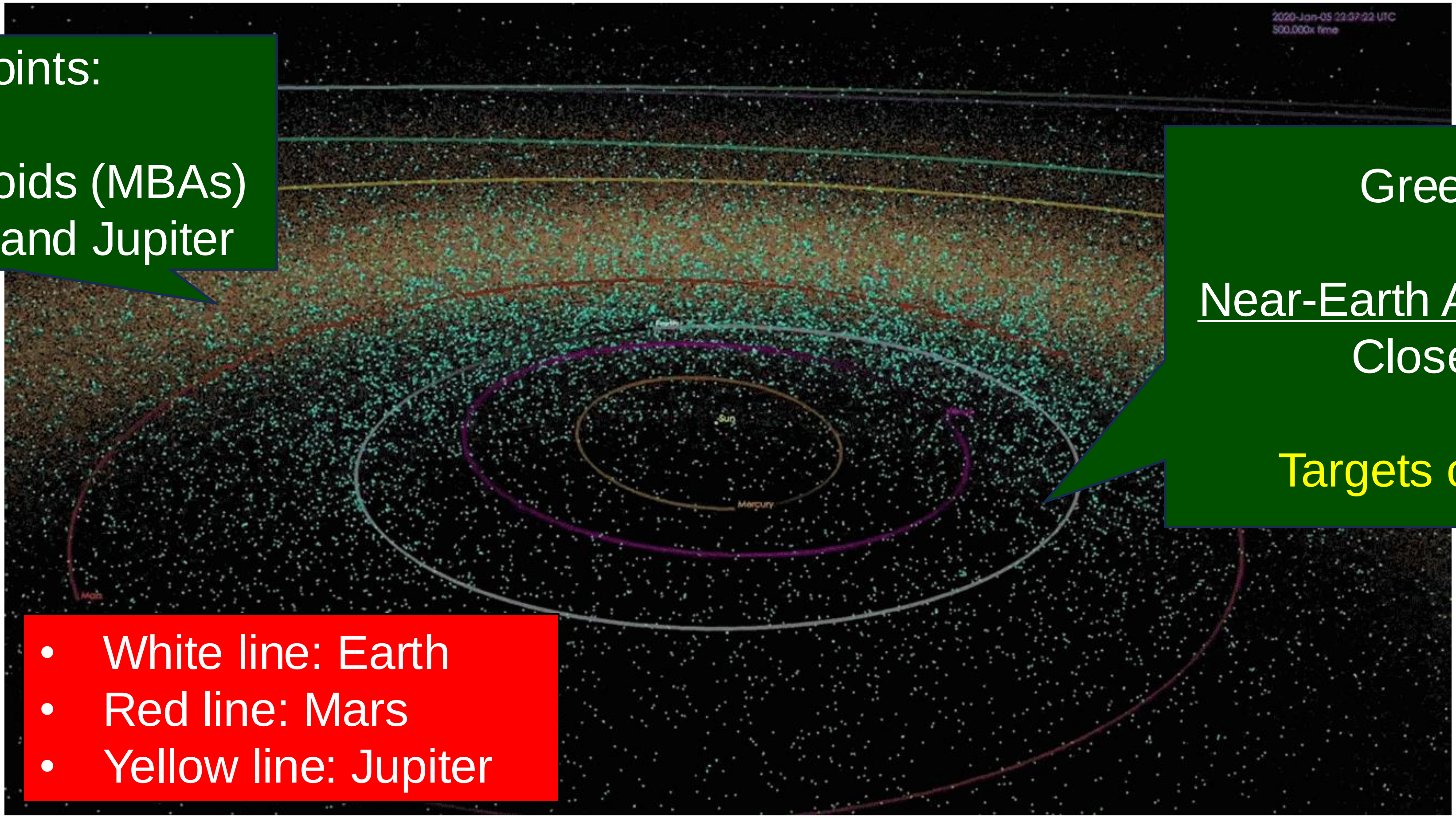


EOU Seminar
2024/12/20 14:45-16:15
M1 Kazuya DOI

Contents

1-1. Classification of Asteroids

Classification by Orbit



Yellow points:

Main-Belt Asteroids (MBAs)
Between Mars and Jupiter

Green points:

Near-Earth Asteroids (NEAs)
Close to Earth

Targets of this study !

- White line: Earth
- Red line: Mars
- Yellow line: Jupiter

Fig 1. Orbit of Asteroids movie.

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., Itolawa, Ryugu

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

1-2. Origin of NEAs

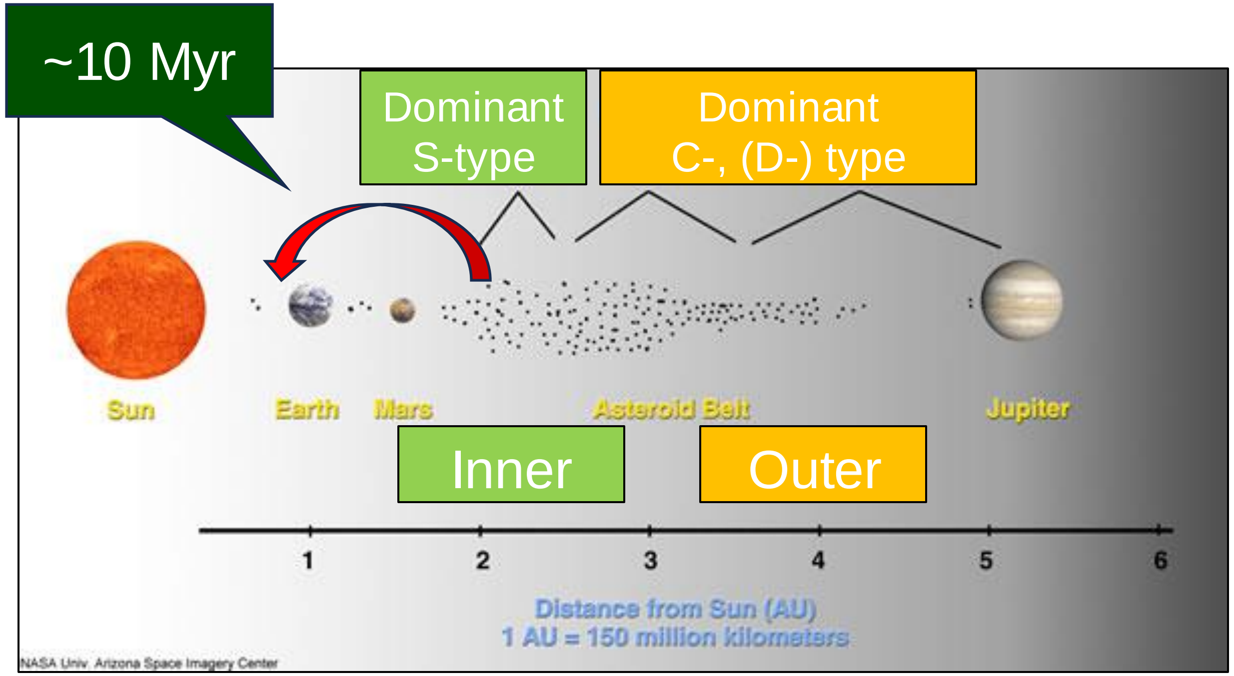


Fig 5. Simple model of distribution of asteroids in the Solar System.

<u>Asteroids as survivors of planetesimals</u>

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

<u>Most NEAs originate from the Inner Main-belt</u>

- 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

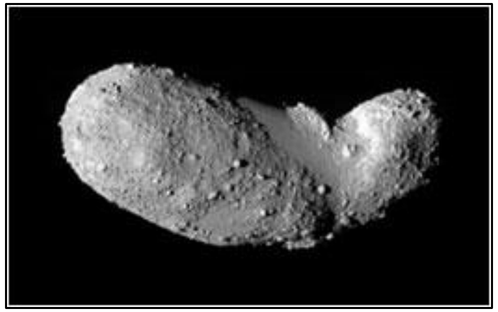


Fig 6, 7. S-type Asteroid Itokawa, C-type Asteroid Ryugu.

<u>5 major Types: Classification by surface composition</u>

"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.

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)	 Blue → Red	Relatively featureless spectrum Steep red slope	0.02-0.06	Primitive carbonaceous Organic-rich compounds Hydrated minerals
C (C,B,F,G)	 Blue → Red	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)	 Blue → Red	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)	 Blue → Red	Moderately steep red slope (λ < 0.7 μm) Shallow to deep absorption at 1.0 and 2.0 μm	0.10-0.22	Stony composition Magnesium Iron silicates
V	 Blue → Red	Moderate to steep red slope Very deep absorption at 1.0 μ	0.60	Volcanic basalts Plutonic rocks

C-type
Low albedo

S-type
High albedo

1-3. Taxonomy

<u>Most NEAs are S-type, while C-type are rare.</u>

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

<u>C-type asteroids are dark</u>

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

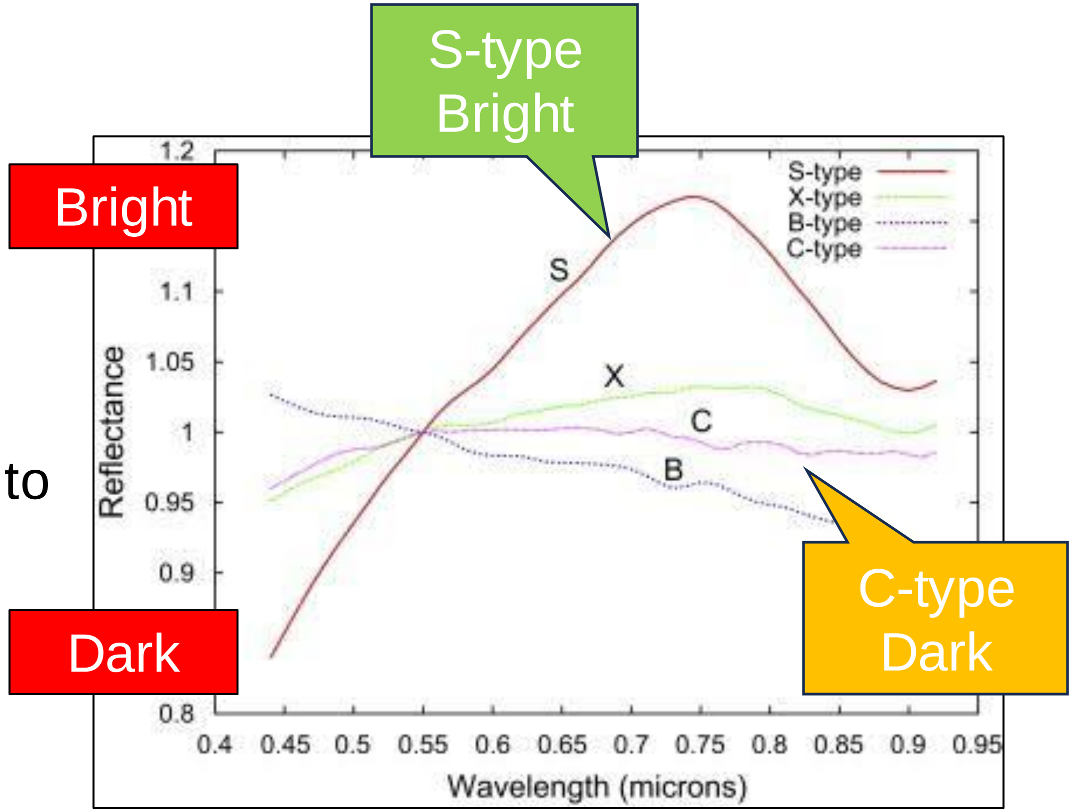


Fig 8. Relative reflectance of each type asteroids (visible range).

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.

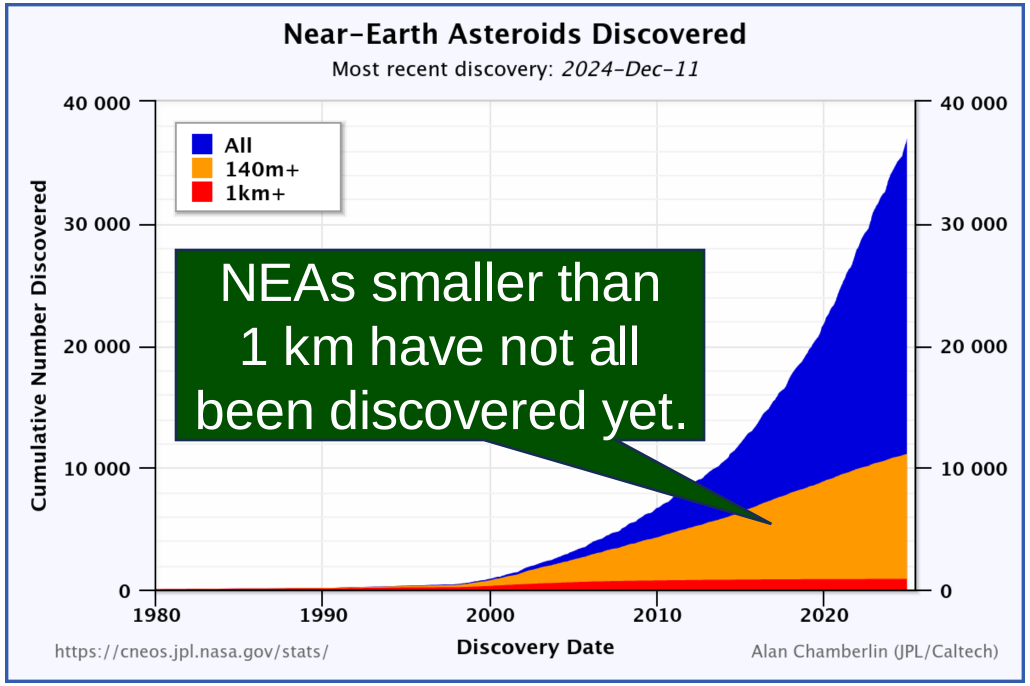
<u>Observation Opportunities</u>

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

1-4. Number

<u>1.4 million discovered (as of December, 2024)</u>

- The number of discoveries is increasing steeply.
  Due to improvements of observational instruments and skills.



We can not deal with the unknown !

<u>Number of NEAs (as of December, 2024)</u>

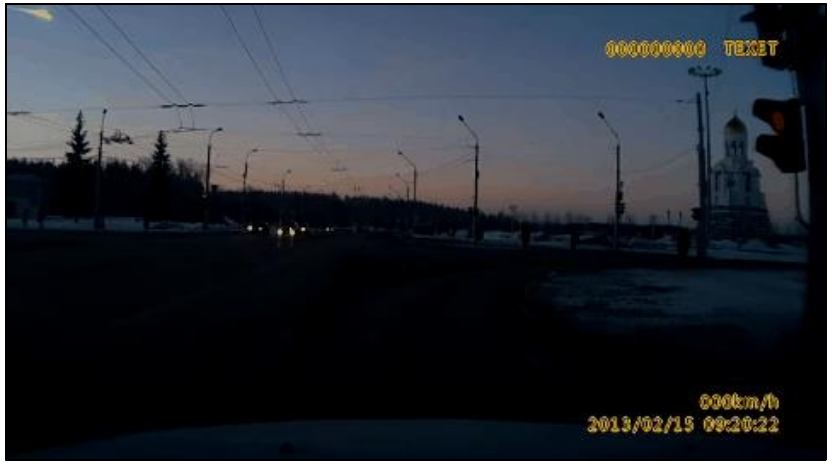
- ~36,000 have been discovered,
  but the **physical properties of many newly discovered NEAs are unknown**.
- Most NEAs larger than 1 km have been discovered because they are bright,
  but many NEAs smaller than 1 km remain undiscovered because they are dark.

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.

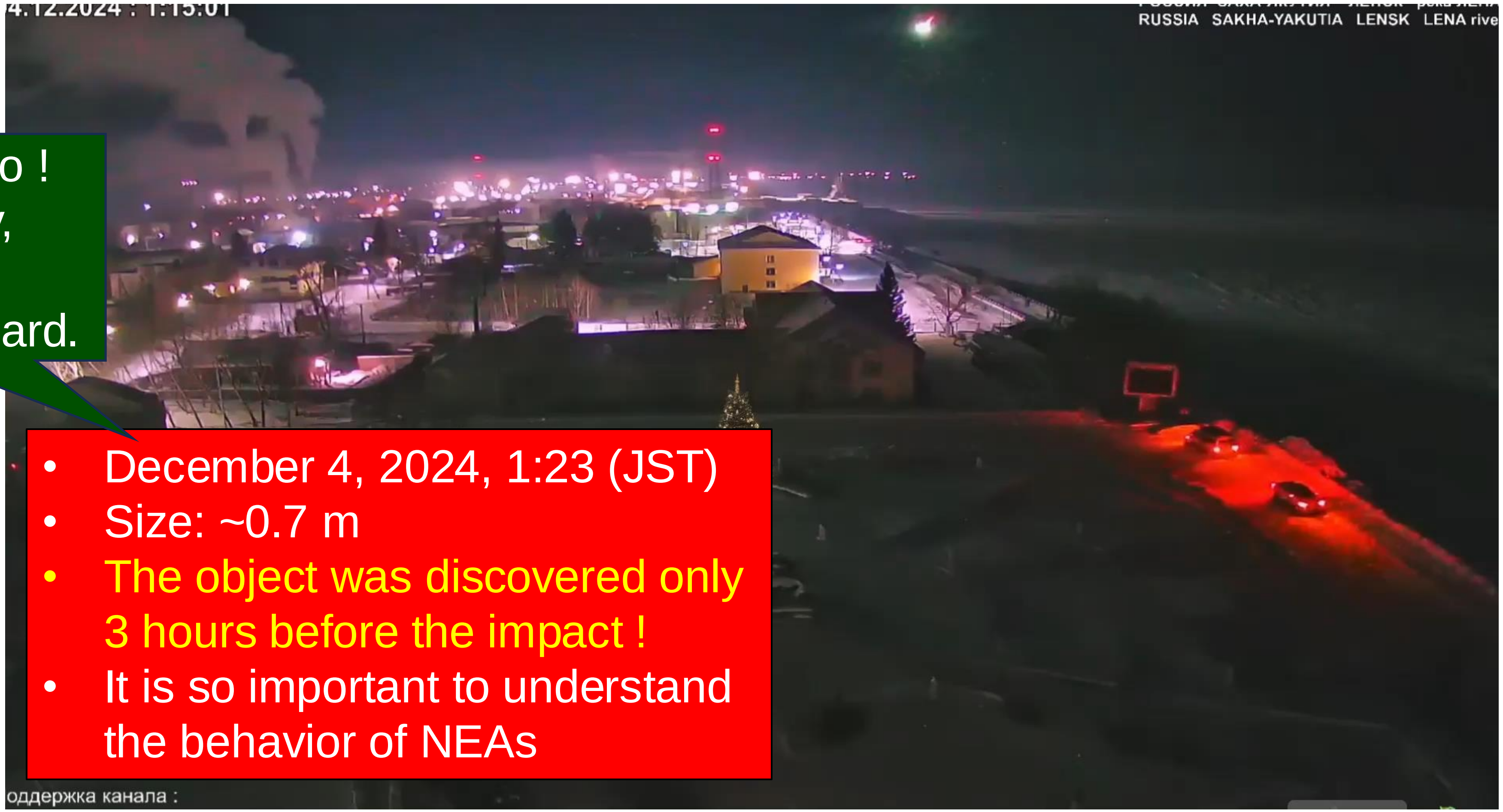


- So now, multiple missions are being conducted to achieve and contribute Planetary Defense.

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)

<u>Recent impact on Earth !</u>



~2 weeks ago !
Fortunately,
there was
no human hazard.

- December 4, 2024, 1:23 (JST)
- Size: ~0.7 m
- The object was discovered only 3 hours before the impact !
- It is so important to understand the behavior of NEAs

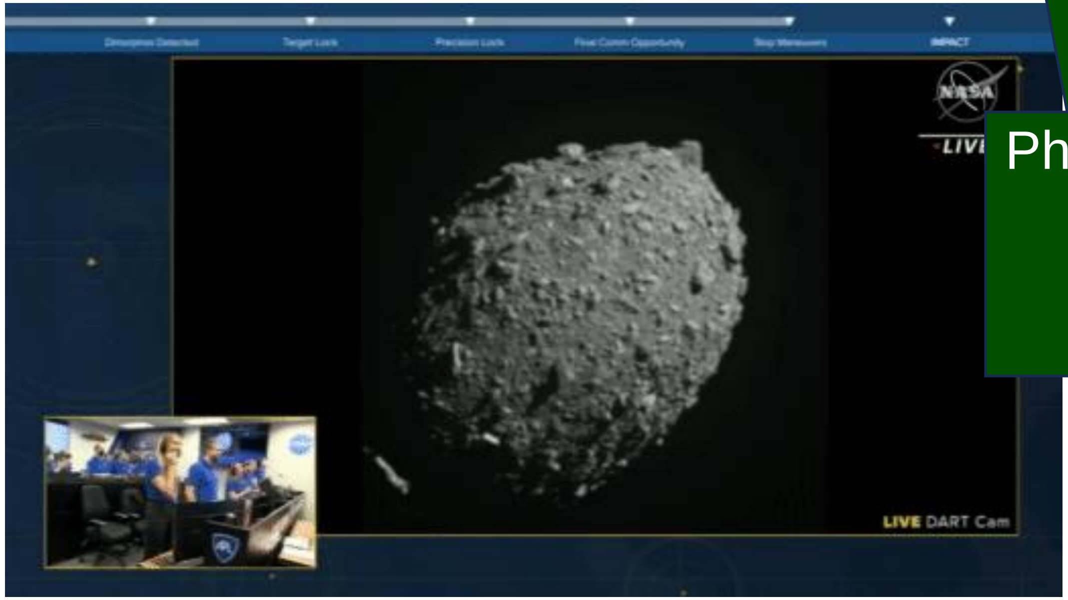
Fig 13. Impact of C0WEPC5 movie.

1-6. Planetary Defense Missions

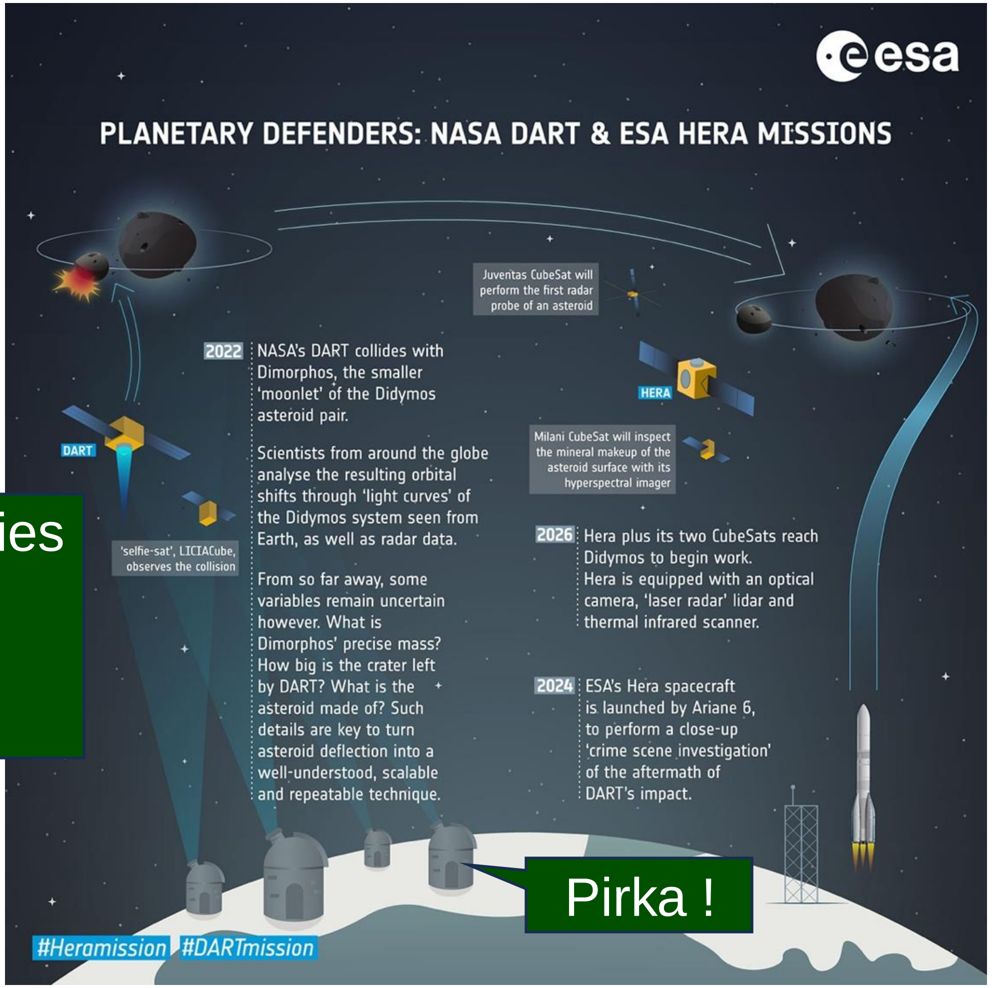
Avoiding collisions
Predicting hazard

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.



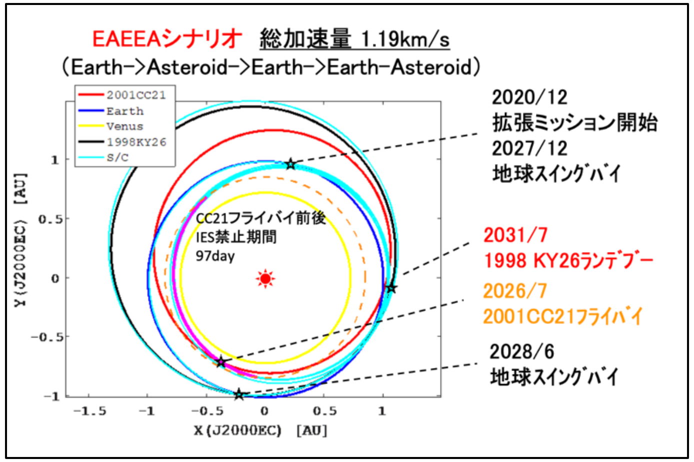
Pirka !

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**.



I observed with Seimei & Pirka.

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 ?

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

2. Purpose and Goals

Tab 2. The hazard based on physical properties.

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

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.

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

Pirka

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.

Seimei

Other observations

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

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

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.

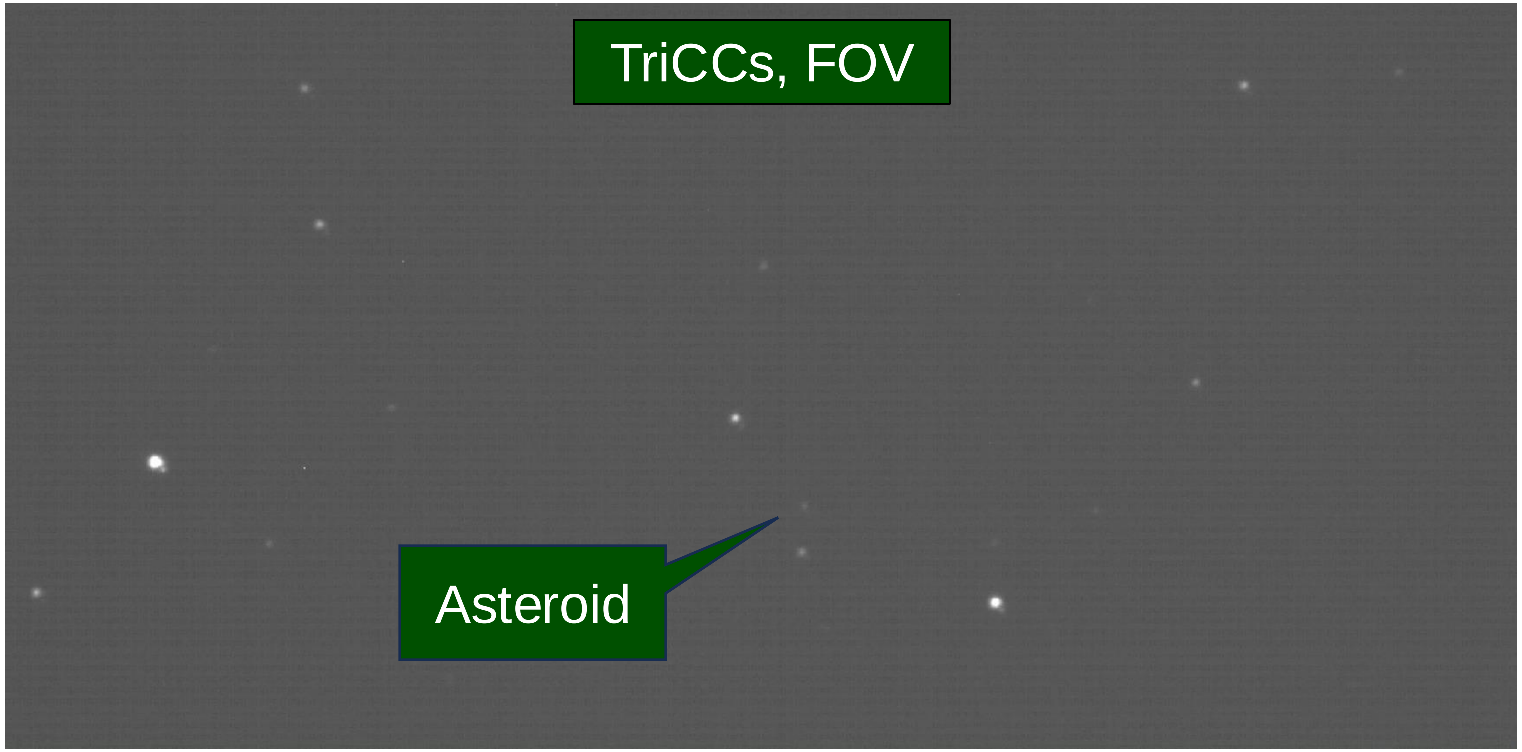


Fig 20. 2 fits data of target Asteroids blink movie.

3-3. (A) Polarimetric observations

<u>Polarization</u>

- 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 <u>surface properties</u>.

Unpolarized & Polarized light

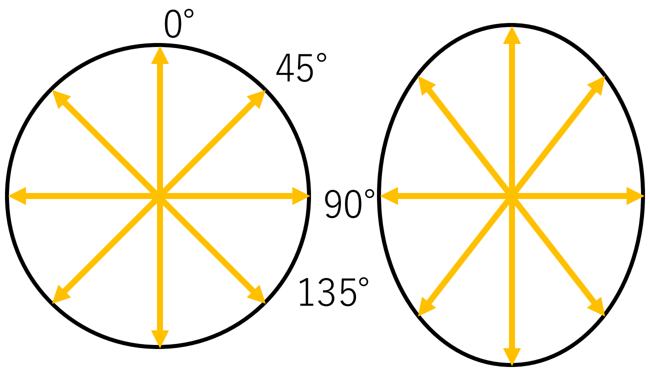


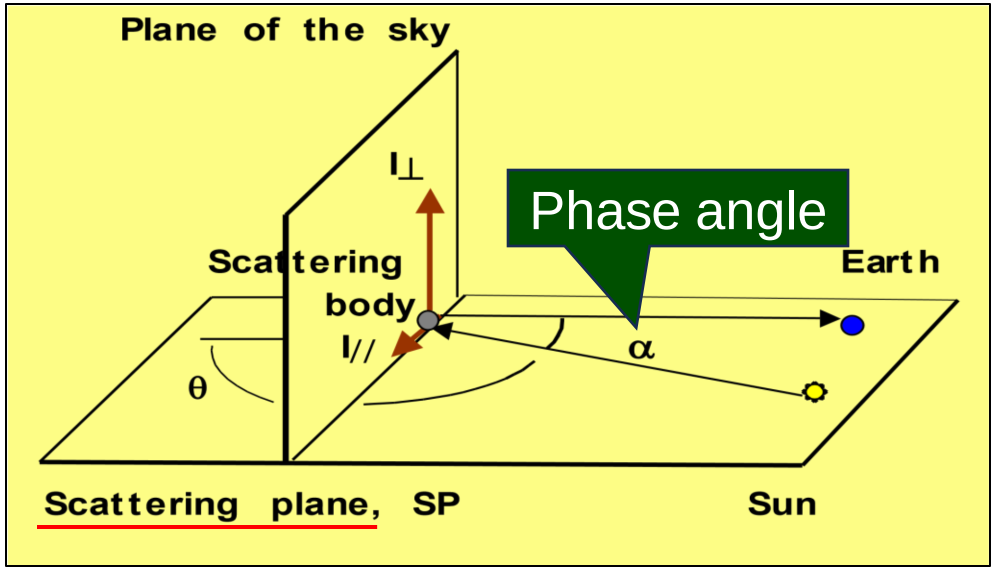
Fig 21, 22, 23. Polarization filter movie, Polarization of Asteroid, Unpolarized and polarized light.

3-3. (A) Polarimetric observations

<u>Polarization degree</u>

- Linear Polarization: $\mathbf{P_r} = \frac{\mathbf{I_{\perp} - I_{\parallel}}}{\mathbf{I_{\perp} + I_{\parallel}}}\ \%$
- Polarizer: Wollaston Prism

separate into Ordinary-ray (O-ray: $I_{\perp}$) and Extraordinary-ray (E-ray: $I_{\parallel}$)



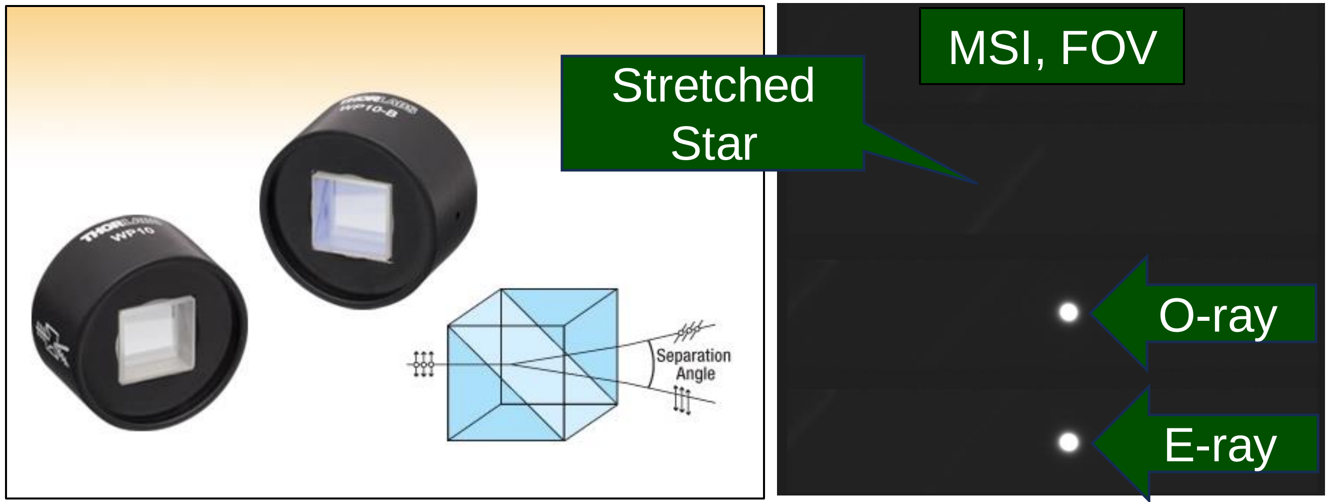
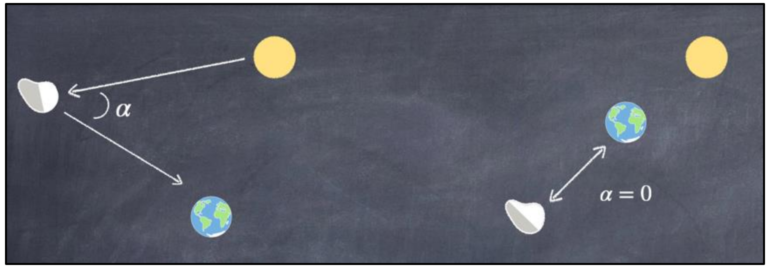


Fig 24, 25, 26. Basic information of Polarization, Wollaston Prism, MSI FOV.

3-3. (A) Polarimetric observations

- Linear Polarization: $\mathbf{P_r}$ 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) Obtain various data !

$\mathrm{P_r}$ vs α linear polarization curve

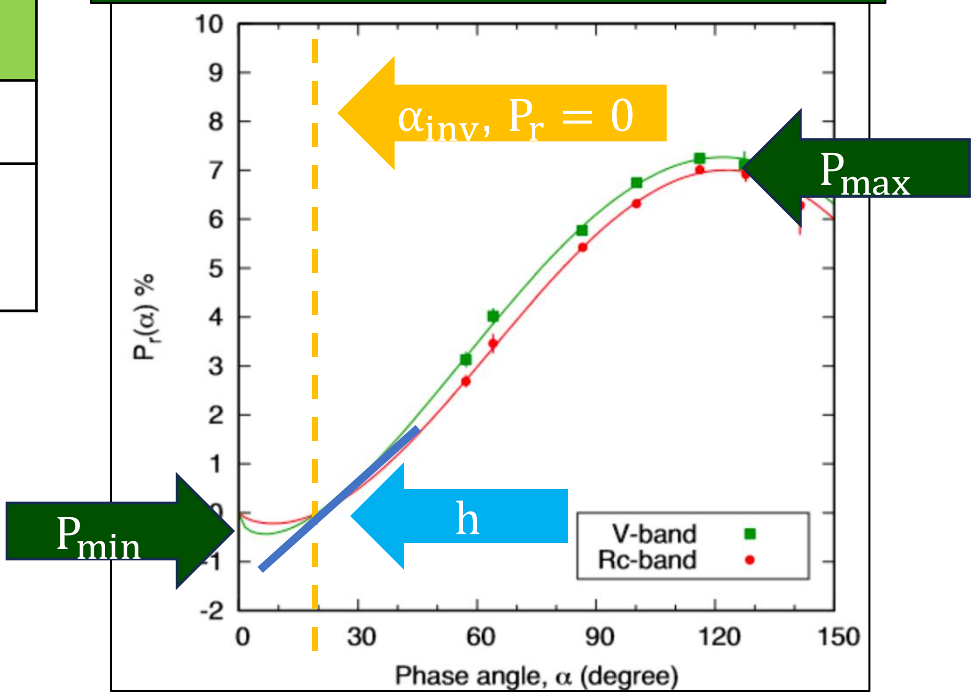


Fig 27. NEA 1566 Icarus. [Ishiguro et al., 2017]

- Polarization curve and detect polarization parameters.

α_{inv}: inversion angle

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

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

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

3-3. (A) Polarimetric observations

<u>Surface composition (Empirically)</u>

- Polarization curve shape (visually)
- Slope: h, $\mathrm{P_{min}}$ & 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	$\mathrm{P_{max}}$	$\mathrm{P_{min}}$
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.

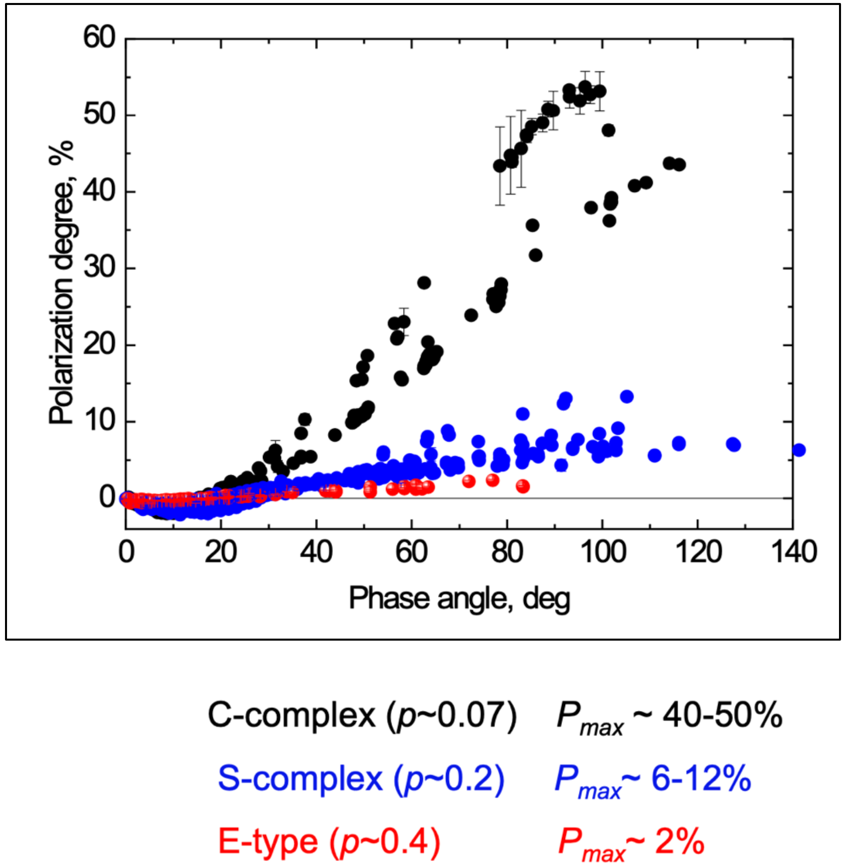


Fig 28. Polarization of typical C-, S-, E-Type Asteroids include NEAs. [Belskaya, 2024]

3-3. (A) Polarimetric observations

<u>Albedo (Empirically)</u>

- Slope: h

$$\log_{10} \mathrm{A} = \mathrm{C}_1 \log_{10} \mathrm{h} + \mathrm{C}_2$$

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	$\mathrm{P}_{\mathrm{max}}$	$\mathrm{P}_{\mathrm{min}}$
C Type	Small	Steep	High	Deep
S Type	Large	Mild	Low	Shallow

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

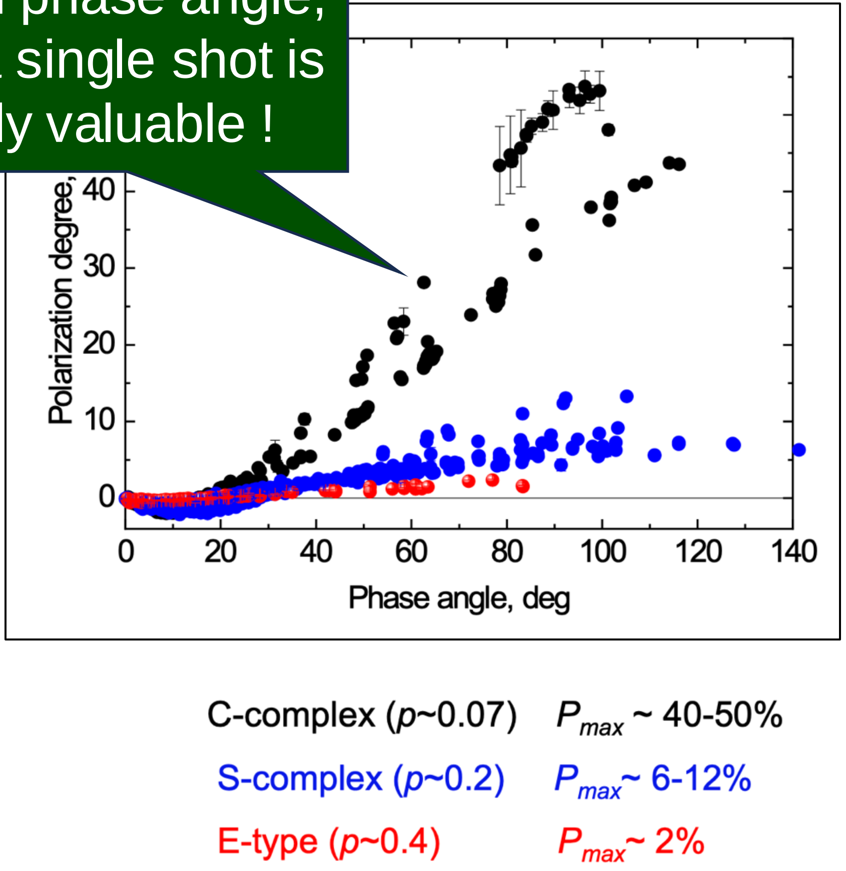


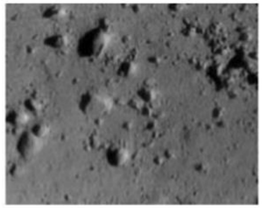
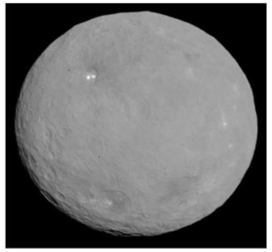
Fig 28. Polarization of typical C-, S-, E-Type Asteroids include NEAs. [Belskaya, 2024]

3-3. (A) Polarimetric observations

<u>Regolith: Grain size & Porosity (Empirically)</u>

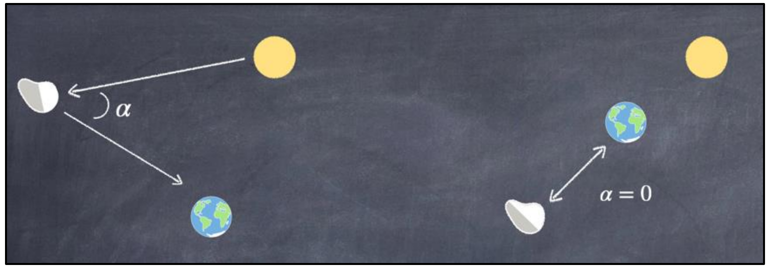
- Grain size: P_{max} & Albedo
- Porosity: P_{max}

Tab 5. Grain size and Porosity relationship.

Regolith of several asteroids and moon			
25143 Itokawa	433 Eros	The moon	1 Ceres
			

Rough — Grain size — Fine

High — Porosity — Low



P_r vs α linear polarization curve

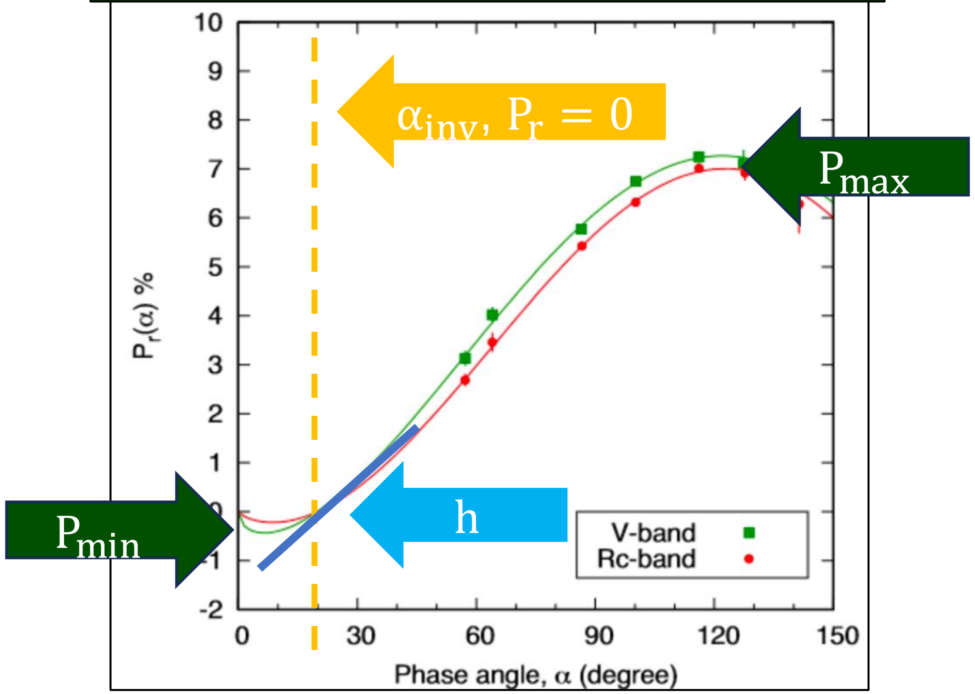


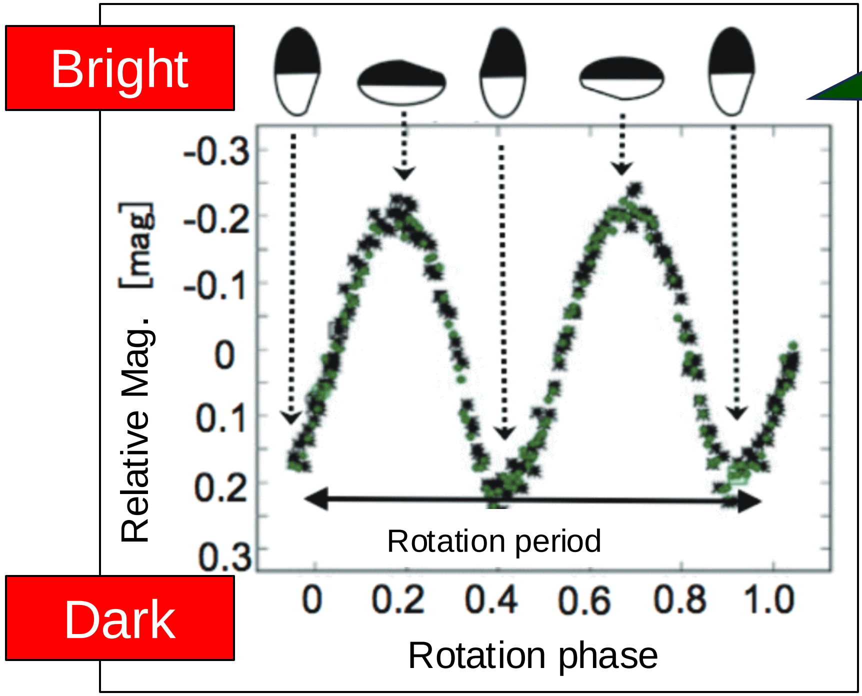
Fig 27. NEA 1566 Icarus. [Ishiguro et al., 2017]

3-4. (B) Photometric observations

Plus !

<u>**Local** surface composition</u>

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



Normal light curve
(No filter)
Only Rotation period

Color light curve
The local surface composition of each sides, corresponding to the rotation period can be understood !

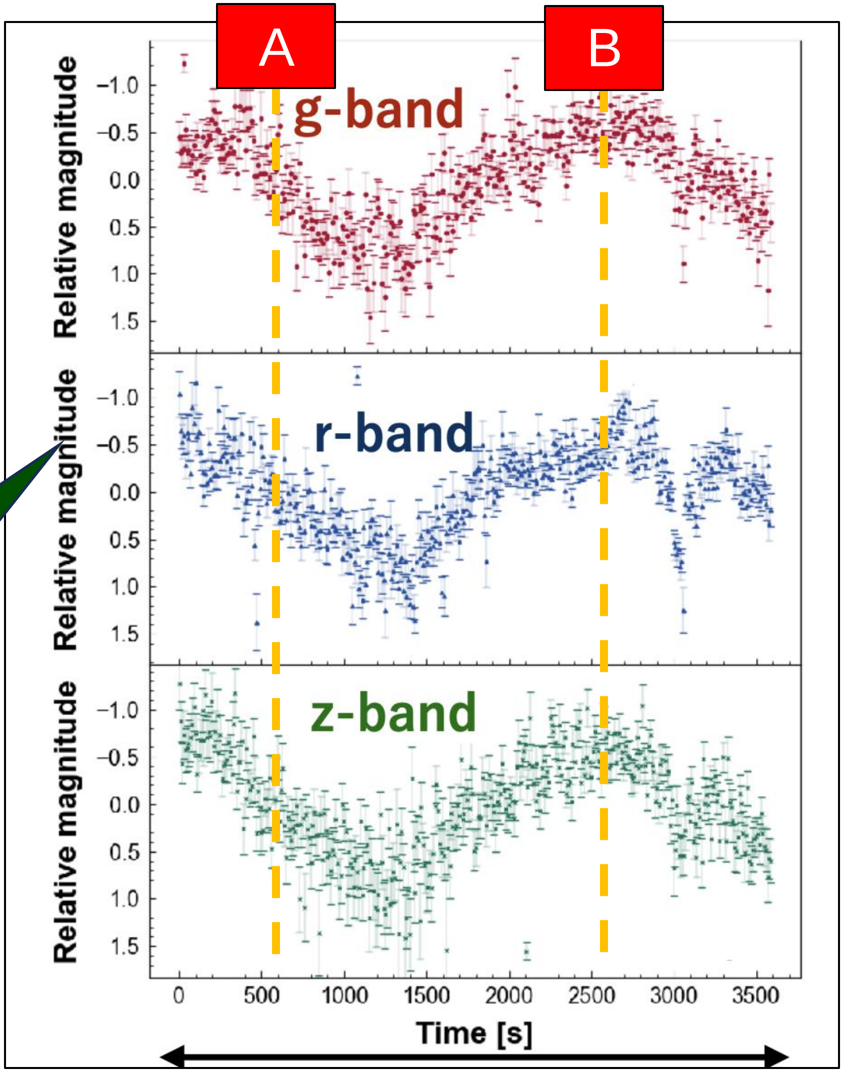


Fig 29, 30. Rotation period of asteroid,
TriCCs color light curve of tiny NEA. [Beniyama et al., 2021]

3-5. 1.6 m Pirka Telescope & MSI

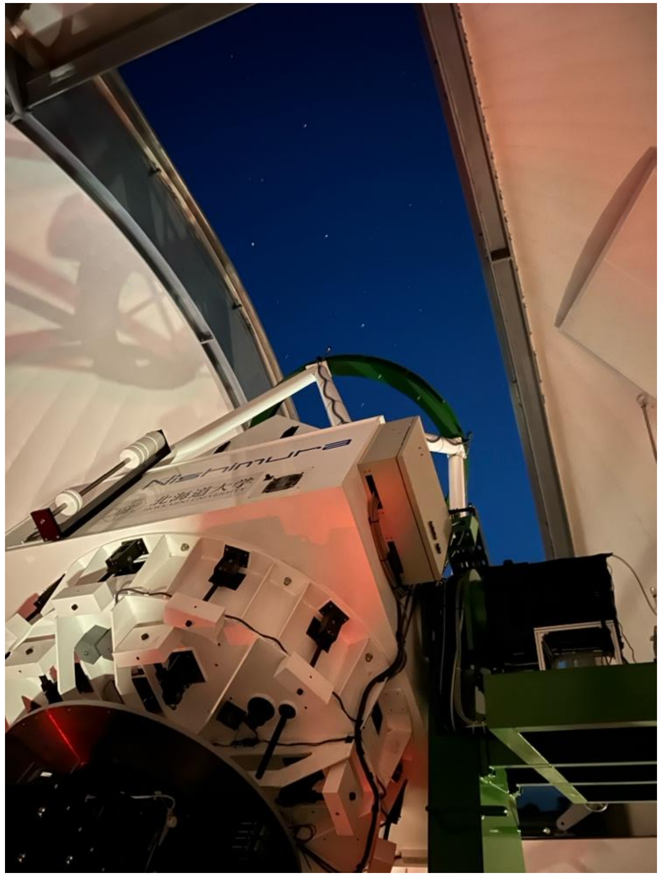
Pirka Telescope

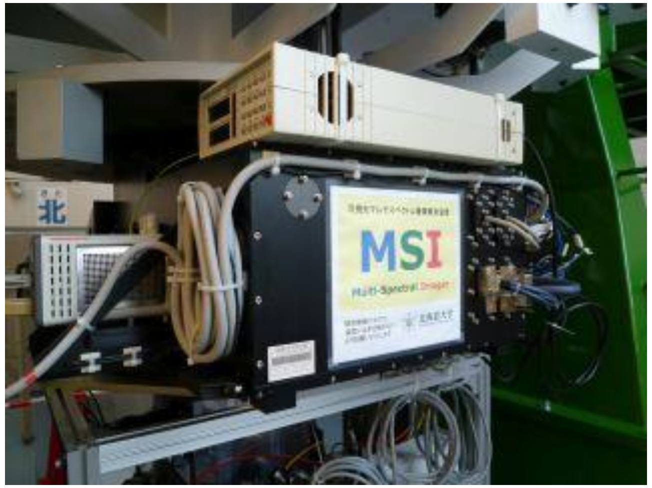
- Location: Nayoro Observatory
- Own: Hokkaido Univ.

MSI (Multi-Spectral Imager)

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

Can conduct polarimetry





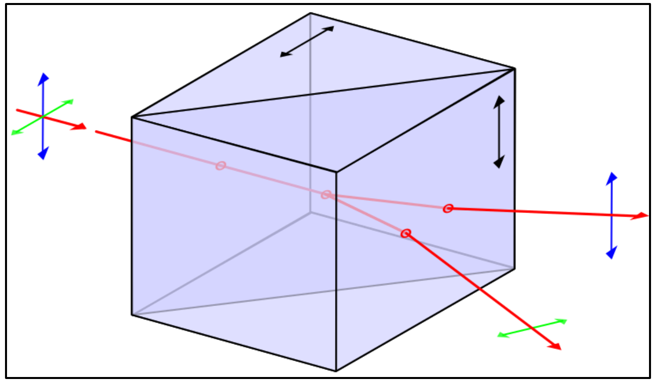


Fig 31, 32, 33. Pirka Telescope, MSI, Wollaston prism.

3-6. 3.8 m Seimei Telescope & TriCCs

<u>Seimei Telescope</u>

- Location: Okayama Observatory
- Own: Kyoto Univ., and open use by NAOJ

  The largest optical telescope in East Asia

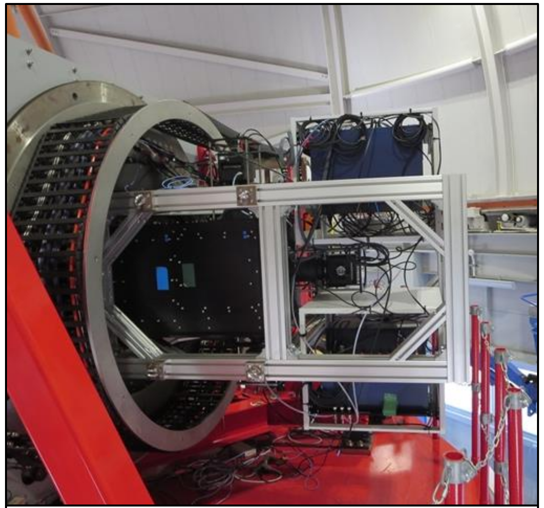
<u>TriCCs (Tricolor CMOS Cameras)</u>

Imaging mode:

<u>Tri-colors simultaneous photometry</u>

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

Color light curve



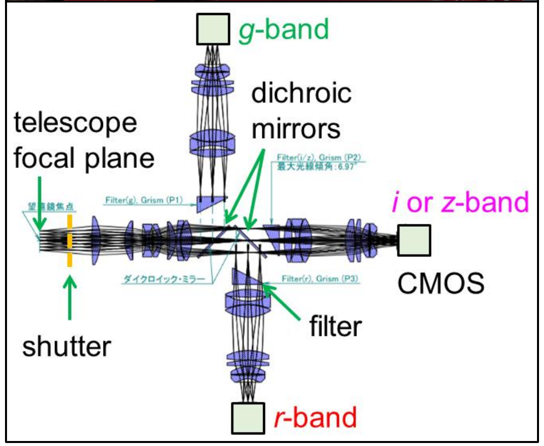
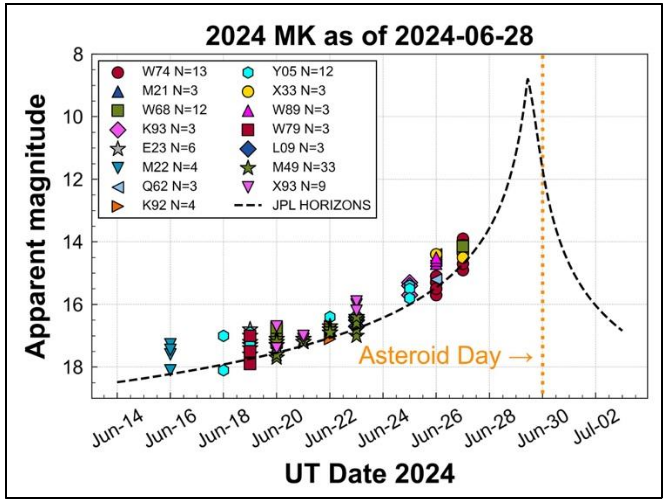


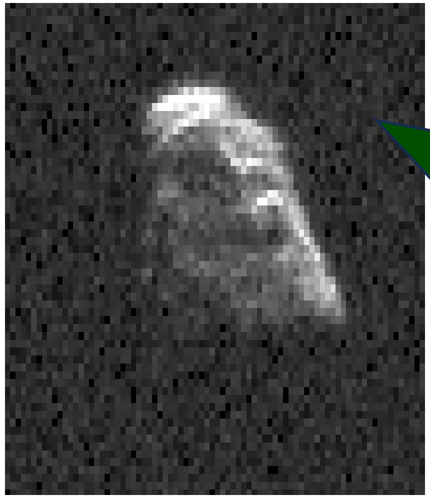
Fig 34, 35, 36. Seimei Telescope, TriCCs, Imaging mode details of TriCCs.

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

<u>Observations</u>

- 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 ± 0.03 %
	26.8°	1.84 ± 0.04 %
	27.1°	3.33 ± 0.04 %
	27.7°	3.96 ± 0.04 %
2. 7/2	101.0°	37.63 ± 1.22 %

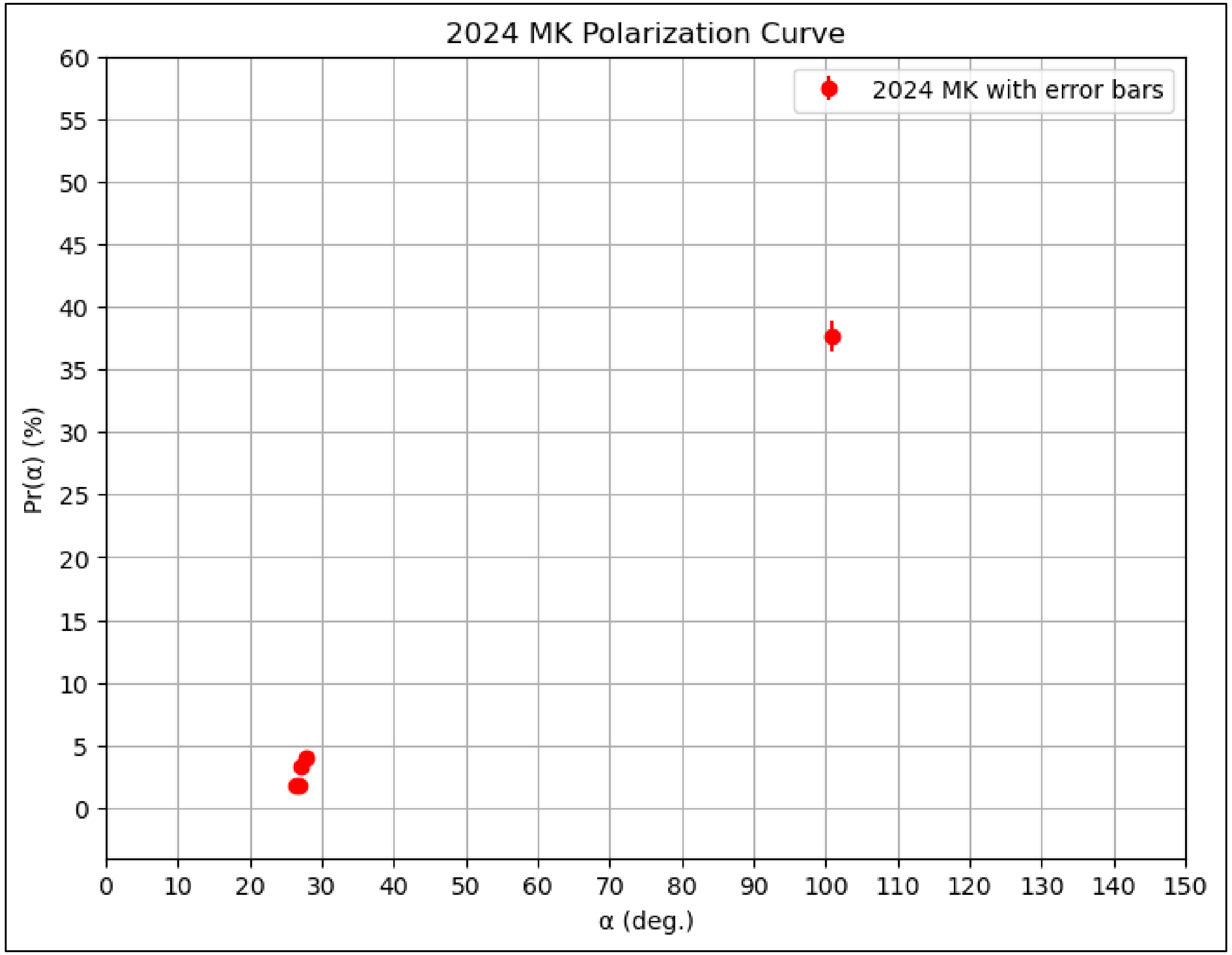


Fig 40. Polarization degree of 2024 MK.

4-3. 2024 MK Discussion

- Comparison with previous Polarimetric observation results of NEAs.

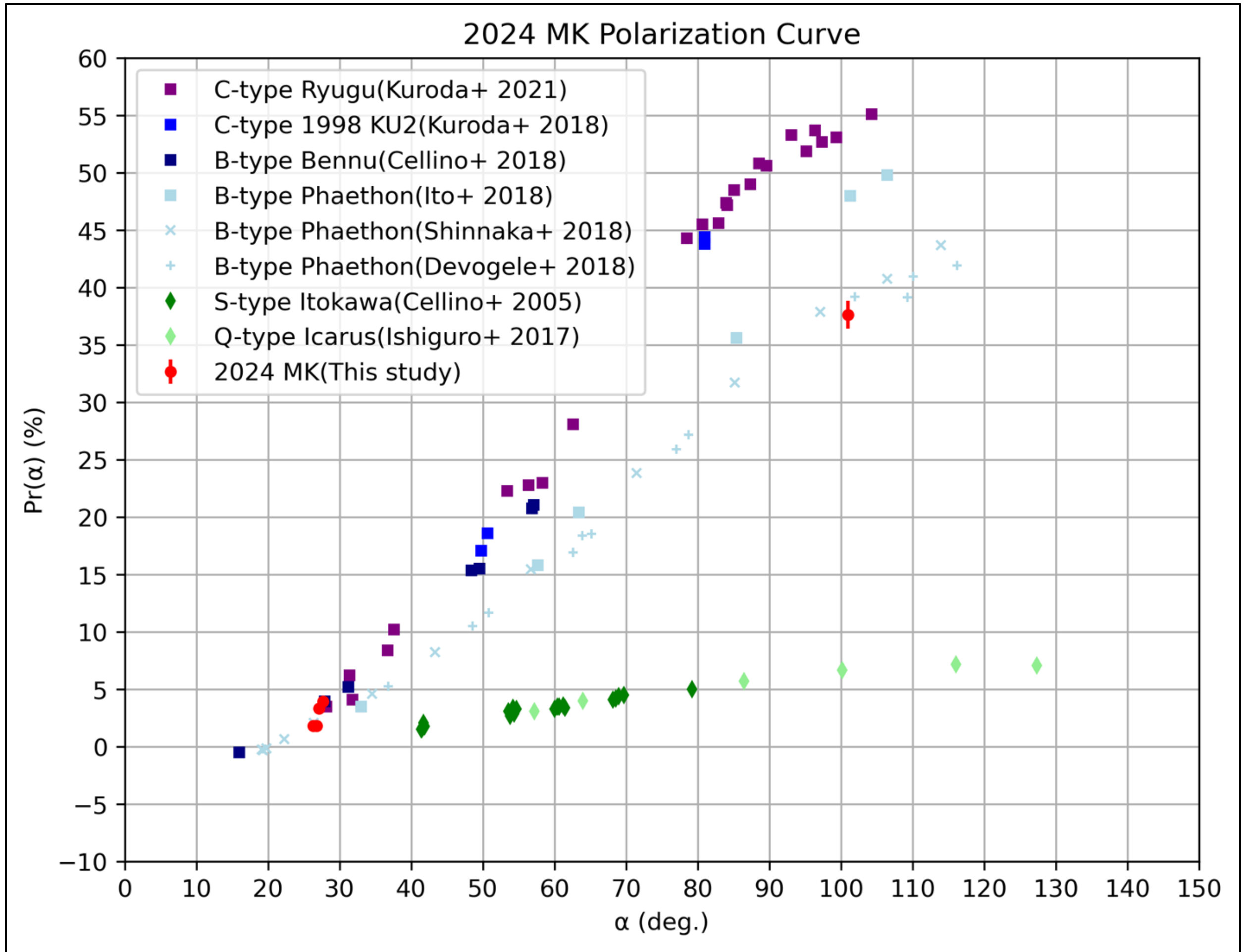


Fig 41. Polarization degree of 2024 MK and Several previous results.

4-3. 2024 MK Discussion

- Comparison with previous Polarimetric observation results of NEAs.

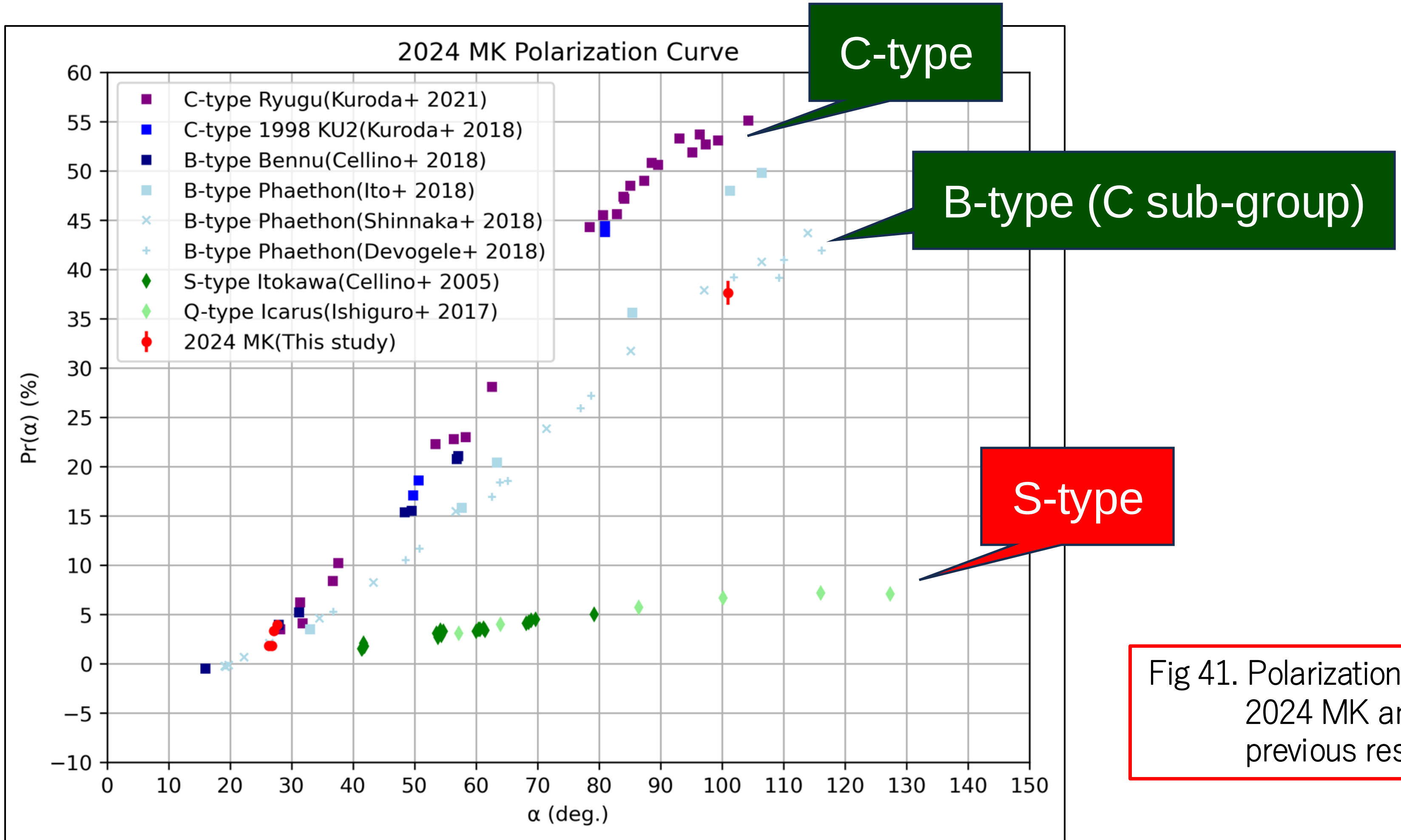


Fig 41. Polarization degree of 2024 MK and Several previous results.

4-3. 2024 MK Discussion

<u>C-type, especially sub-group B-type</u>

- 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) ?

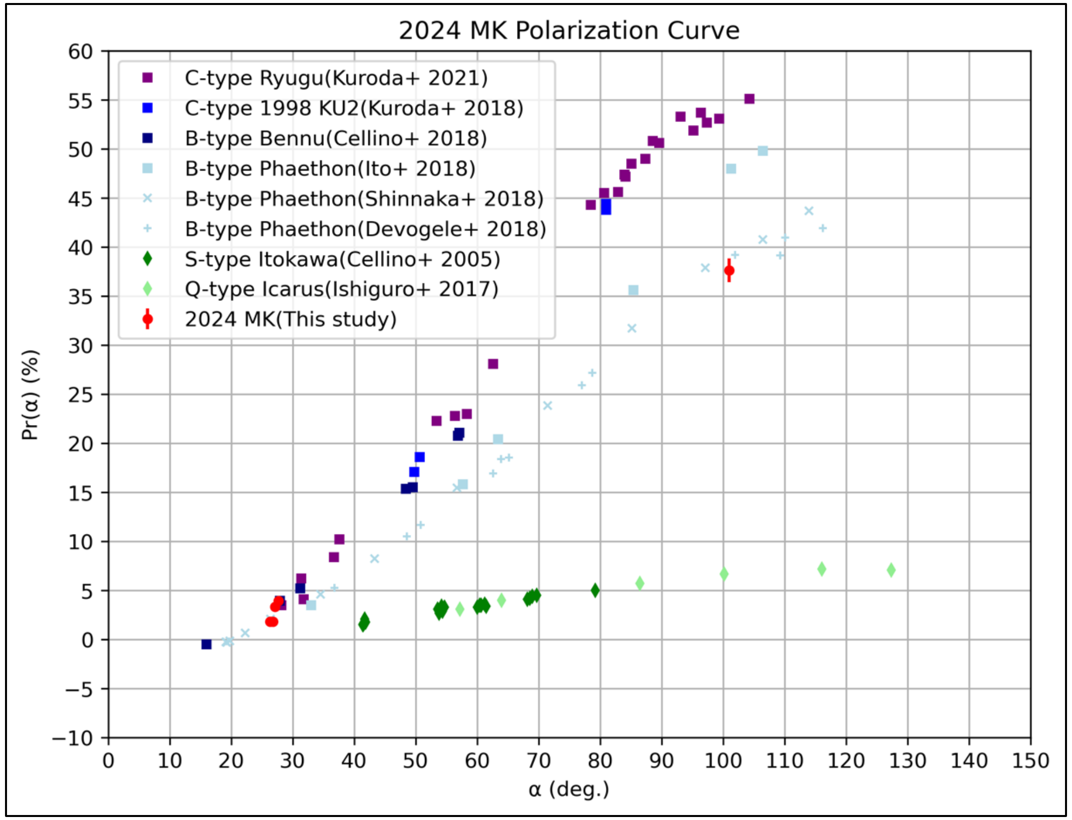


Fig 41. Polarization degree of 2024 MK and Several previous results.

4-4. 2024 MK Future works

<u>Future works</u>

- Draw the Polarization curve (possible ?)

  Lumme-Muinonen function

  $$P_r(\alpha) = b(\sin\alpha)^{c_1}(\cos\frac{\alpha}{2})^{c_2}\sin(\alpha - \alpha_{inv})$$

  b, C_1, C_2: 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.

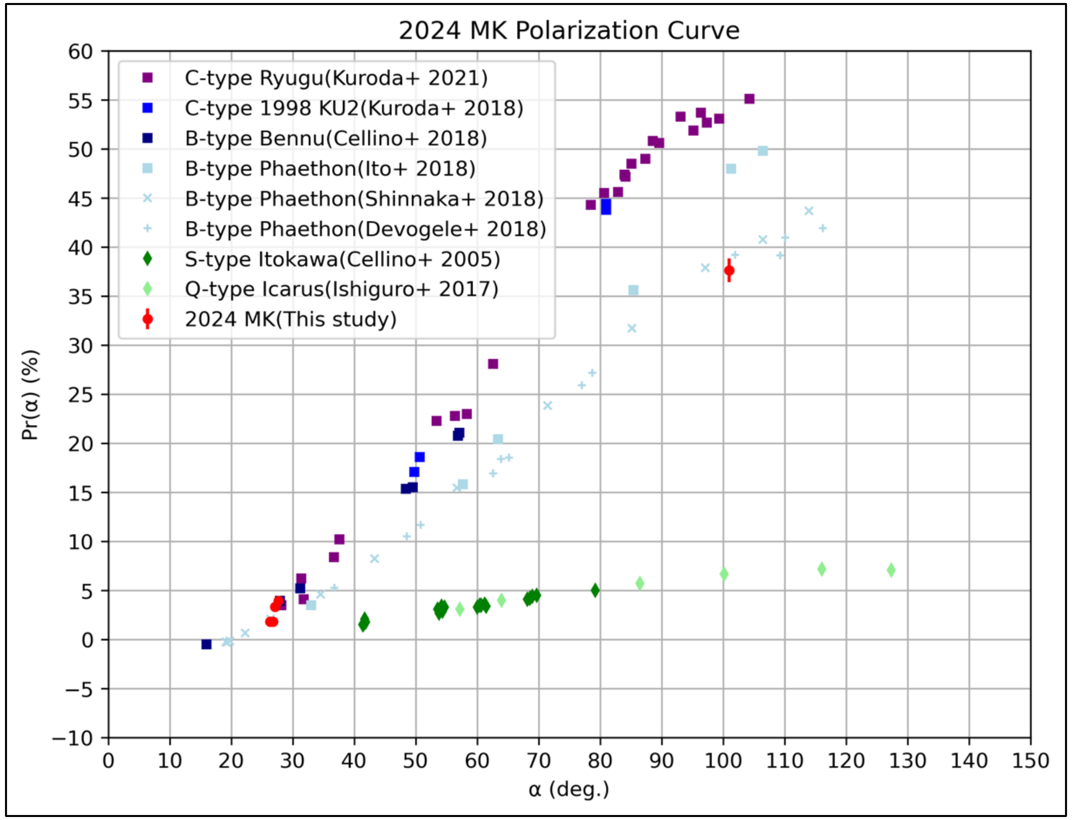


Fig 41. Polarization degree of 2024 MK and Several previous results.

5-1. Torifune information and observations

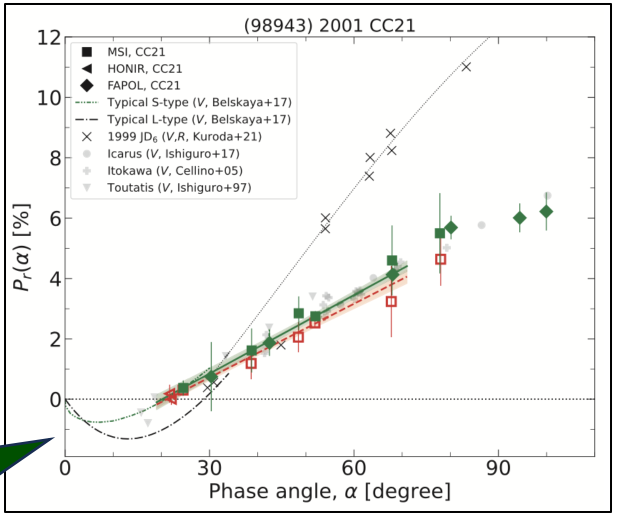
<u>Information</u>

- 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 × 294 × 209 m	~500 m
Surface	Rubble pile	?

Polarimetry
S-type



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

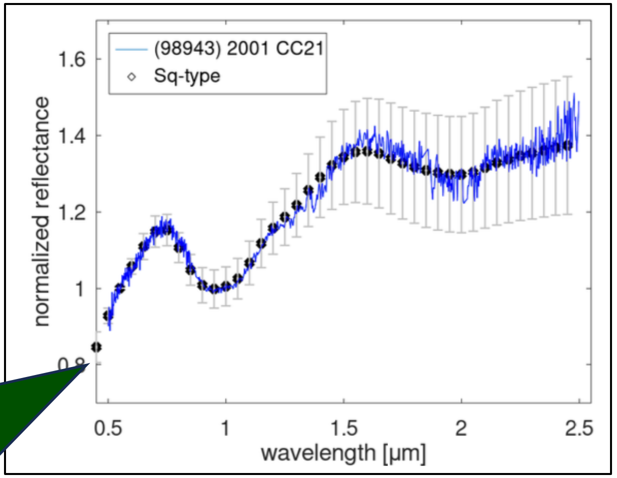


Fig 42, 43. Polarization curve of Torifune.
[Geem et al., 2023],
Reflectance spectral of Torifune
[Popescu et al, 2024 (not published)]

5-1. Torifune information and observations

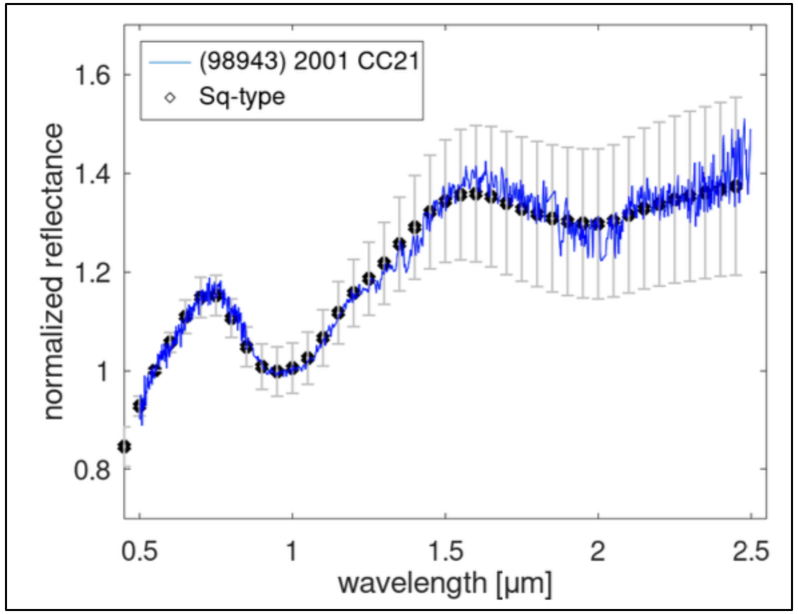
Information

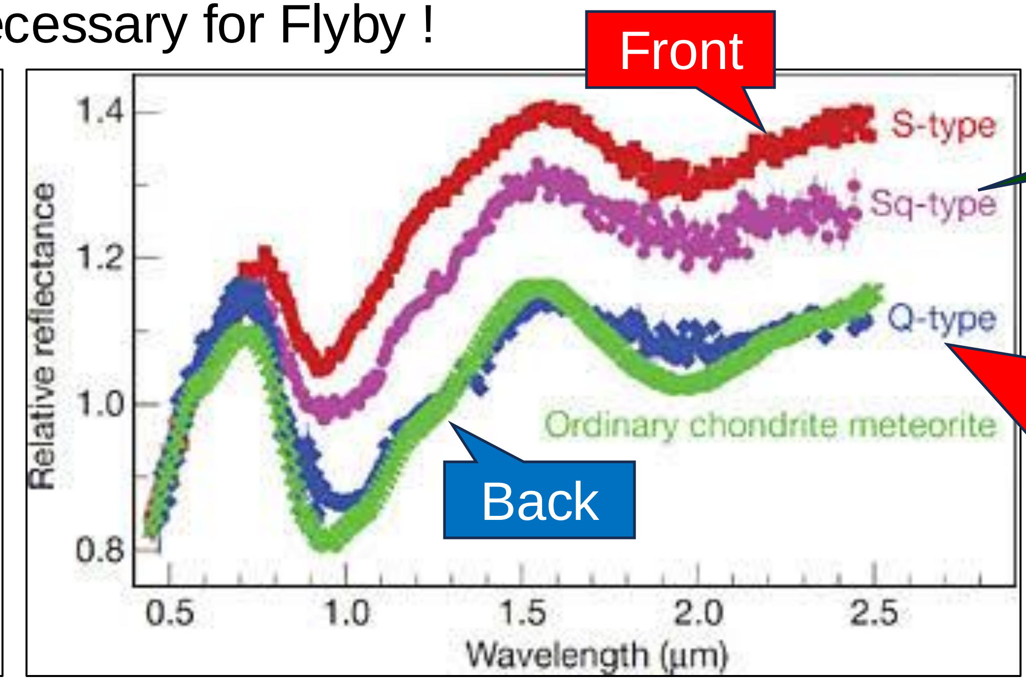
- Spectroscopic observation result: Sq-type (S sub-group)

  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





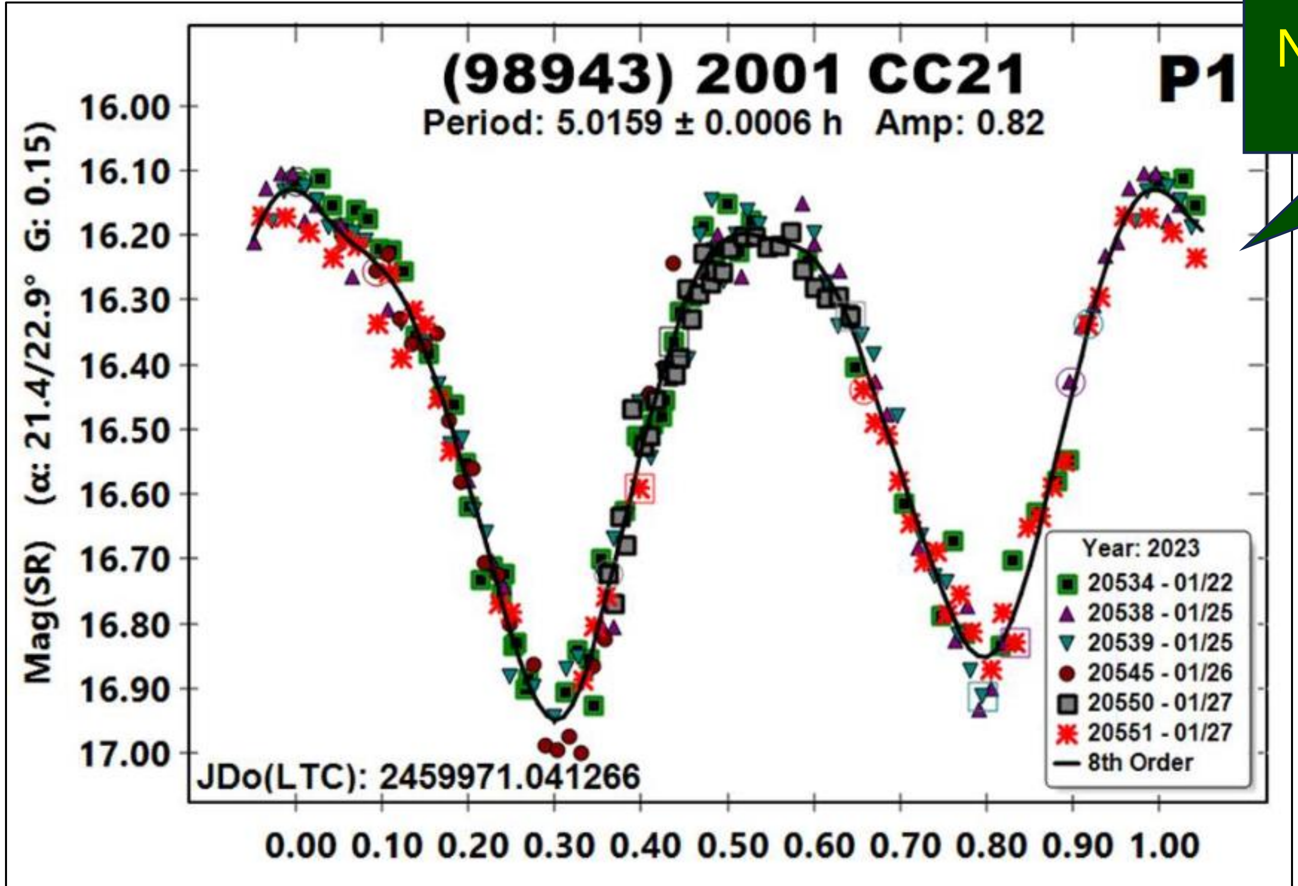
2. Mean case
Front side is S-type, back side is Q-type
Mean is Sq-type.

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

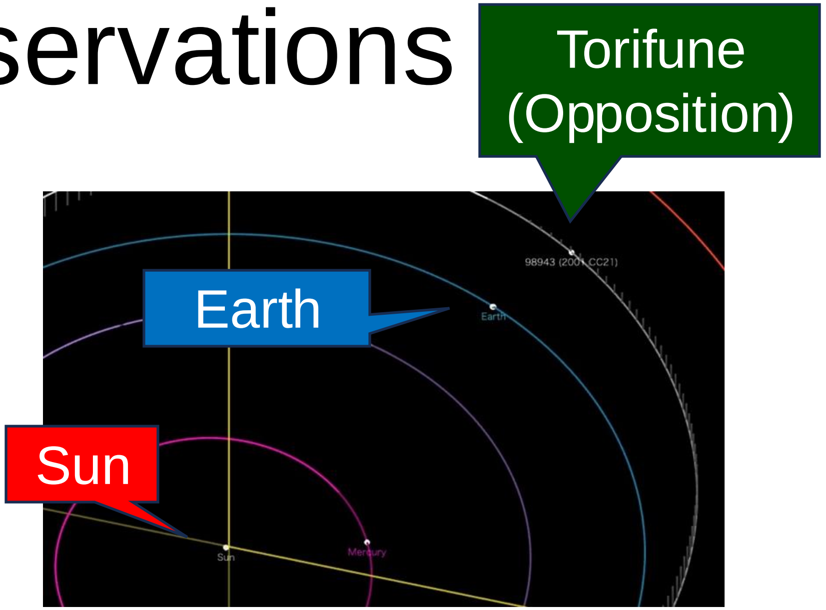


Normal light Curve
(no filter)

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



<u>Observations</u>

- 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	

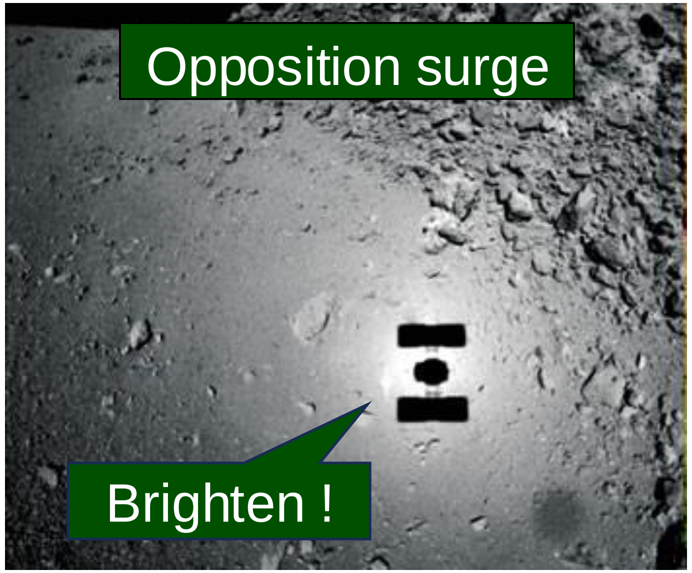


Fig 46, 47. Torifune's position at 11/27, 28, Opposition surge of Itokawa and Hayabusa.

5-2. Torifune Future works

<u>Future works</u>

- 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.

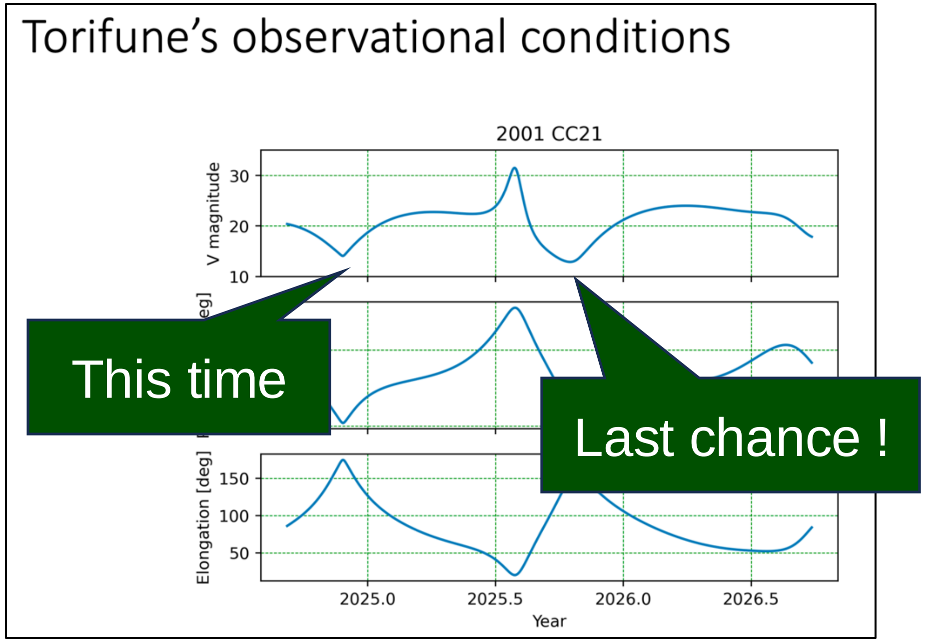


Fig 48. Observational conditions of Torifune.

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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