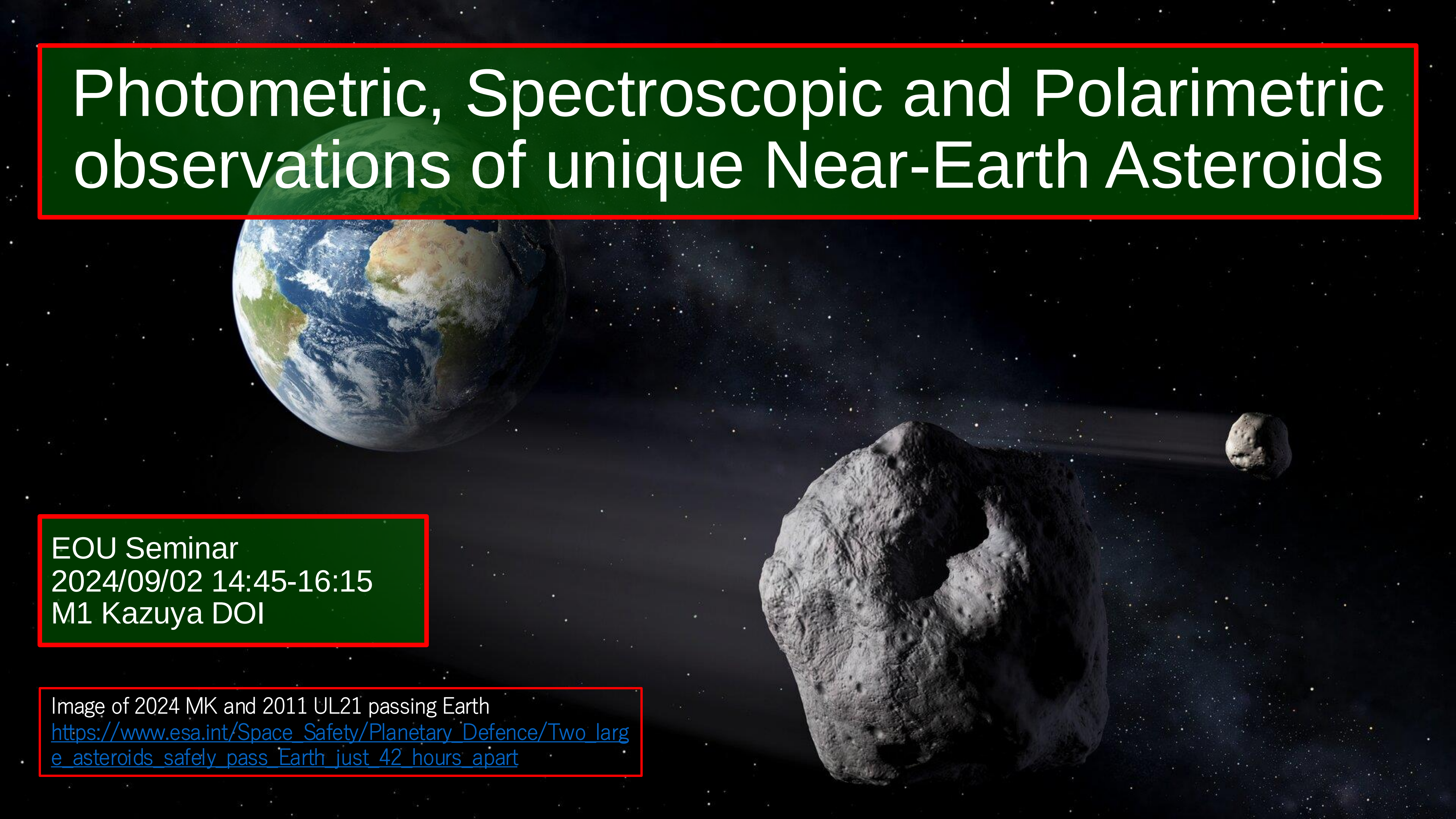


Photometric, Spectroscopic and Polarimetric observations of unique Near-Earth Asteroids

EOU Seminar
2024/09/02 14:45-16:15
M1 Kazuya DOI

Image of 2024 MK and 2011 UL21 passing Earth
https://www.esa.int/Space_Safety/Planetary_Defence/Two_large_asteroids_safely_pass_Earth_just_42_hours_apart

Content

1-1. Origin of Asteroids

Survivors of rocky planetesimals

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

Sources of Earth's water and minerals?

- The presence of water, minerals and amino acids has been confirmed.
- Brought to Earth through collisions?
- Asteroids and/or Comets?
- Possibility of the origin of life?

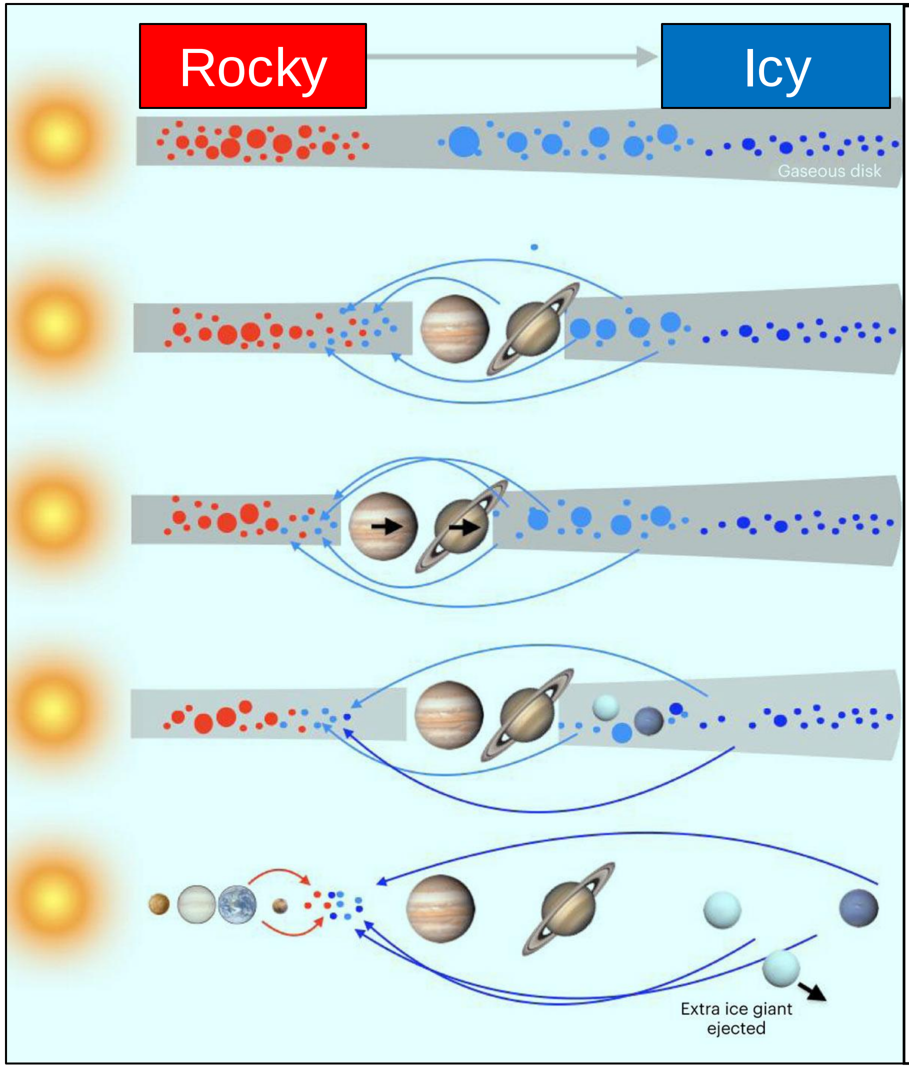


Fig. Solar system formation scenario

Planets were formed through the collisions and accretion of planetesimals.

Rocky planetesimals didn't collide and accrete became Asteroids.

Icy planetesimals became Comets.

1-2. Classification

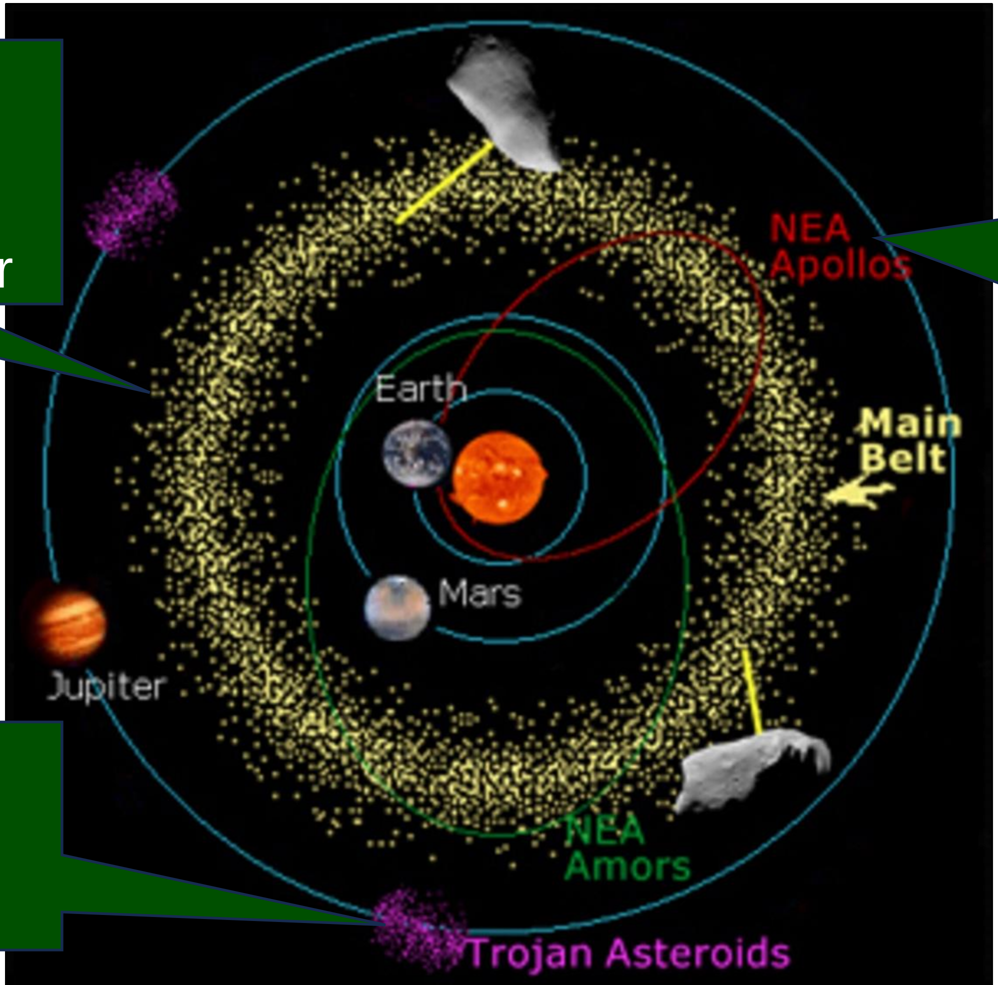
<u>3 major Types Classification by orbit</u>

1. Main-Belt Asteroids (MBAs)

Between Mars and Jupiter

2. Trojan Asteroids

Jupiter’s Lagrange points



3. <u>Near-Earth Asteroids (NEAs)</u>

Close to the Earth

This study targets are NEAs.

Fig. Orbit of Asteroids

1-2. Classification

<u>Potentially-Hazardous Asteroids (PHAs)</u>

- Especially, minimum orbit intersection distance is within 0.05 au, and diameter is more than 140 m.
- PHAs have high probability of collision and significant potential hazard. e. g., Itolawa, Ryugu

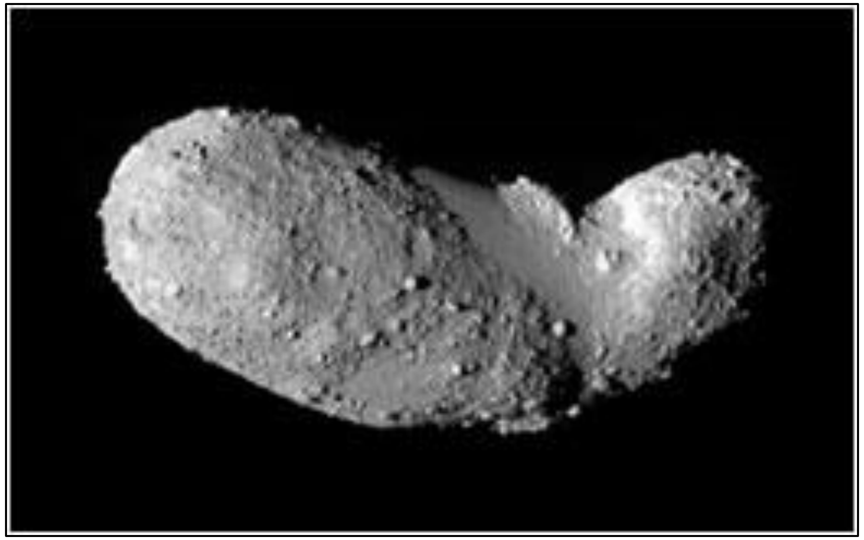


Fig. Itokawa, Ryugu

1-3. Taxonomy

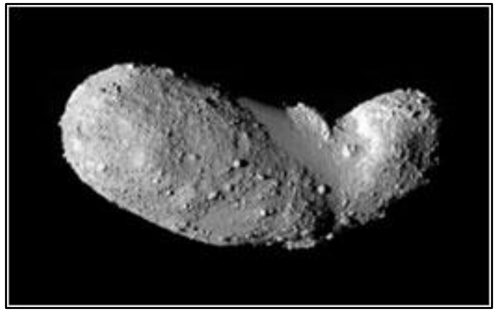


Fig. S Type Asteroid Itokawa, C type Asteroid Ryugu

<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.

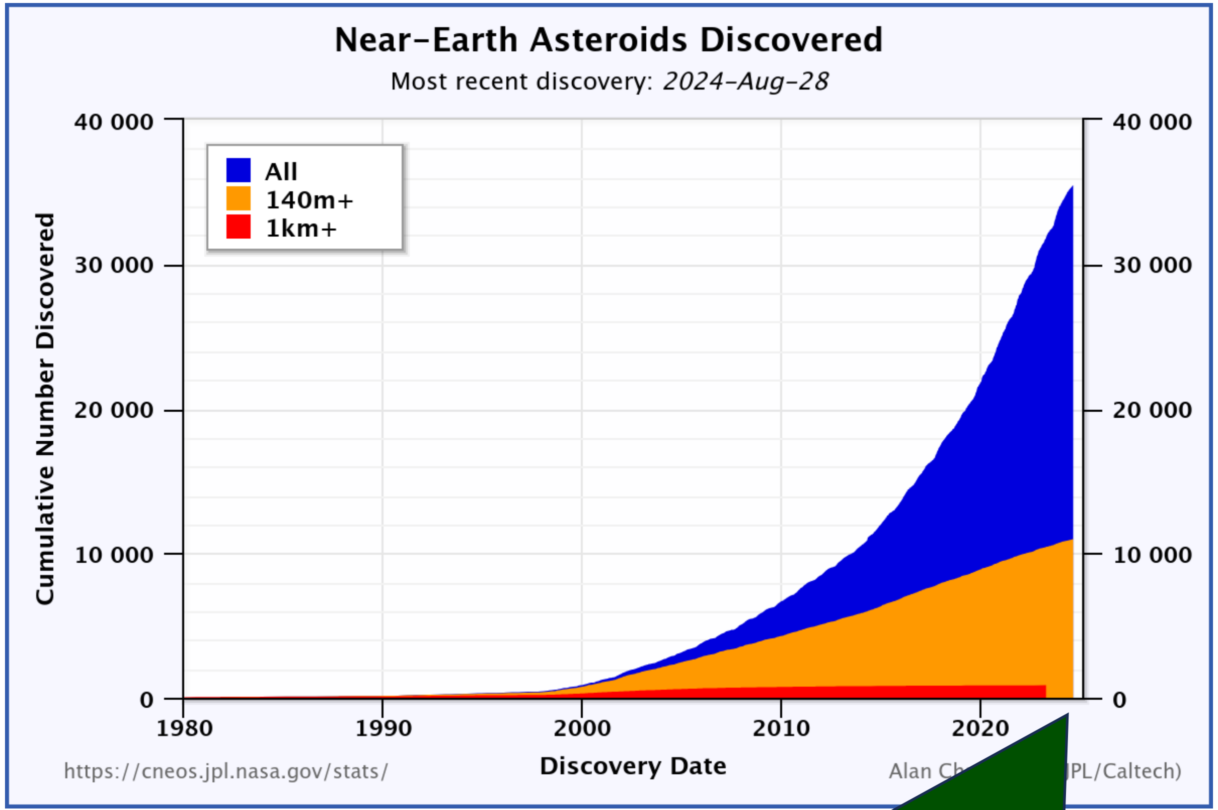
Major Taxonomic Types	Reflectance Spectrum (0.4-0.9 um)	Spectral Features	Visible Albedo	Suspected Composition
D (D,T)	Blue → Red	Relatively featureless spectrum Steep red slope	0.02-0.06	Primitive carbonaceous Organic-rich compounds Hydrated minerals
C (C,B,F,G)	Blue → Red	Slight bluish to slight reddish 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: 0.18-0.40 M: 0.10-0.18 P: 0.03-0.10	E: Enstatite-rich M: metallic, Nickel-Iron P: Carbonaceous, Organics
S (S,Q,A,K,L)	Blue → Red	Moderately steep red slope ($\lambda < 0.7$ 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 ($\lambda < 0.7$ μm) Very deep absorption at 1.0 μm	0.20-0.60	Volcanic basalts Plutonic rocks

Fig. Characteristics of the 5 Types

1-4. Number

1.26 million discovered (as of March, 2023)

- The number of discoveries is increasing steeply.
  Caused by improvement of observational instruments and skills.



Almost large NEAs are discovered

Fig. Number of NEAs discovered as of 2024-Aug-28

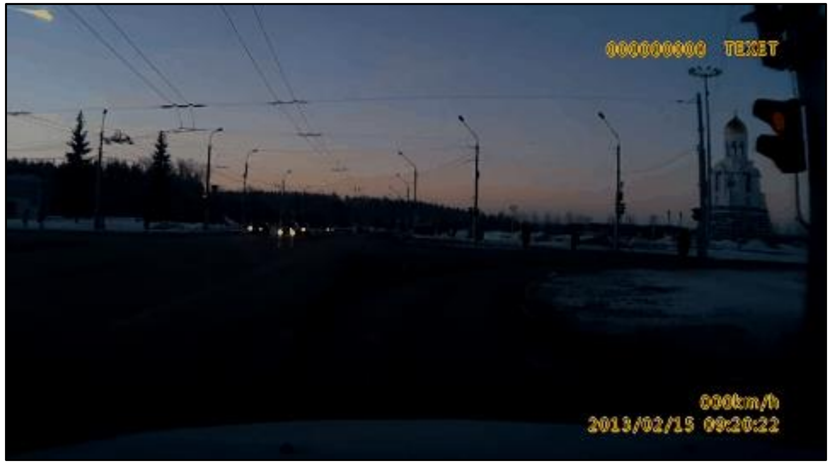
Number of NEAs (as of March, 2023)

- About 34,000 have been discovered.
- Estimated total number : 5 million.
- Most NEAs larger than 1 km have been discovered because they are bright, but many NEAs smaller than 140 m remain undiscovered because they are dark.

1-5. Planetary Defense (Space Guard)

<u>Protecting the Earth from Asteroids (and Comets) collisions</u>

- 66 million years ago, Dinosaurs extinction was caused by collision of ~20 km Asteroid.
- 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 Planetary Defense.

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

1-6. Planetary Defense Missions

Target : Binary Asteroids (NEAs), Didymos-Dimorphos

<u>NASA DART Mission</u>

- Change the orbit of Dimorphos (satellite) by impacting it with a DART spacecraft.

<u>ESA HERA Mission</u>

- Investigate the details of Dimorphos after the collision. precise mass, crater size, etc.

- Reveal the <u>physical properties</u> of NEAs, especially PHAs, which is important to avoid collisions and predict the potential hazard from impact.

Size, Composition, etc.

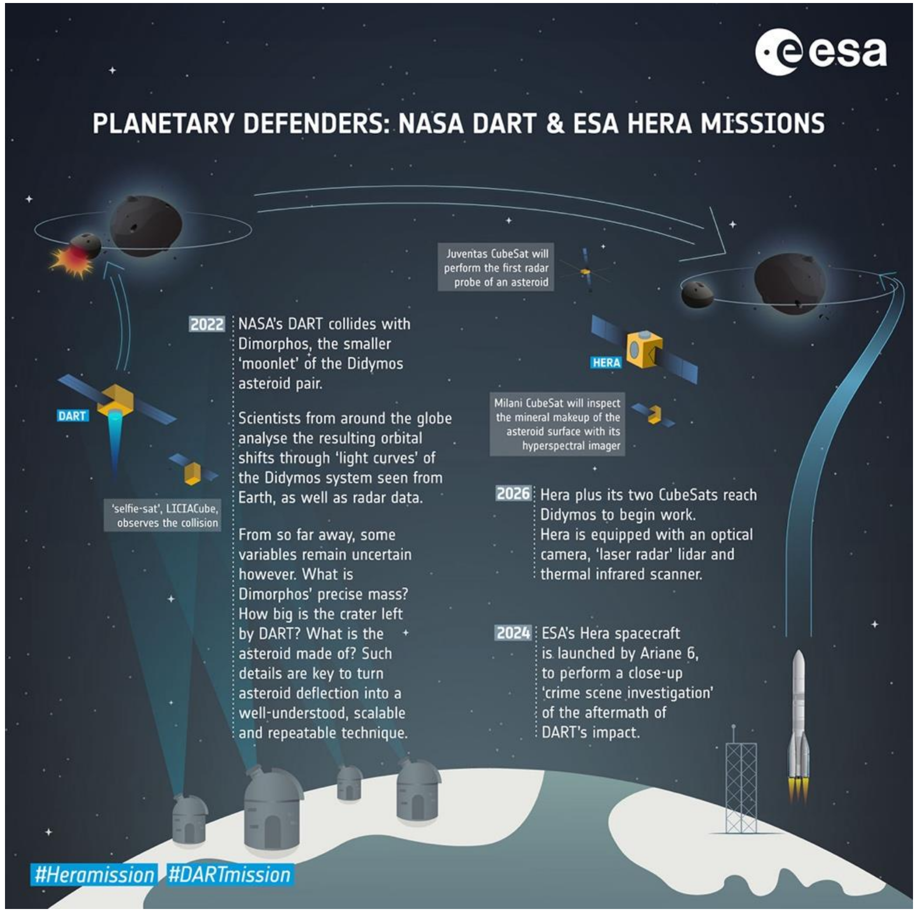


Fig. DART Mission & HERA Mission

2. Purpose and Goals

Significance of the Asteroids study

- The origin and evolution of the solar system and life.
- Minerals and water resources.
- Planetary Defense. etc.

Hazard of collisions

Size is Large? Small?
Composition is Stony? Carbonaceous?
Porosity is High? Low?

Goals

- Obtaining the information needed to understand NEAs and realize Planetary Defense.
- Contributing to the Hayabusa2 extended mission. (same target will observe)

Purpose

- Deriving the physical properties of unique NEAs through ground-based observations.

  size, surface composition, albedo, regolith, etc.

  today's main topics are observation methods and targets NEAs

3-1. Observation methods

<u>Physical properties of Asteroids</u>

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

etc.

Pirka & Seimei

(A) <u>Photometric observations</u>

- Size
- Rotation Period
- Surface composition (rough)

etc.

Not yet

Seimei

(B) <u>Spectroscopic observations</u>

- Surface composition (precise)

In the future

(C) <u>Polarimetric observations</u>

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

In progress

Pirka

<u>Other observations</u>

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

- Orbit • Size • Shape
- Rotation Period etc.

3-2. Detecting targets Asteroid

<u>Detection method</u>

- “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 targets Asteroid.

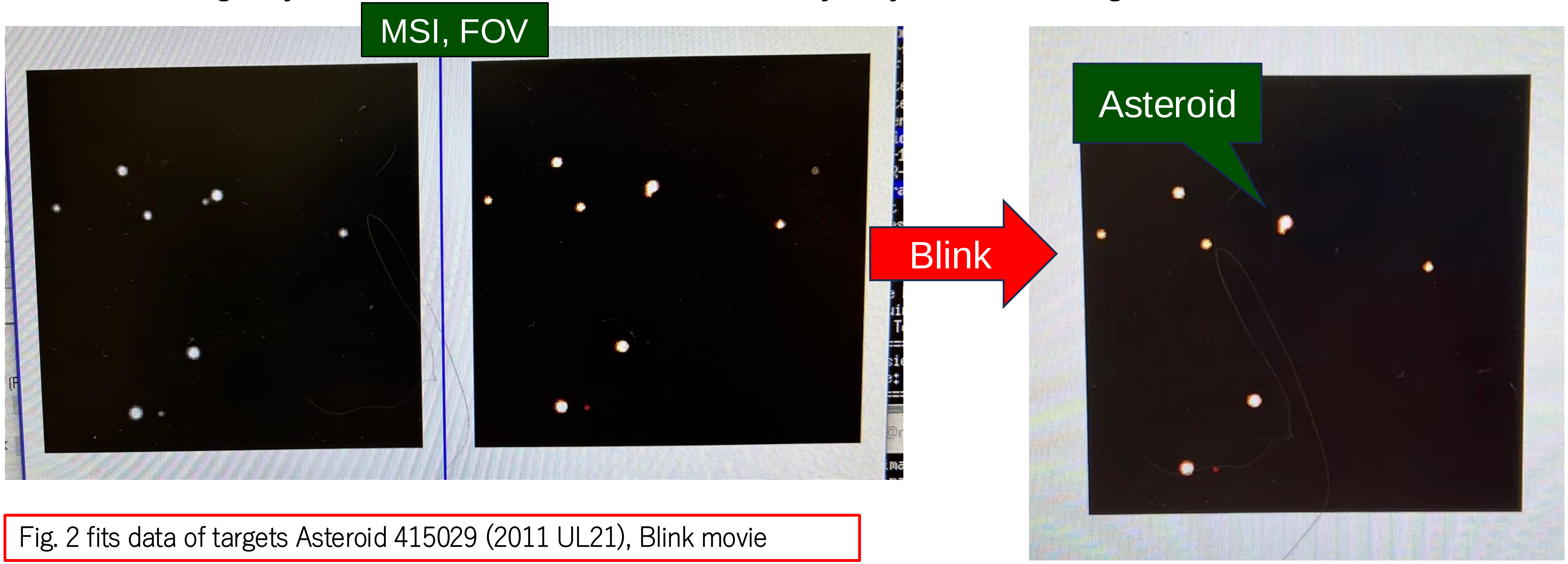


Fig. 2 fits data of targets Asteroid 415029 (2011 UL21), Blink movie

3-3. (A) Photometric observations

- Size
- Surface composition (rough)

Preprocessing of the CCD images and Aperture Photometry

- Correcting raw data (preprocess) is almost the same for the analysis of spectroscopic and polarimetric observations data as well.

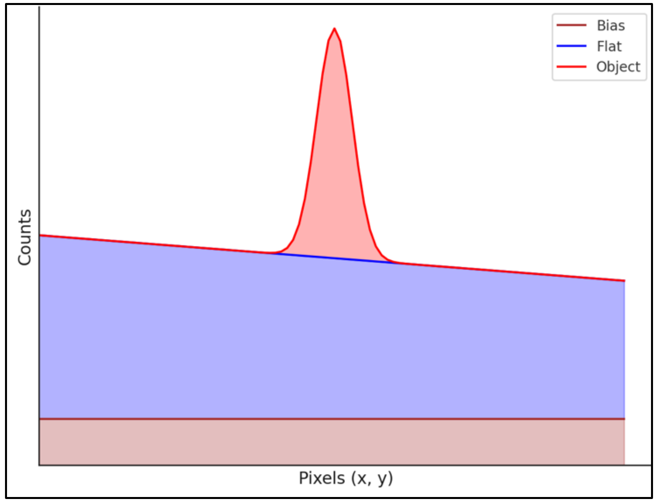
Derivation of **Size**

- Diameter can estimate from V-mag. (1 au from Sun and Earth) & albedo (A).

$$D = \frac{C \times 10^{-0.2\mathrm{Vmag.}}}{\sqrt{A}}$$, C : constant

[Fowler et al., 1992]

Preprocess & Aperture Photometry



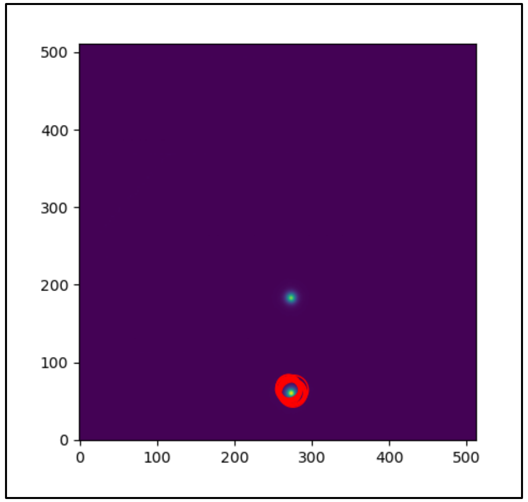


Fig. Raw data counts vs pixels image,
Aperture photometry of Asteroid (Polarization data)

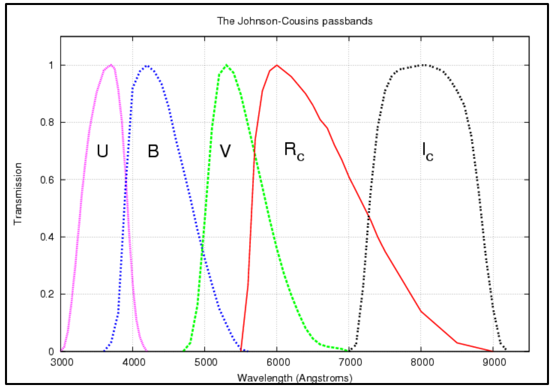
3-3. (A) Photometric observations

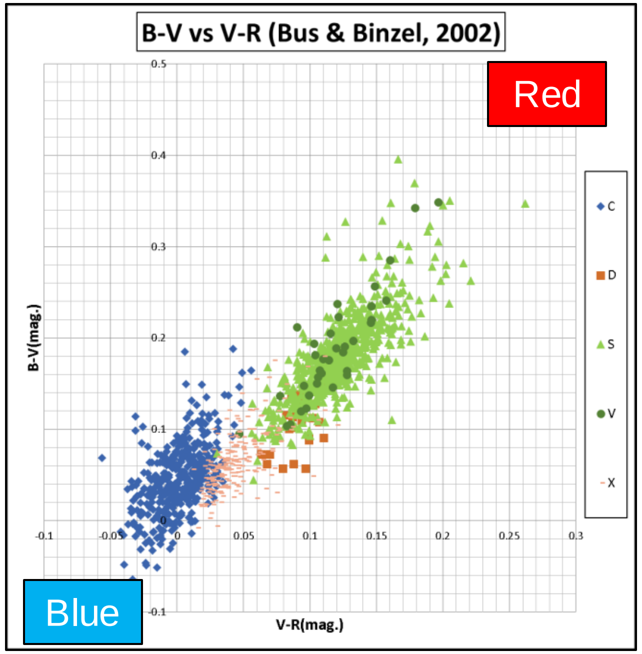
- Size
- Surface composition (rough)

<u>Derivation of **Taxonomy Type (rough surface composition)** from 2 color index</u>

- Difference in magnitude for each band values (B-V mag., V-R mag., etc.) can plot the 2 color index. [Bus et al., 2002]

Optimal for dark Asteroids!





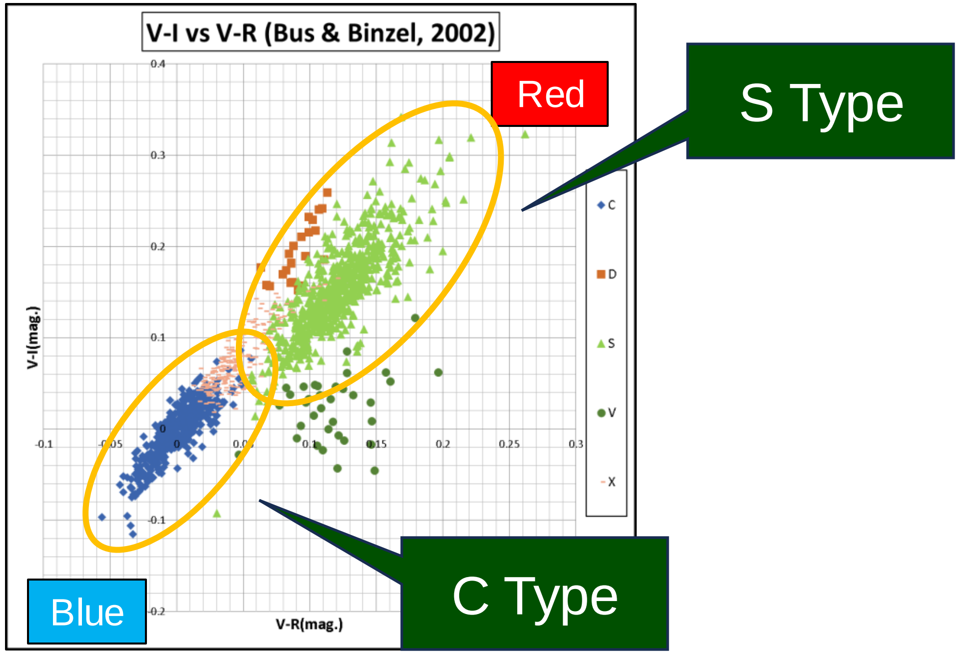


Fig. Johnson-Cousins filter transmittance wavelength, 2 color index of 1,447 Asteroids[Bus et al., 2002]

3-4. (B) Spectroscopic observations

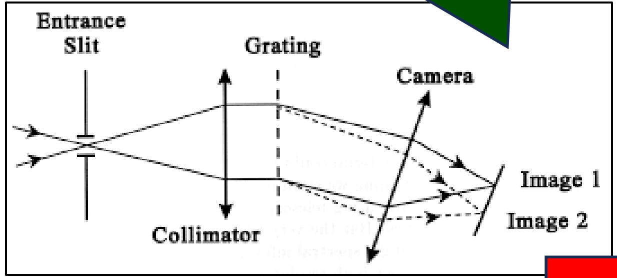
- Surface composition (precise)

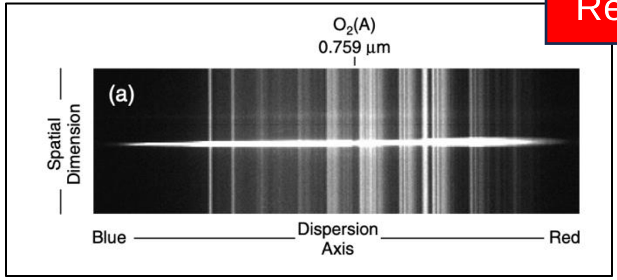
Difficult for dark Asteroids, Large telescope is required!

Derivation of **Surface composition (precise)** from reflectance spectrum

- slope, presence or absence of absorption bands
- 5 major Types can be classified into finer 26 subgroups. [Bus et al., 2002]

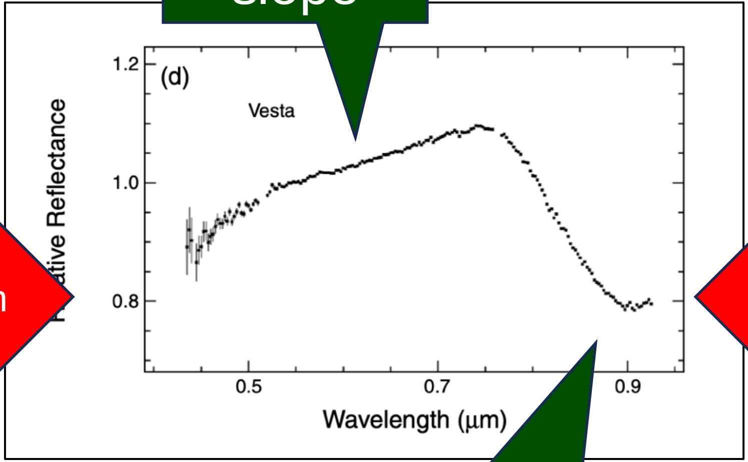
Vesta's raw data through the slit





Reduction

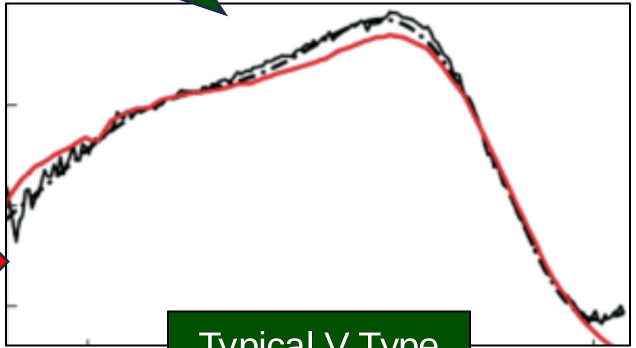
slope



Absorption band

Match!

Determine the surface composition by comparing it with meteorites



Typical V Type

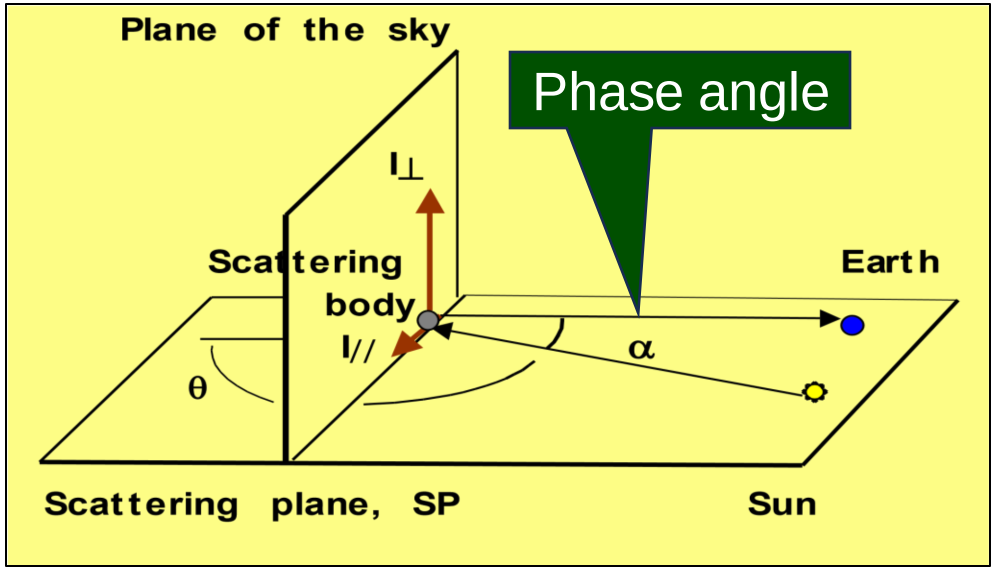
Fig. Vesta's reflectance spectrum[Bus et al., 2002]

3-5. (C) Polarimetric observations

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

- Asteroids reflect sunlight, polarization dependent on the <u>surface properties</u> occurs.
- Linear Polarization : $\mathrm{P_r} = \frac{I_{\perp} - I_{\parallel}}{I_{\perp} + I_{\parallel}}$ %
- Polarizer : Wollaston Prism

  separate into Ordinary-ray (O-ray) and Extraordinary-ray (E-ray)



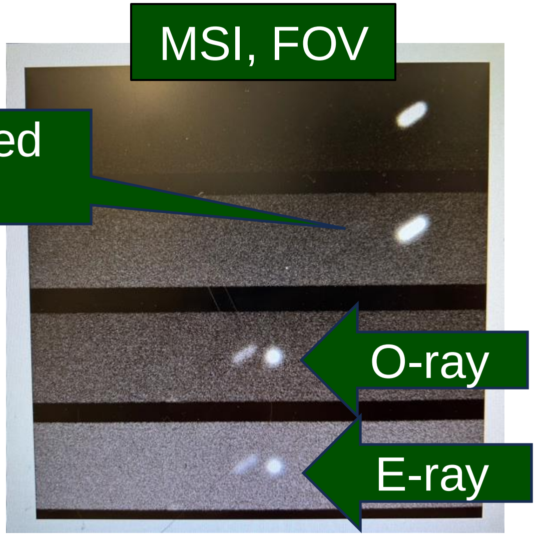


Fig. Basic information on Polarization, Wollaston Prizm, Polarized Asteroid

3-5. (C) Polarimetric observations

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

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

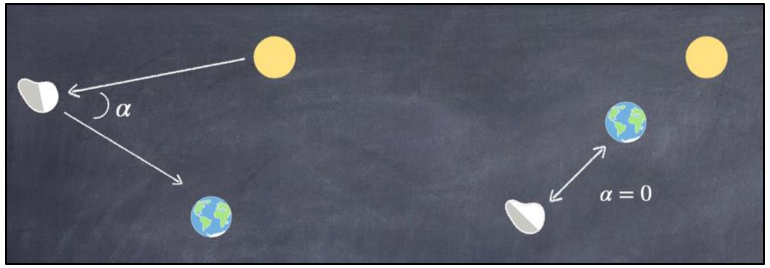


Fig. Phase angle

	MBAs	NEAs
Distance from the Earth	Far	Close
Change in phase angle over a few days	Small	Considerable Obtain various data

- <u>NEAs have large variations of phase angle.</u>

Optimal for NEAs!

P_r vs α linear polarization curve

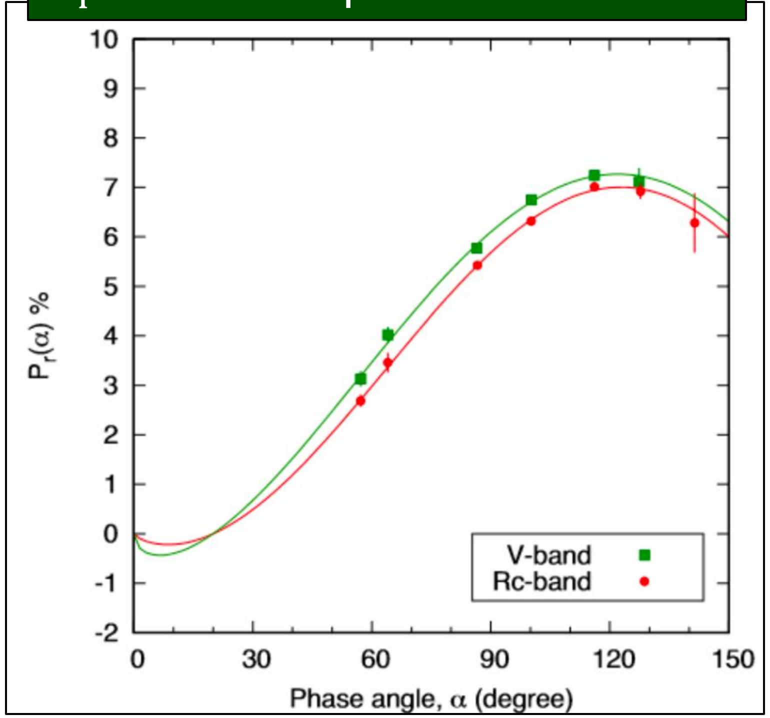


Fig. NEA 1566 Icarus[Ishiguro et al., 2017]

3-5. (C) Polarimetric observations

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

Similar to Asteroids

Polarization of the Moon

- The correlation between linear polarization degree and its various surface properties

Polarization of the Moon	albedo	α_{inv}	h	P_{max}	P_{min}
Maria (dark)	low	<20	steep	high	deep
Highland (bright)	high	~20	gentle	low	shallow

Derivation of **Albedo** from Polarization curve

- α_{inv} : angle of the P_r changes from negative to positive branch
- Slope : $h = \frac{dP_r}{d\alpha}$ at α_{inv} (when $P_r = 0$) estimate albedo (A)

  $\log_{10} A = C_1 \log_{10} h + C_2$, C_1 and C_2 : constant

  [Cellino et al., 1999]

P_r vs α linear polarization curve

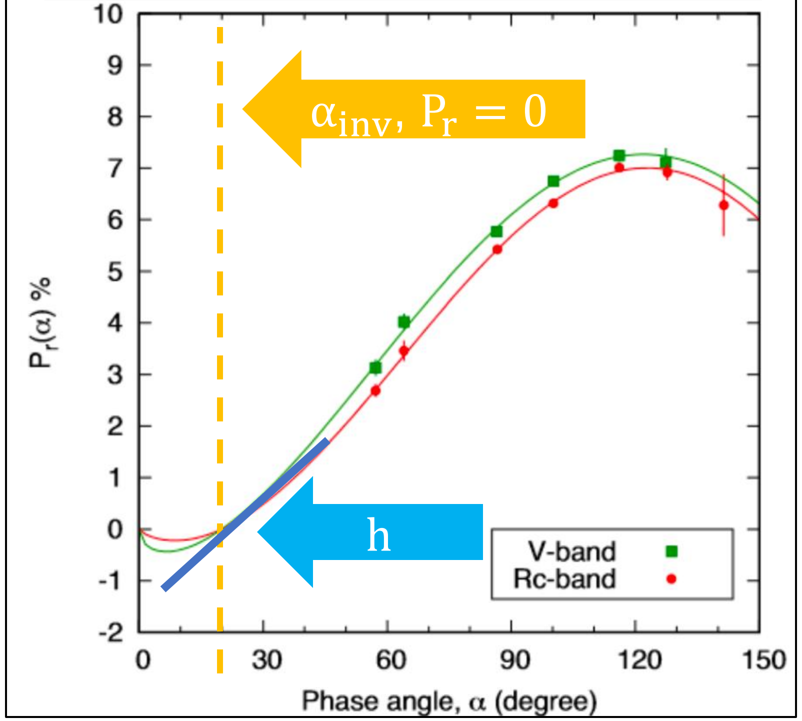


Fig. NEA 1566 Icarus[Ishiguro et al., 2017]

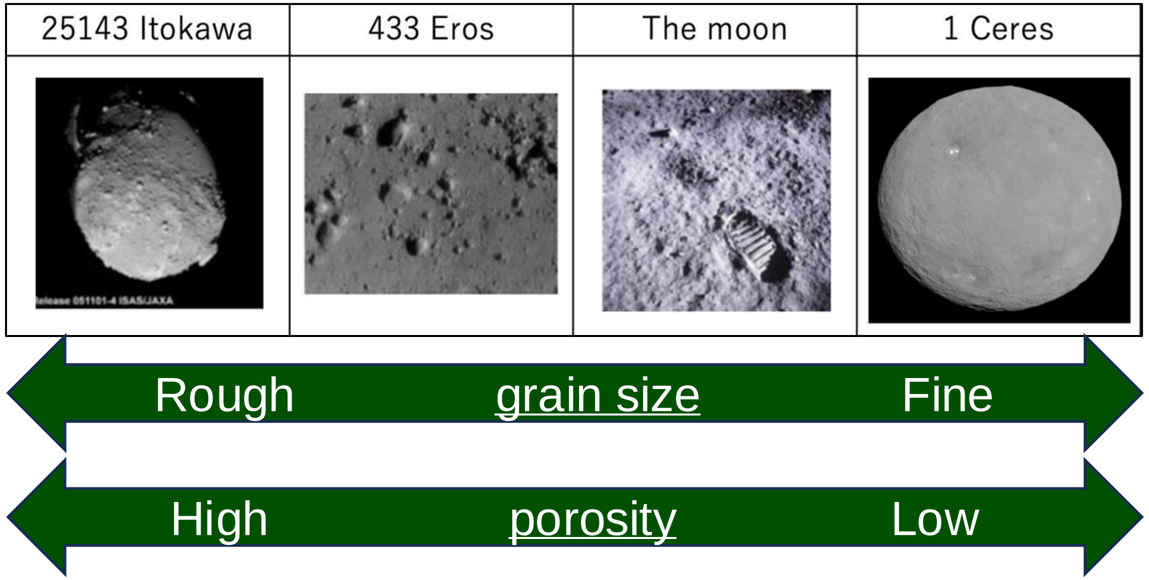
3-5. (C) Polarimetric observations

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

Derivation of **regolith (grain size & porosity)** from Polarization curve

- P_{max} , P_{min} : Maximum, Minimum polarization degree
- P_{max} & albedo (A) estimate grain size
- P_{max} estimate porosity

Regolith of several asteroids and moon



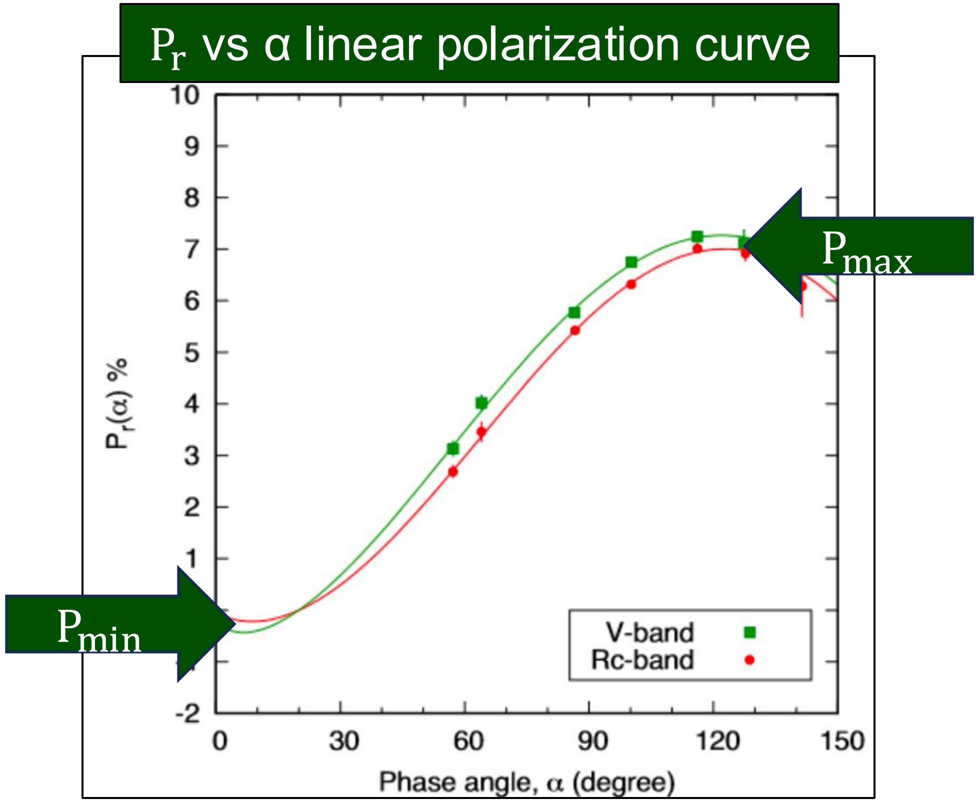


Fig. NEA 1566 Icarus[Ishiguro et al., 2017], Regolith

3-5. (C) Polarimetric observations

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

- Derivation of **Taxonomy Type (rough surface composition)** from Polarization curve
- Slope : h, P_{min} & α_{inv} estimate Taxonomy Type (C or S or E(X))

Polarization of Asteroids	albedo	h	P_{max}	P_{min}
C Type	low, 0.03-0.10	steep	high	deep
S Type	high, 0.10-0.22	gentle	low	shallow

- It is certain that the polarization degree of Asteroids depends on surface properties, but the detail remain unclear.
- Examples of polarimetric observations are limited, but effective in revealing the surface properties of Asteroids.

Pr vs α linear polarization curve

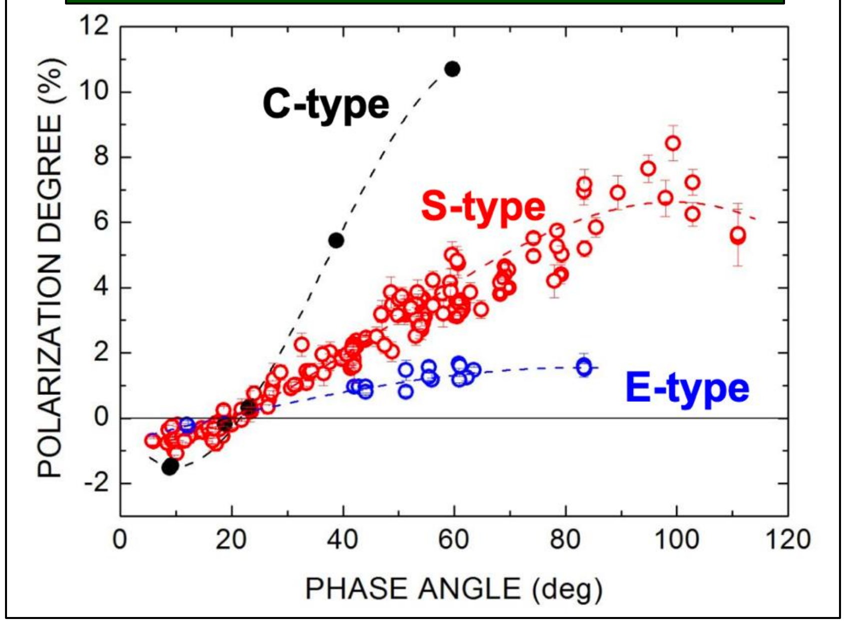


Fig. Polarization of typical C, S, E-Type Asteroids

3-6. 1.6 m Pirka Telescope & MSI

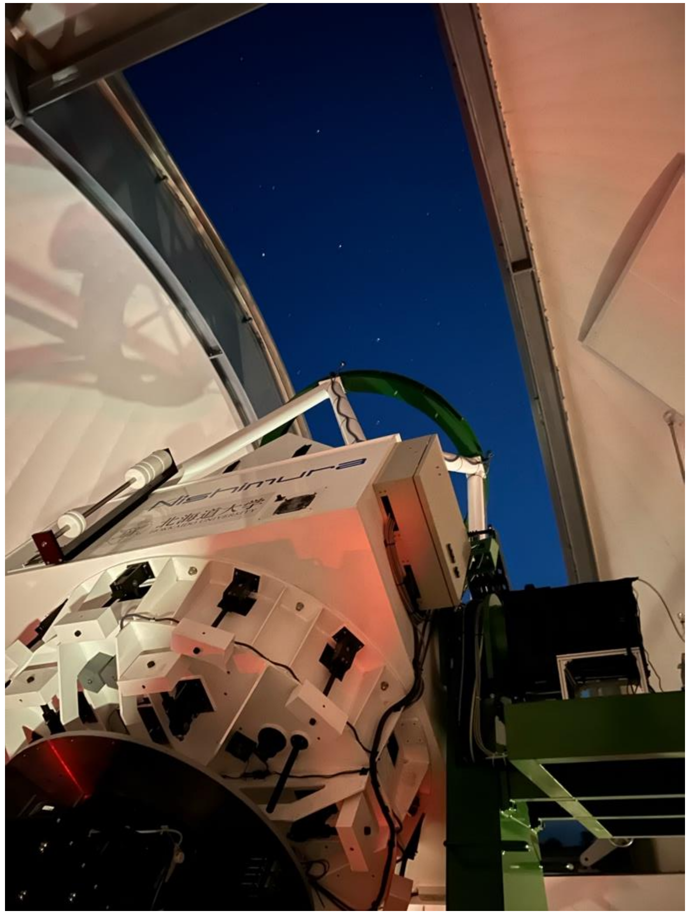
<u>Pirka Telescope</u>

- Location : Nayoro Observatory
- Own : Hokkaido Univ.

<u>MSI (Multi-Spectral Imager)</u>

- 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 photometry and polarimetry



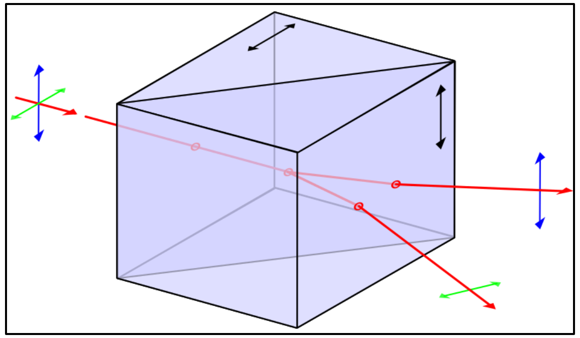


Fig. Pirka Telescope, MSI, Wollaston prism

3-7. 3.8 m Seimei Telescope & TriCCs

Seimei Telescope

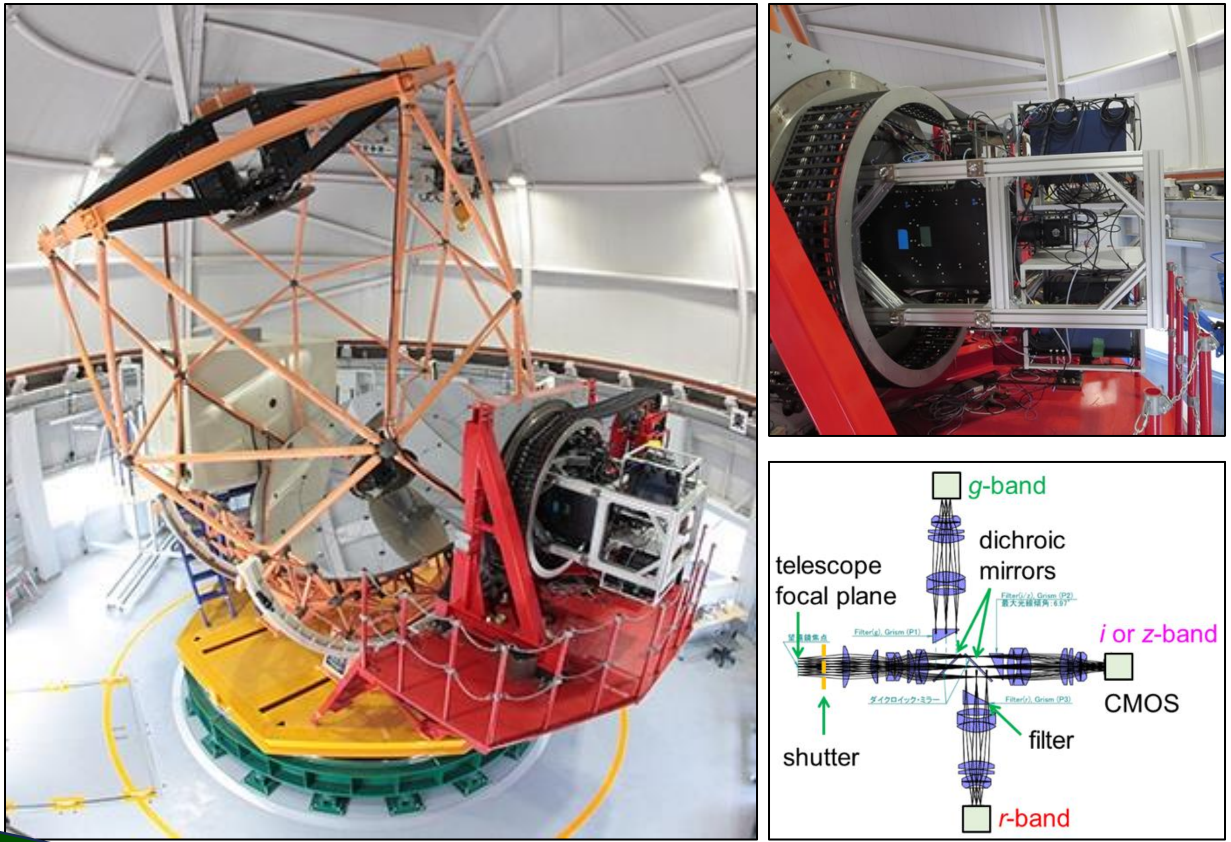
- Location : Okayama Observatory
- Own : Kyoto Univ., and open use by NAOJ

TriCCs (Tricolor CMOS Cameras)

- Imaging and Slit Spectroscopy mode

Slit Spectroscopy mode

- FOV : 1.0 ’ (width) × 10-11 ’ (length)
- Wavelength : grism_g (0.4-0.55 μm), r (0.55-0.7 μm), iz (0.7-1.05 μm)
- Wavelength resolution ($R= \lambda/d\lambda$) : ~700
- Limit Mag. : 18 Mag. (600s exp. time)



Can conduct photometry and Spectroscopy

Fig. Seimei Telescope, TriCCs

4-1. Targets : 2024 MK

<u>Unique Characteristics</u>

- NEA
- Discovered : 2024/06/16

  only 13 days before it passes
- Closest approach : 2024/06/29

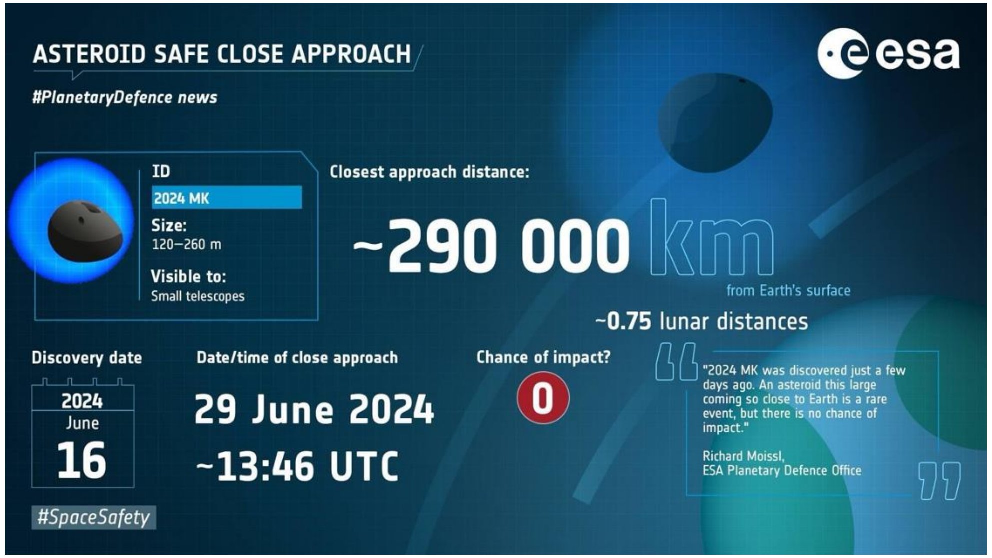
  0.75 distance between Earth and Moon

<u>Observations</u>

- Pirka, MSI (Polarimetry)
- Date : 2024/06/29 (α=15-27 deg.)

  rare opportunity occurs once every few decades

  2024/07/02 (α=100-101 deg.)



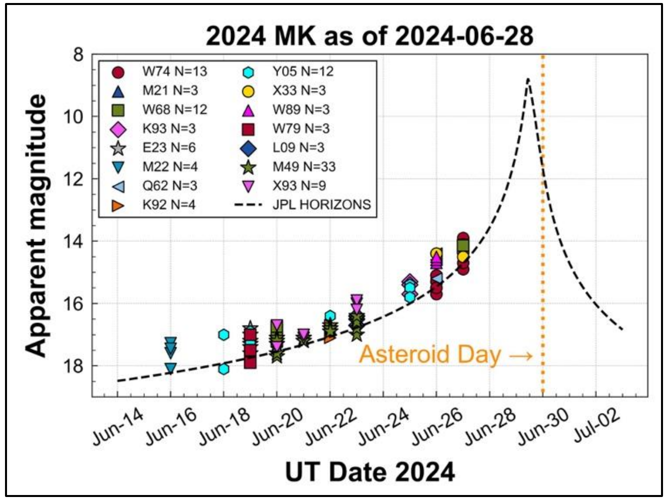
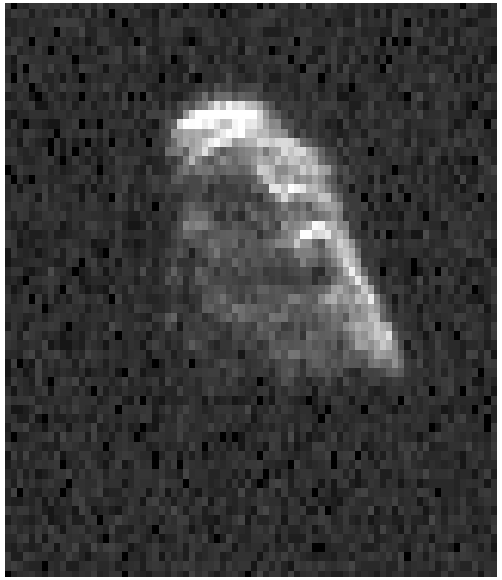


Fig. ESA's information,
Apparent magnitude variations, Orbit movie

4-1. Targets : 2024 MK

Other observations at the same time

- Tracked by NASA's Goldstone Solar System Radar, derived its shape and size : ~150 m.



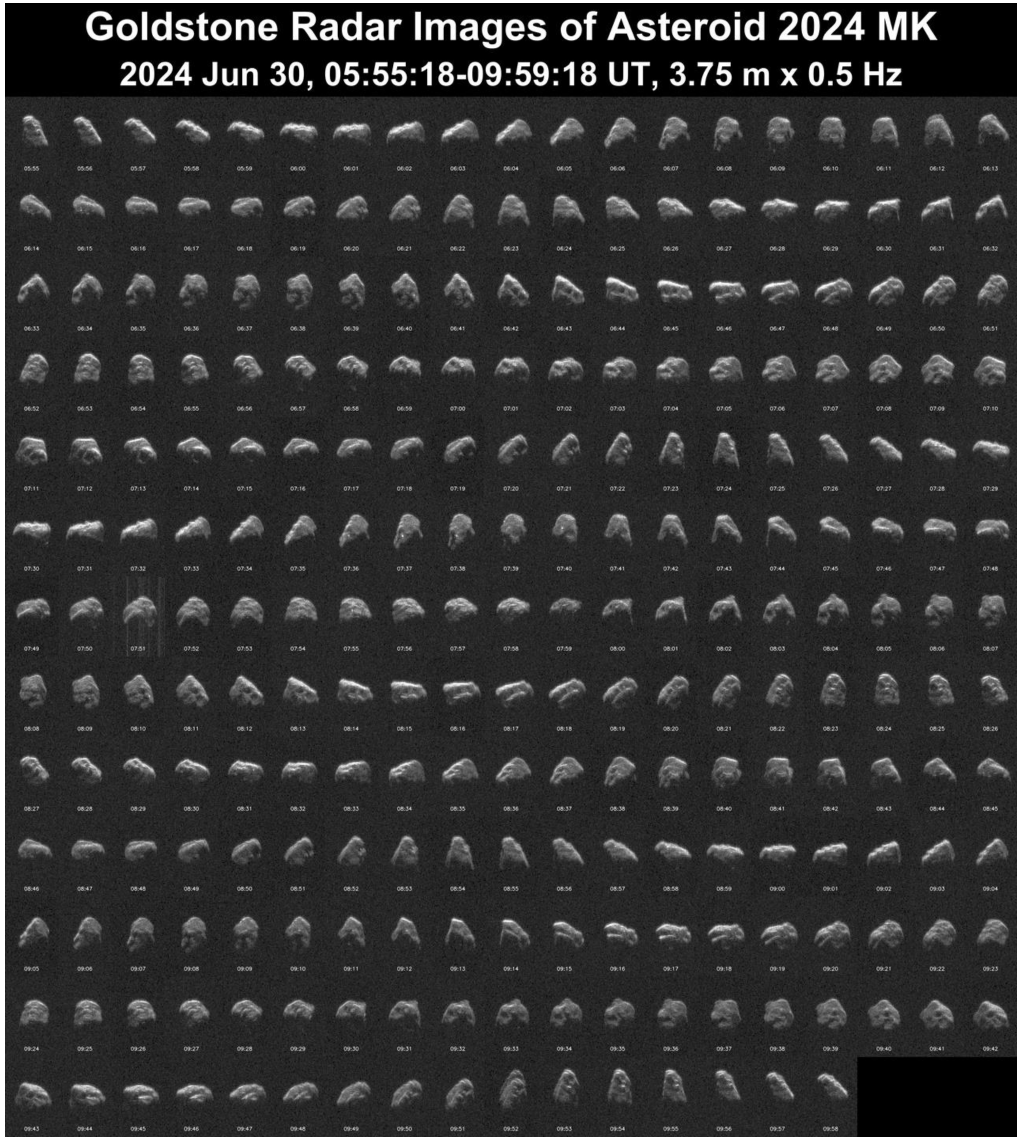


Fig. Goldstone Rader, Rader images and animation

- Other physical properties can't be derived.

This study will derive (surface composition, albedo, etc.), but analysis is not yet.

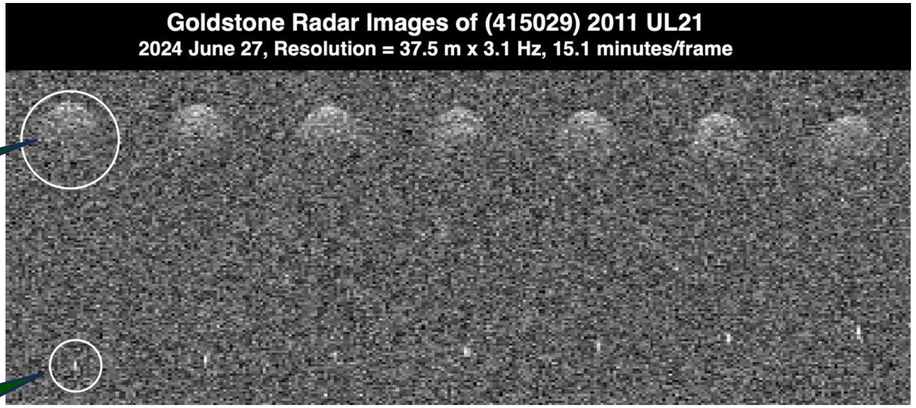
4-2. Targets : 2011 UL21

<u>Unique Characteristic</u>

- PHA
- Closest approach : 2024/06/27
- Size : 2.3 km, larger than 99% of all NEAs
- Orbit : steeply inclined (i=34 deg.)
- Has a satellite (Binary Asteroid)

  Distance : ~3 km

  Size : ~400 m



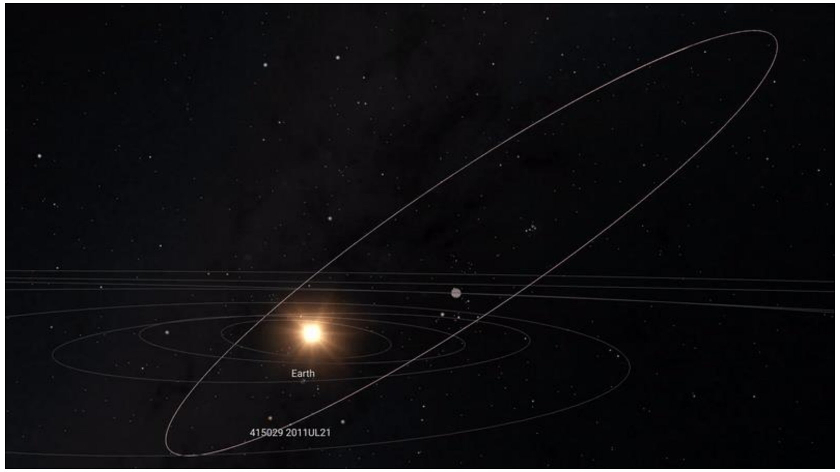


Fig. Rader Images, ESA's information, Orbit movie

4-2. Targets : 2011 UL21

Observations

- Pirka, MSI (Polarimetry)
- Date : 2024/07/04 (α=45 deg.)
  2024/07/25 (α=40 deg.)
  2024/07/26 (α=39 deg.)
  2024/08/06 (α=38 deg.)
  2024/08/15 (α=36 deg.)
  2024/08/28 (α=35 deg.)

- Asteroid systems, 2011 UL21-a satellite are not spatially resolved.

4-3. Targets : 2024 KH3

Unique Characteristics

- PHA
- Closest approach : 2024/08/10
- NASA issued an alert for this approaching Asteroid

Relative velocity to Earth : 11.4 km/s (so fast)

Observations

- Pirka, MSI (Polarimetry)
- Date : 2024/08/06 (α=40 deg.)

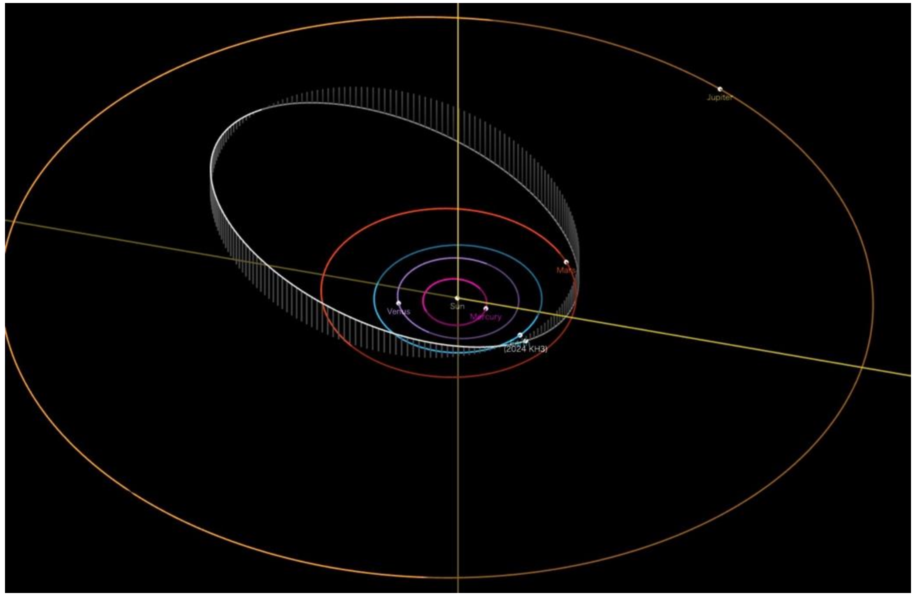


Fig. Orbit

4-4. Targets : 2001 CC21

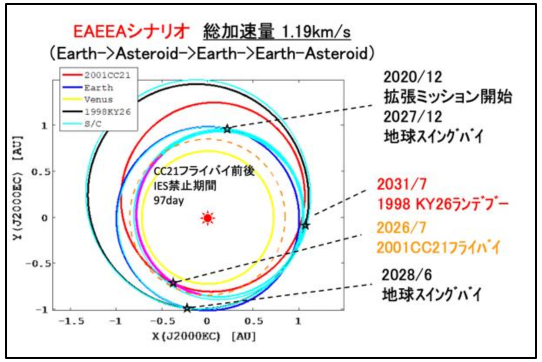
JAXA Hayabusa2 extended mission (Hayabusa2#) targets Asteroid.

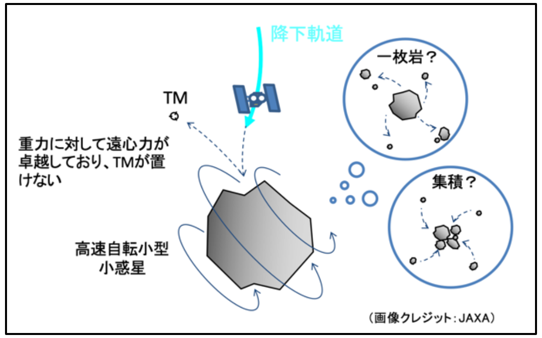
<u>Mission objectives</u>

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.

<u>Targets Asteroids</u>

1. 98943 (2001 CC21), Flyby in July 2026. Flyby speed is 5 km/s.
2. 1998 KY26, Rendezvous in July 2031.
   Size : 20-40 m, Rot. Period : 10 min. Monolith?





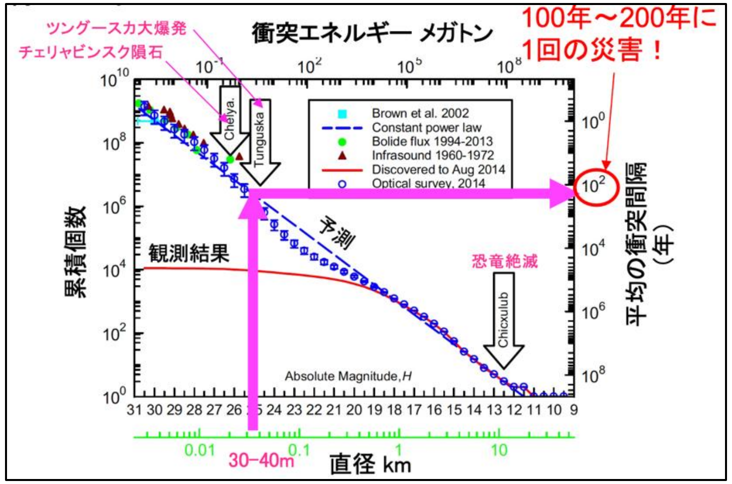
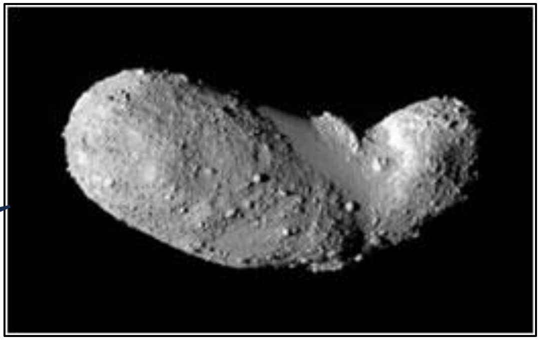


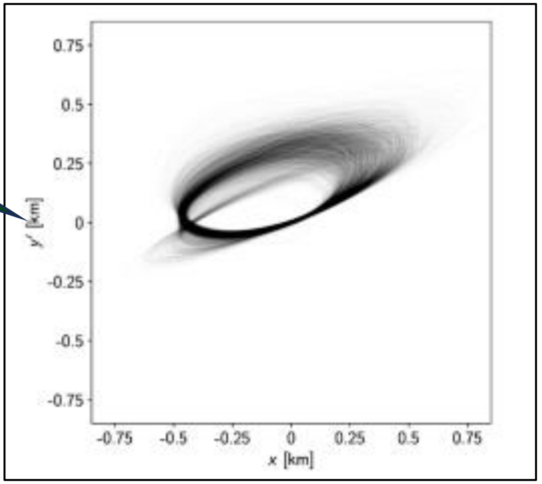
Fig. JAXA EAEEA scenario, 1998 KY26, Potentially impact
https://www.hayabusa2.jaxa.jp/topics/20200731_exm/

4-4. Targets : 2001 CC21



Itokawa

2001 CC21
Shape model



Unique Characteristic

- NEA
- Similar to Itokawa (Hayabusa targets Asteroid)

	Itokawa	2001 CC21
Taxonomy	S Type	S (Sk)? L? Type This study
Size, Shape	535 × 294 × 209 m	~500 (Model : 840 × 310) m
Surface	Rubble pile	?

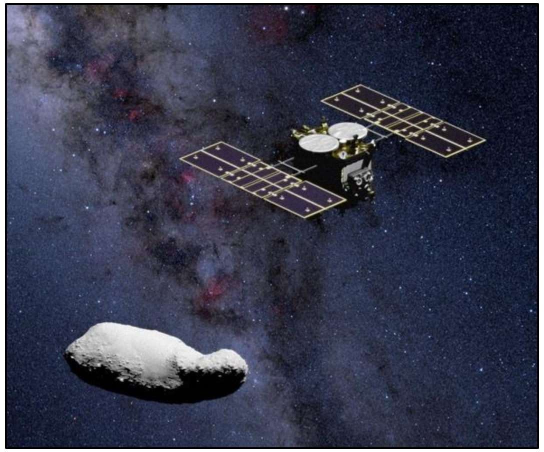
Comparing two Asteroids, can better understand the surface phenomena

Observations

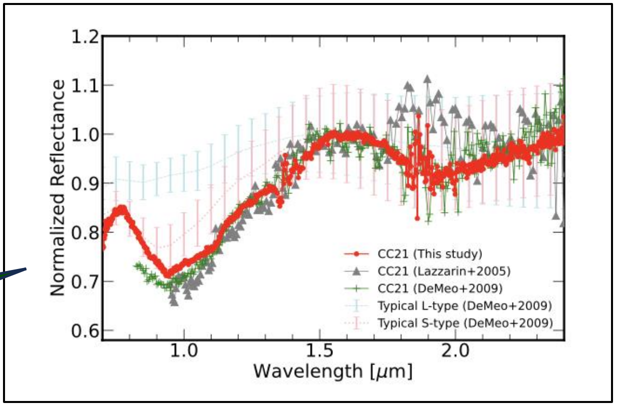
- Seimei, TriCCs (Spectroscopy)
- Date : 2024/11/27,28.

More details in Chapter 6.

Fig. Light curve, Shape model, 2001 CC21 Flyby image
https://www.perc.it-chiba.ac.jp/news/2024/08/02/3296/



4-4. Targets : 2001 CC21

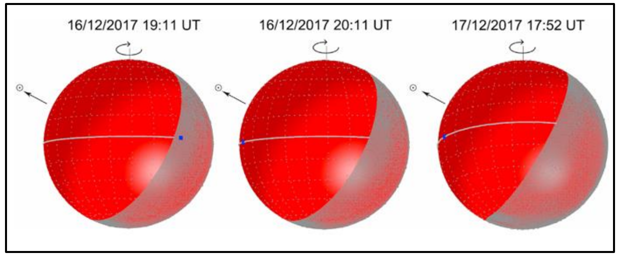


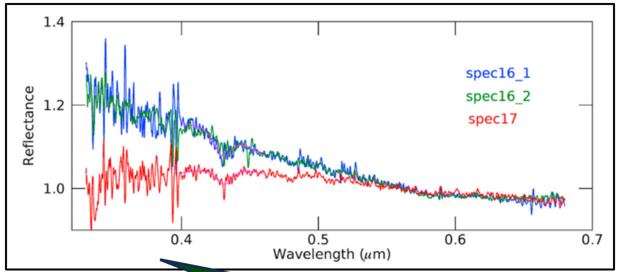
2001 CC21 (NIR)

<u>Previous Studies</u>

- 5 results from spectroscopic observations.

	Wavelength	Taxonomy
1. Binzel et al., 2004.	0.4-0.9 μm (VIS)	L Type
2. Lazzarin et al., 2005.	0.5-2.5 μm (VIS + NIR)	Sk Type
3. DeMeo et al., 2009.	0.8-2.5 μm (NIR)	Sw (S, Sk) Type
4. Binzel et al., 2019.	0.8-2.5 μm (NIR)	S Type
5. Geem et al., 2023.	0.7-2.4 μm (NIR)	S Type





- Visible wavelength observation results are either L or S (S complex) type.

  Different aspects observed? Effects of atmosphere?

  This study will observe 0.4-1.05 μm wavelength (VIS) to determine the type.

Phaethon (VIS)
Spectral
variations

Fig. Spectrum of 2001 CC21 [Geem et al., 2003], Phaethon observed aspect model and spectral discrepancy [Lazzarin et al., 2019]

5. Results

<u>2024 MK</u>

- 2 nights of polarimetric data.

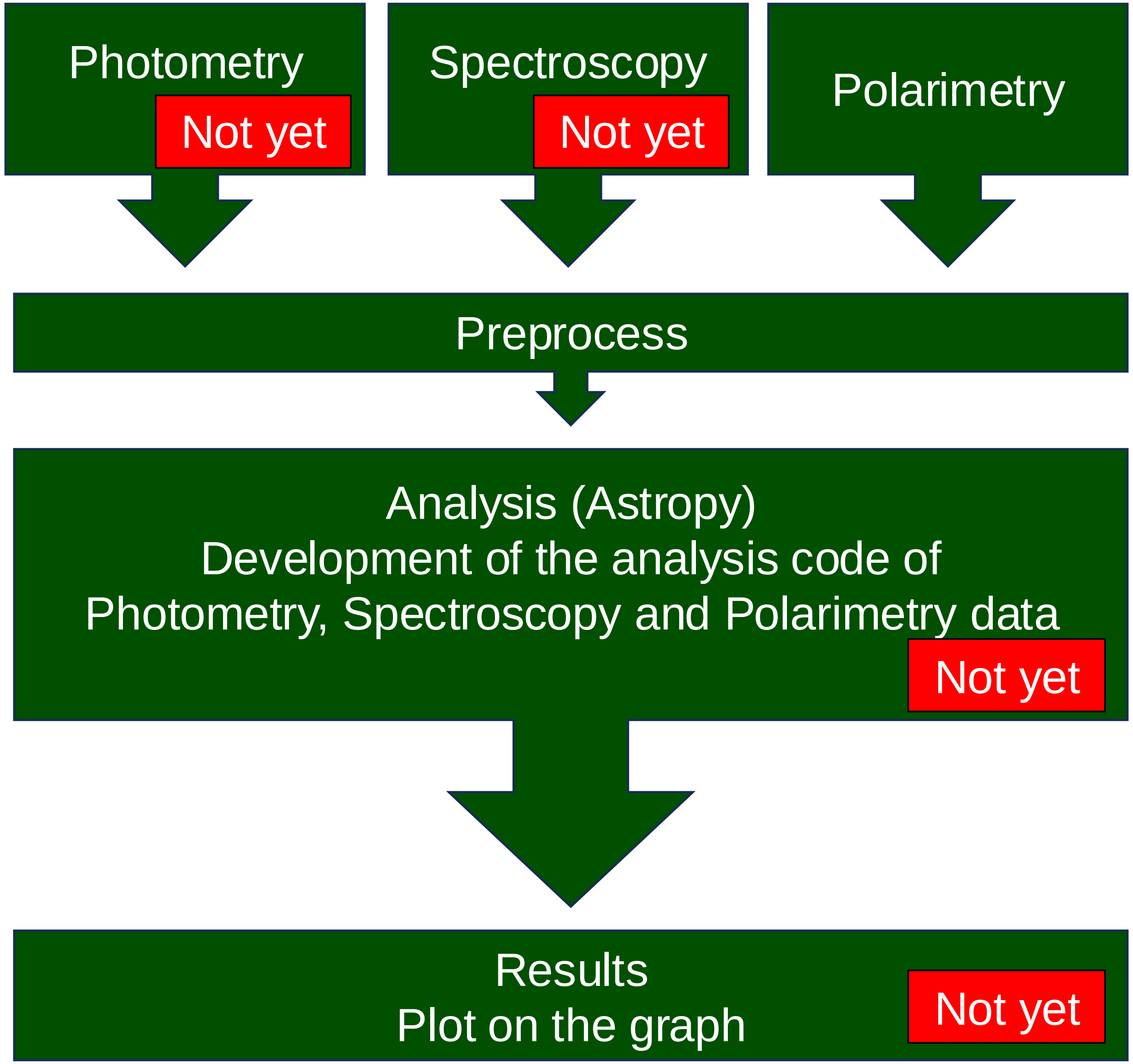
<u>2011 UL21</u>

- 6 nights of polarimetric data.

<u>2024 KH3</u>

- 1 night of polarimetric data.

The analysis is currently in progress



6. Future works and observation plans

1. Continue observations unique NEAs with the Pirka Telescope.
   Analyze data of 2024 MK, 2011 UL21 and 2024 KH3, etc. (future observations).

2. 2024 Second half Open use observations with the Seimei Telescope.
   at the Okayama Branch Office of the NAOJ, Hawaii Observatory
   My proposal was accepted by NAOJ referees.

   Allocated observation time : 11/27, 28 Early night (about 6 hours)
   Observation methods : Spectroscopy (0.4-1.05 μm), Photometry
   Visual mag. : 16.7 mag. (brightest, α=5-6 deg.)

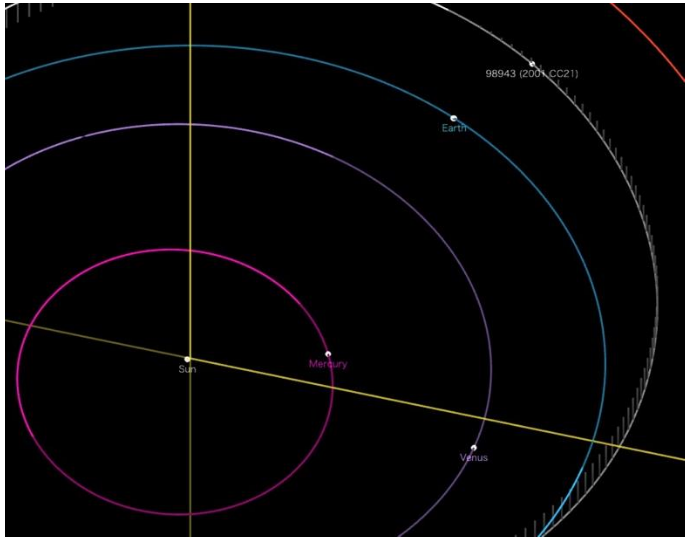


Fig. 2001 CC21's position at 11/27, 28

6. Future works and observation plans

Future observations by Pirka Telescope targets candidate

- Heracles
- Sisyphus

  Binary asteroids, like 2011 UL21

- 2001 MZ7

  Excessively high albedo Asteroid (~0.85)

- Other Asteroids that appear unexpectedly, like 2024 MK

6. Future works and observation plans

<u>Importance and urgency of observing 2001 CC21</u>

- The speed of Hayabusa2's Flyby is so fast. The exposure time and gain values for the onboard cameras need to be determined <u>before the Flyby</u>.
  (can't be spatially resolved in advance)
- Therefore, it is necessary to reveal detailed surface information by Spectroscopic observations with Seimei Telescope. (the biggest Optical Telescope in Japan)

Fig. Okayama observatory, Hayabusa2 Flyby Image
http://okayama.mtk.nao.ac.jp/
https://www.hayabusa2.jaxa.jp/

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- Grain size

  Umov's law and particle size

  $\log_{10} A + a \log_{10} P_{max} = b,\ d = 0.03\exp(2.9b)$