

PIAZZI 200: new frontiers in astrometry, small bodies and technologies,
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Photometric characterization of NEAs: rotation, taxonomy, and candidate evidence for internal cohesion

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Loiano

(about 30 km from Bologna)

Light pollution

Cassini
Telescope

Guesthouse

Google Earth

Image © 2024 Airbu

Stazione astronomica e Parco delle Stelle di...

Data di acquisizione delle immagini: 11/7/2023

44°15'37.60"N 11°19'47.63"E elev 749 m alt 2.35 km

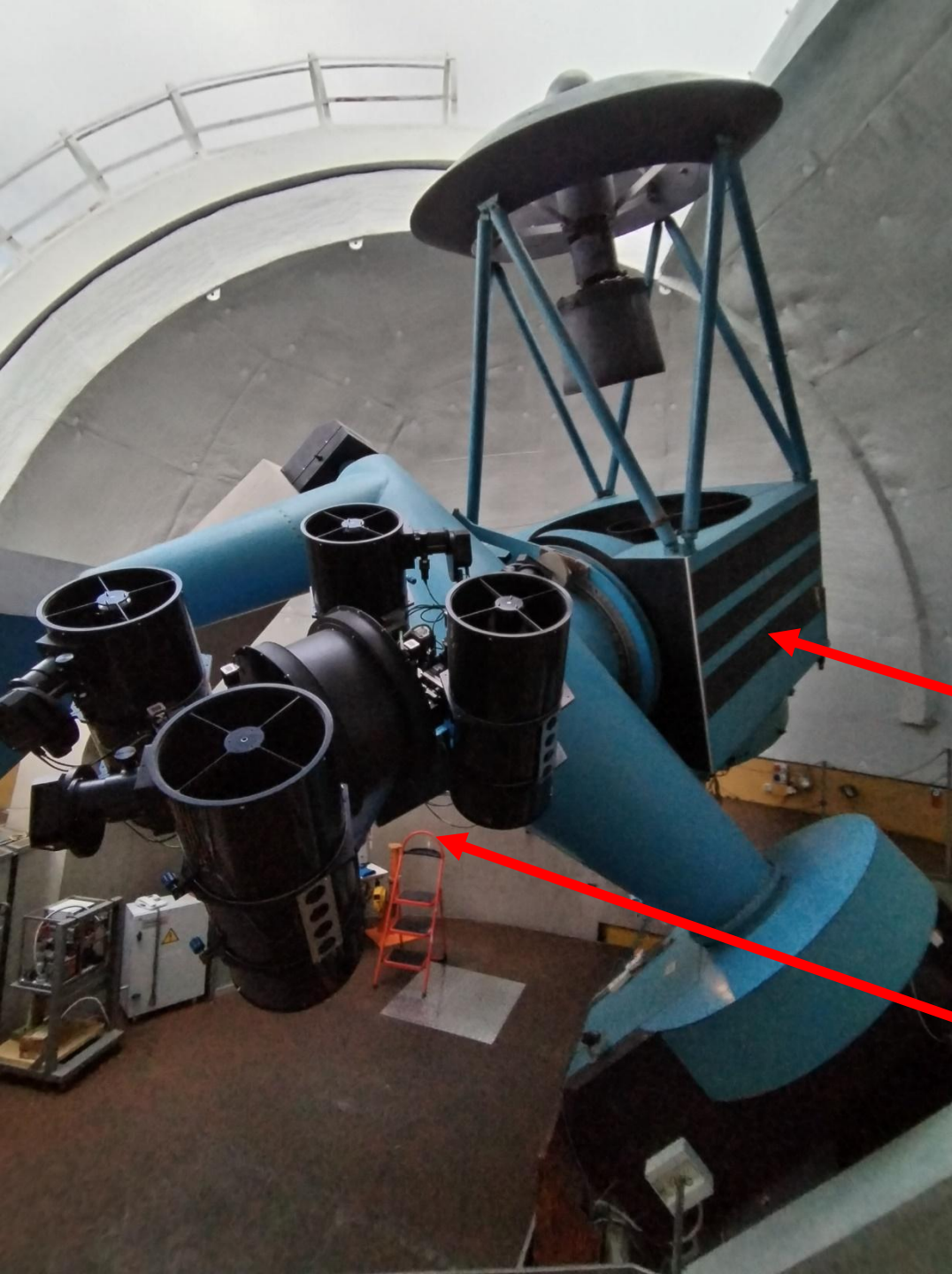
1985



The “G. D. Cassini“ telescope is hosted in a building inaugurated in 1976.

The dome’s diameter is 12 meters, while the height from the ground is about 20 meters.

Path of the Planets



The “Cassini” is a 1.5-m F/4.8 Ritchey-Chretien telescope with a CCD plate scale of about 0.6 arcsec/pixel and a field of view of 13 x 13 arcmin. “Cassini” is Italy's second-largest optical telescope.

“**Cassini**” optical telescope

TANDEM telescope array (4 Newtonian reflectors, 0.35 m, F/3)
Used for space surveillance and tracking activities.



BFOSC = Bologna Faint Object and Spectrograph Camera

Secondary CCD, FLI 1001E
1024 x 1024 pixel, with **Peltier cell** for cooling.

MAIN CCD, EEV LN/1300-EB/1
Back-illuminated, 1340 x 1300 pixel

Dewar (CCD is cooled with liquid nitrogen)

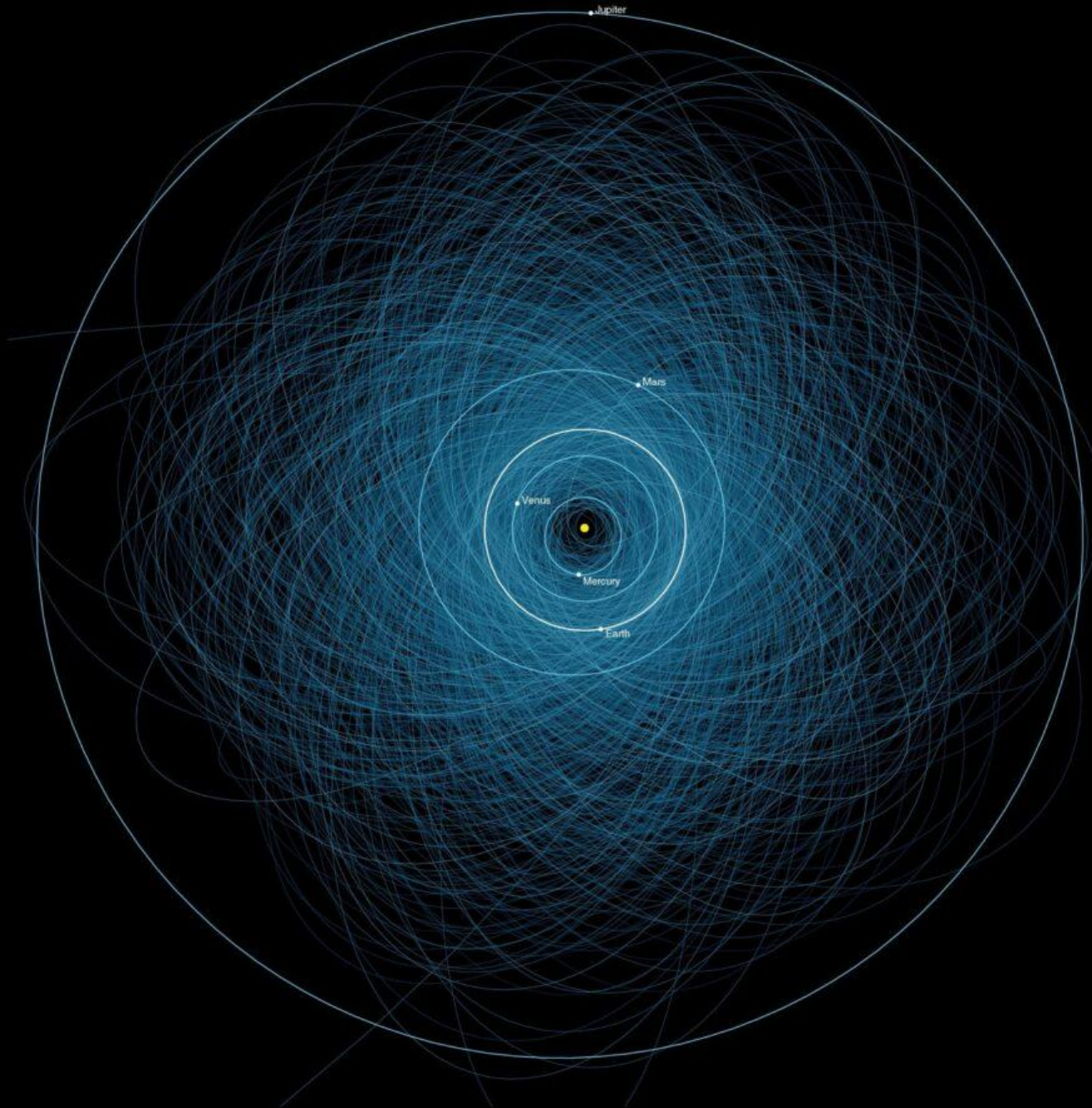
- **U, B, V, R, I**, Johnson-Cousin filters
- **G, R, Z, I**, Thuan-Gunn filters.
- Spectral range 330 - 1100 nm
- Spectral wavelength calibration is obtained through exposures of a Fe hollow-cathode lamp filled with He-Ar.

Near Earth Objects

Over **42,000 near-Earth objects** (NEOs), composed mostly of asteroids and a very small number of comets, were known in 2026. About **1,600 are on the risk list**, i.e., a non-zero probability of impact has been computed.

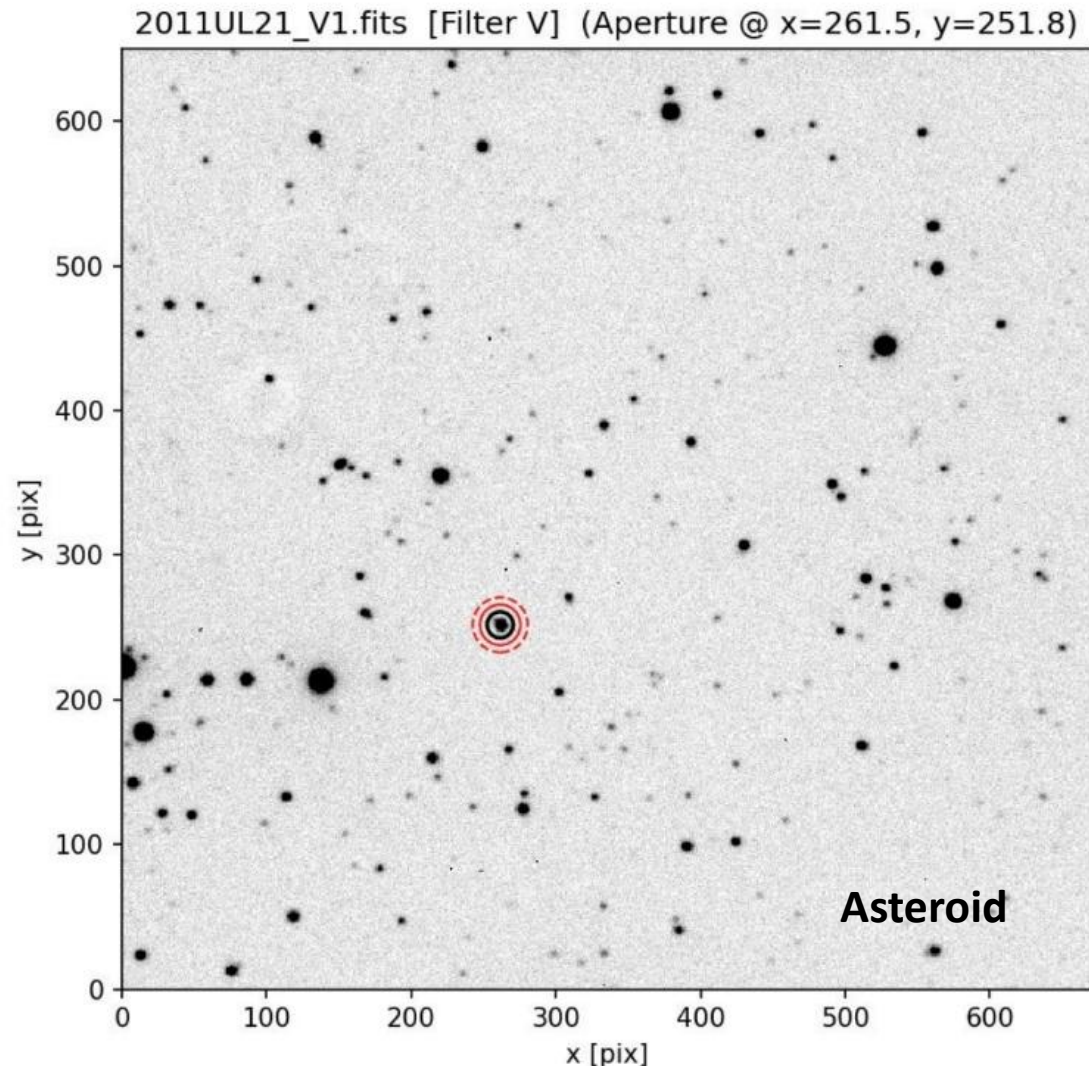
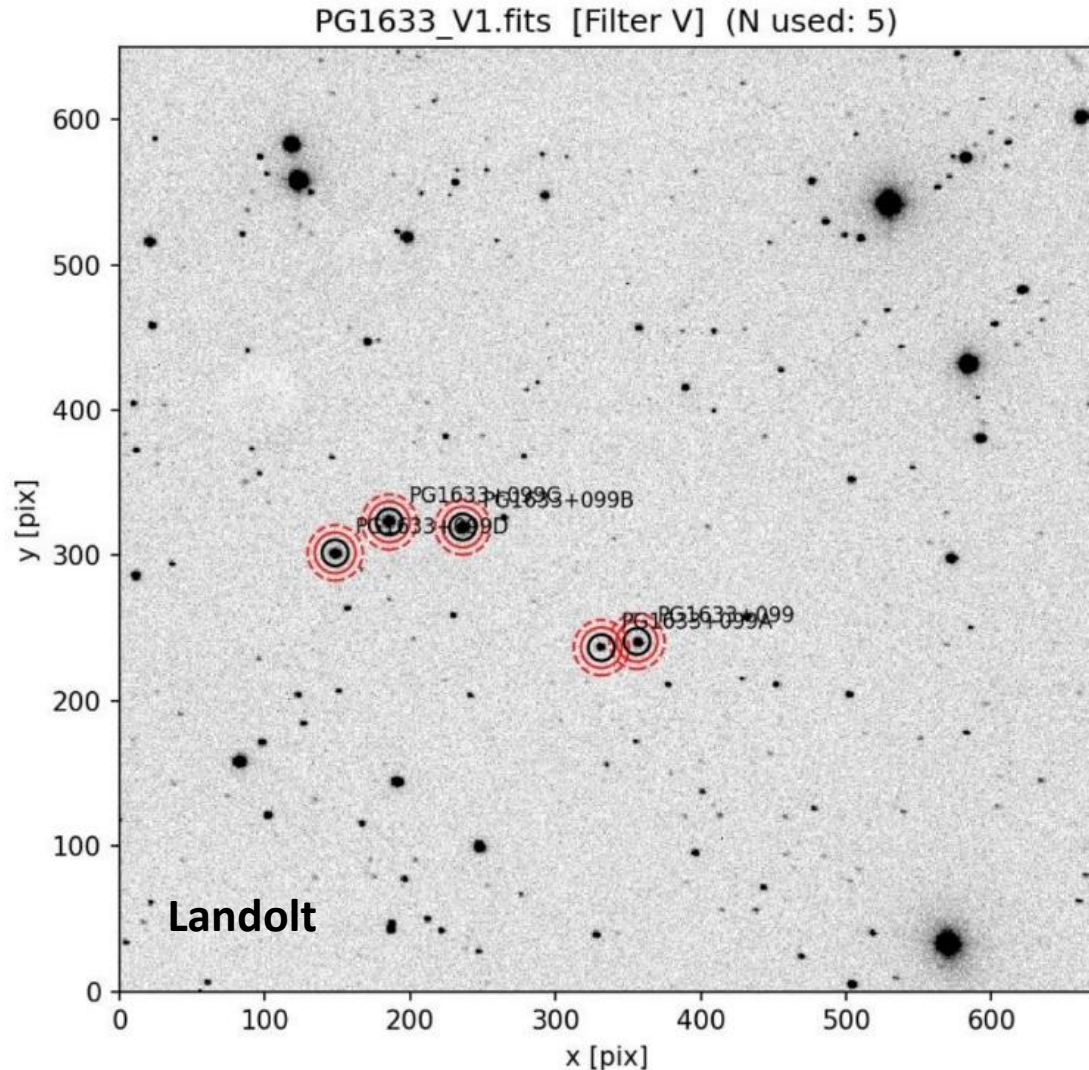
Not only is it necessary to discover the greatest number of NEOs, but also to **characterize them** by estimating **composition, size, and rotation period**.

For NEOs with dimensions larger than 200-300 meters, **measuring the rotation period** and using a **model of an asteroid with a cohesive rubble-pile structure**, a lower-order estimate of the asteroid's strength can be made. These data can be used statistically to better predict the effects of orbital deflection techniques that can be applied to minimize the risk of collision with Earth.

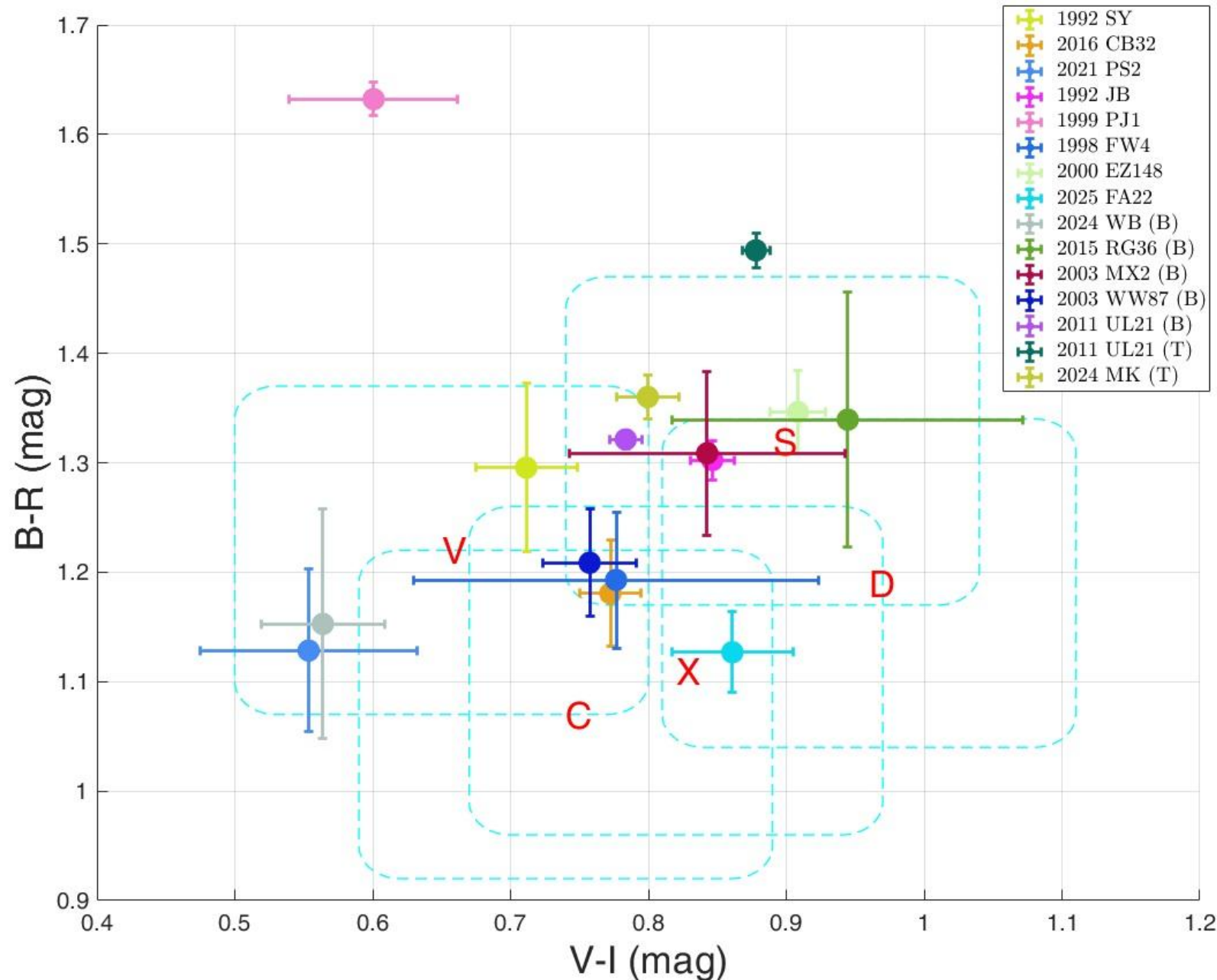


BVR_cI_c mag measurements

- **Standard calibration procedures:** master bias and master dark subtraction; master flat-field division.
- **Magnitude calibration:** using aperture photometry and Landolt standard fields at the same airmass as the target, during nights with stable atmospheric transparency.
- **Computing the difference between mag:** color indices B-V, V- R_c , and R_c - I_c .



Distribution of the color indices

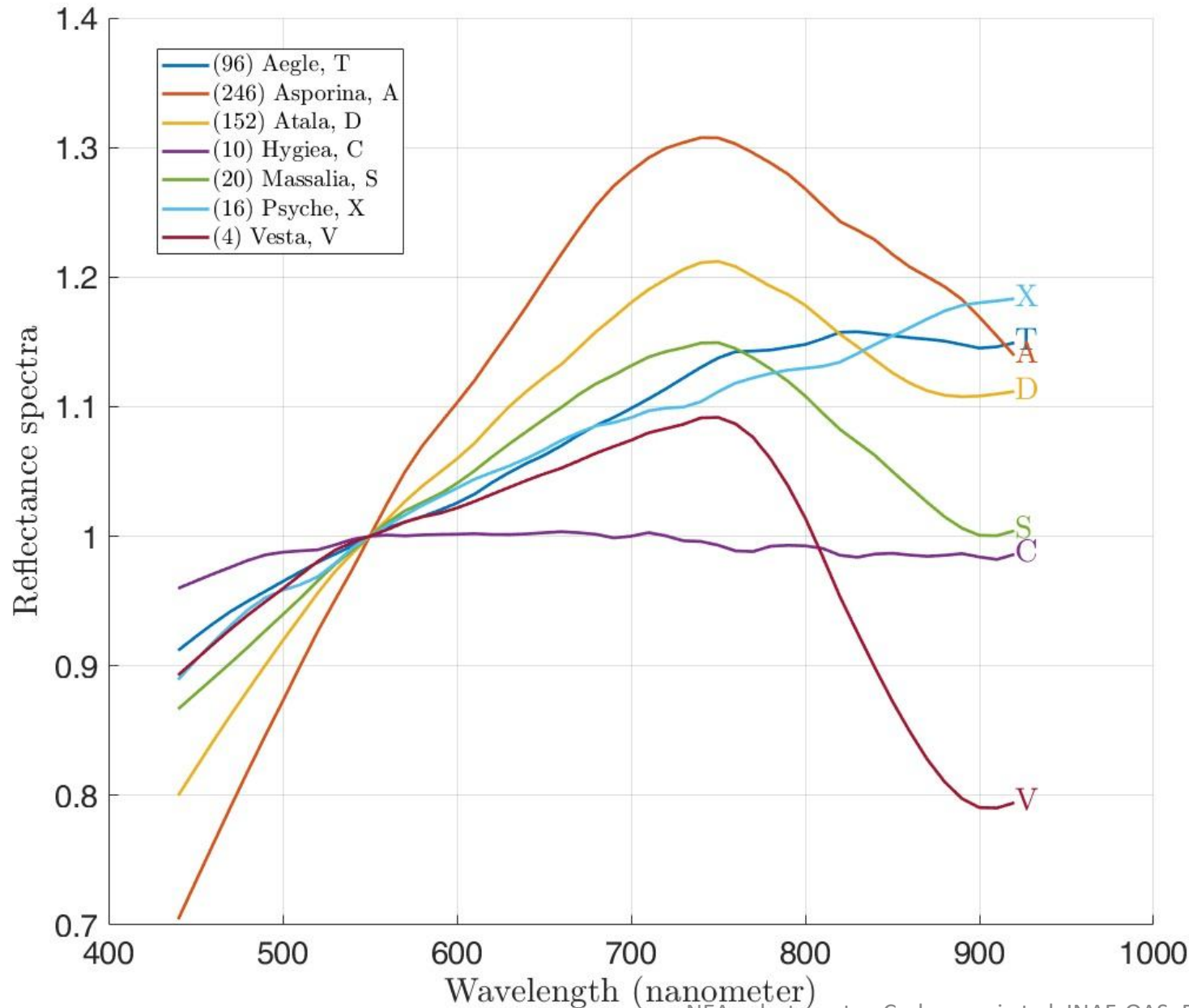


The position of the observed NEAs in a $B - Rc$ vs $V - Ic$ diagram with the positions of the main taxonomic classes.

The taxonomic class boundaries are within 0.15 mag from the mean values given in Dandy et al. (2003).

For taxonomic classification, we use the asteroid's reflectance curve.

Asteroid's reflectance spectra



The reflectance from an asteroid's surface changes if we change the wavelength. The left image shows the **typical reflectance spectra** for some important asteroid taxonomic classes.

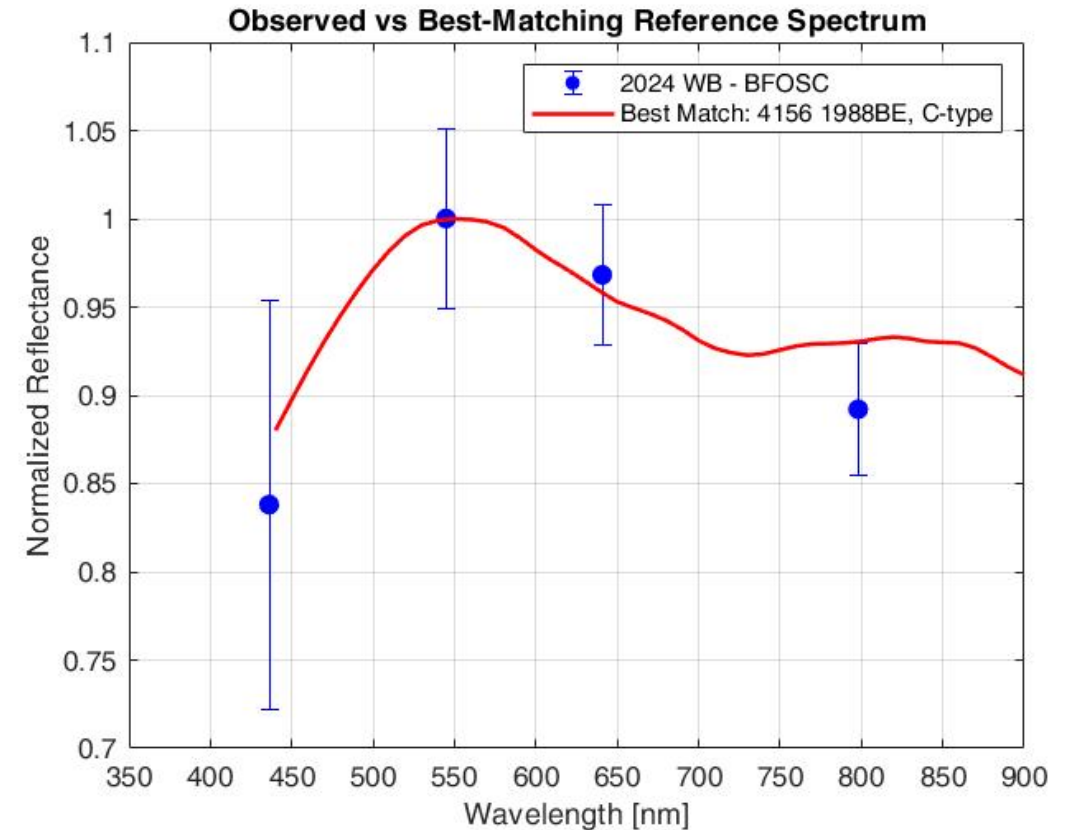
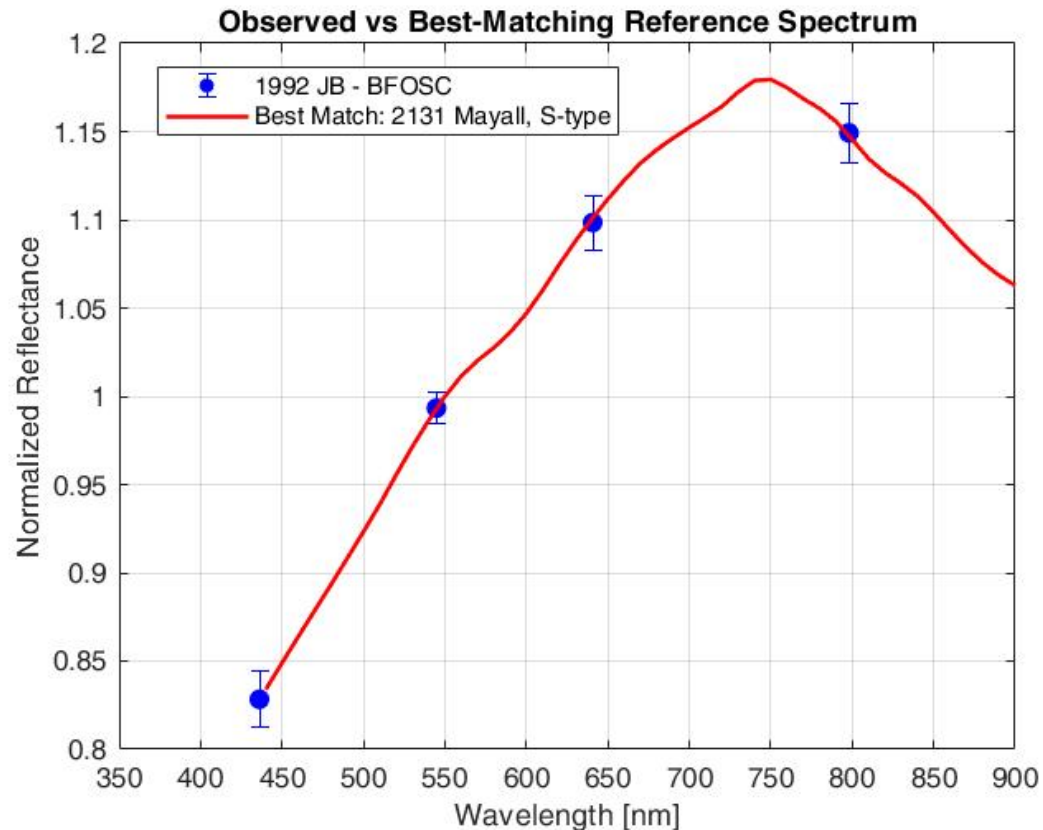
While the slopes between 750 and 450 nm are quite similar, excluding the C-complex, the curves are well differentiated towards the near-infrared, which facilitates asteroid classification when the magnitude in this band is also measured.

All the reflectance spectra are normalized to one at 550 nm. Reflectance curve is computed as follows:

$$R_f = 10^{-0.4[(f-V)-(f-V)_\odot]}$$

Taxonomic classification with reflectance spectra

We computed the reflectance values and compared them with the reflectance curves of asteroids of known taxonomy. As a reference, we adopted the reflectance curves observed during the second phase of the **Small Main-belt Asteroid Spectroscopic Survey (SMASS II)**. For each asteroid, we adopted the classification that minimizes the distance between the observed four-point reflectance and the full reflectance curve.



We estimated the **robustness of each taxonomic assignment through a Monte Carlo procedure**. For each asteroid, 500 synthetic color sets were generated by sampling the measured color indices within their Gaussian uncertainties. Each color set was converted to reflectance and classified using the same minimum-distance criterion adopted for the nominal solution. The taxonomic probability was then defined as the fraction of realizations assigned to each class.

Observed NEAs: color indices and taxonomy

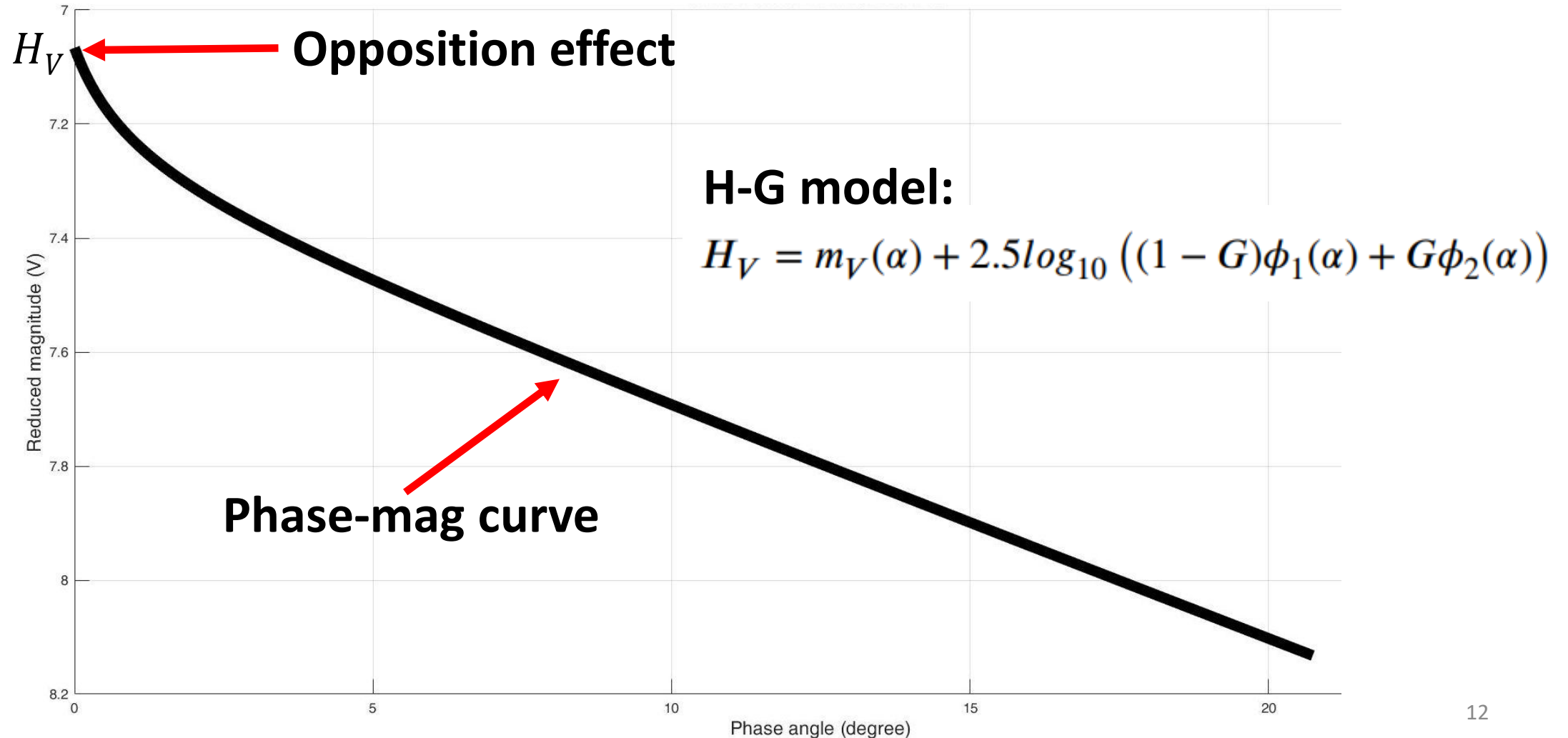
Summary of the near-Earth asteroids observed with BFOSC (B) and TANDEM (T) with mean V mag at the time of observation, mean color indices, and the taxonomic class derived from the observed reflectance curve, comparing it with the reflectance curves database. The percentage between parentheses is the maximum probability of the taxonomic classification obtained from a Monte Carlo computation, as explained in the text. An asterisk near the classification indicates an uncertainty; to find out the specific reasons, please refer to the comments dedicated to each asteroid in the appendix.

NEA	Obs Date	r, au	Δ , au	α	Inst.	$\bar{V}$	$B - R_c$	$B - V$	$V - R_c$	$V - I_c$	Taxonomy
2011 UL ₂₁	30 Jun 2024	1.054	0.063	51.8	T	12.1	1.49 ± 0.01	0.93 ± 0.01	0.56 ± 0.01	0.88 ± 0.01	S (100%)
	12 Jul 2024	1.175	0.229	42.0	B	14.8	1.32 ± 0.01	0.85 ± 0.01	0.47 ± 0.01	0.78 ± 0.01	S (49%)
2024 MK	30 Jun 2024	1.016	0.008	95.1	T	15.0	1.36 ± 0.02	0.91 ± 0.02	0.45 ± 0.02	0.80 ± 0.02	S (67%)
2015 RG ₃₆	11 Nov 2024	1.085	0.100	16.8	B	16.5	1.34 ± 0.1	0.81 ± 0.06	0.53 ± 0.1	0.9 ± 0.1	S (60%)
2003 WW ₈₇	15 Nov 2024	1.124	0.204	44.8	B	15.2	1.21 ± 0.05	0.77 ± 0.05	0.43 ± 0.02	0.76 ± 0.03	S (42%)
2003 MX ₂	02 Dec 2024	1.480	0.540	19.1	B	17.0	1.31 ± 0.07	0.89 ± 0.09	0.41 ± 0.02	0.84 ± 0.1	S (50%)
2024 WB	02 Dec 2024	1.068	0.082	06.0	B	16.2	1.15 ± 0.1	0.83 ± 0.1	0.32 ± 0.04	0.56 ± 0.04	C (83%)
2021 PS ₂	07 Mar 2025	1.099	0.120	24.2	B	16.4	1.10 ± 0.1	0.82 ± 0.1	0.27 ± 0.01	0.53 ± 0.08	C (88%)
(9058) 1992 JB	30 Apr 2025	1.107	0.120	32.0	B	15.0	1.30 ± 0.02	0.84 ± 0.02	0.46 ± 0.01	0.85 ± 0.02	S (77%)
	26 May 2025	1.229	0.281	35.5	B	17.0					
2005 VO ₅	27 Jun 2025	1.134	0.120	12.0	B	16.1	—	—	—	—	—
(333284) 1999 PJ ₁	22 Aug 2025	1.323	0.333	18.2	B	17.3	1.63 ± 0.15	1.19 ± 0.09	0.44 ± 0.08	0.60 ± 0.06	V* (81%)
(152664) 1998 FW ₄	18 Sep 2025	1.125	0.123	11.0	B	15.9	1.19 ± 0.06	0.75 ± 0.03	0.44 ± 0.03	0.77 ± 0.14	X (14%)
2025 FA ₂₂	26 Sep 2025	1.050	0.053	25.3	B	16.2	1.13 ± 0.04	0.66 ± 0.05	0.46 ± 0.03	0.86 ± 0.04	X (70%)
(138205) 2000 EZ ₁₄₈	16 Oct 2025	1.453	0.479	14.9	B	15.3	1.34 ± 0.04	0.84 ± 0.03	0.503 ± 0.003	0.91 ± 0.02	S (98%)
(843079) 2016 CB ₃₂	29 Nov 2025	1.183	0.202	12.9	B	16.4	1.18 ± 0.05	0.72 ± 0.03	0.46 ± 0.02	0.77 ± 0.02	X (44%)
(52340) 1992 SY	17 Feb 2026	1.026	0.134	70.0	B	15.9	1.29 ± 0.08	0.87 ± 0.08	0.43 ± 0.02	0.71 ± 0.04	V* (45%)

- **50% of the asteroids belong to the S-complex,**
- **14% to the C-complex**
- **21% to the X-complex**
- **14% to the V-type.**

The phase-mag curve and the absolute mag estimate

For the estimate of **absolute mag** H_V , in first approximation, we used the **mean value of the magnitude in V** using the simple $H - G$ phase-mag curve, defined by **Bowell et al. (1989)**, to **propagate it at zero phase angle**. A more sophisticated model phase-mag curve, the $(H, G1, G2)$ system by **Muinonen et al. (2010)**, also yields the same $H - G$ results for asteroids observed at high phase angle.



BRIGHT ASTEROID



HIGH ALBEDO
 $p_V = 0.25$
e.g., S-type Asteroid



SMALL DIAMETER

D_1

DARK ASTEROID



LOW ALBEDO
 $p_V \approx 0.05$
e.g., C-type Asteroid



LARGE DIAMETER

D_2

$$D = \frac{1329}{\sqrt{p_V}} 10^{-H_V/5}$$

← CONSTANT ABSOLUTE MAGNITUDE ($H=15.0$ mag) →

Dimension estimate

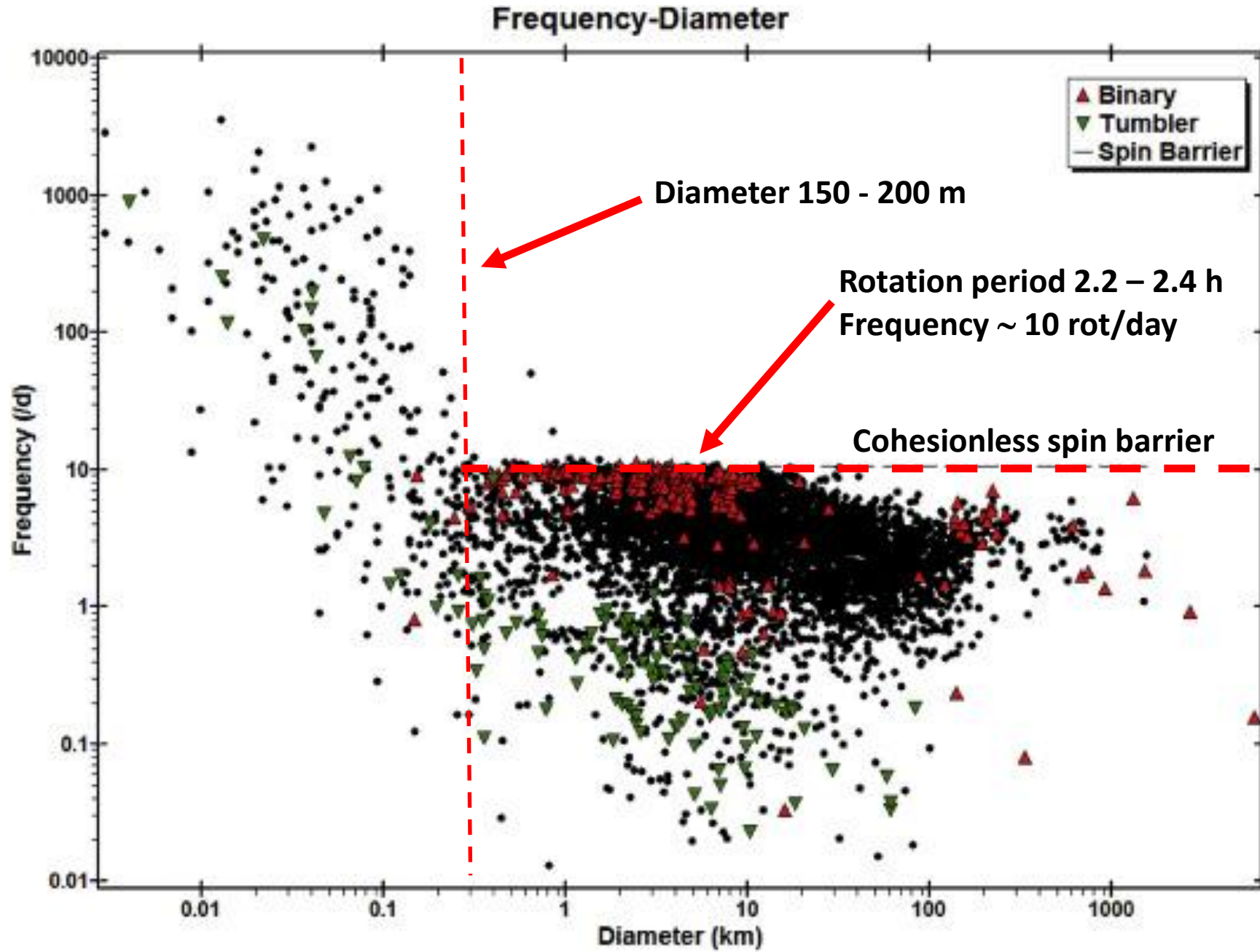
Once the taxonomic class of the asteroid has been determined, the mean geometric albedo values of the class p_V and the absolute mag H_V can be used to estimate its actual size.

Observed NEAs: dimension estimate

Summary of the near-Earth asteroids rotation period, the U quality code, amplitude, mean absolute mag H_V , the effective diameter D (both from HG_1G_2 model), and the minimum axes ratio a/b . In the column marked with “Note”, we report whether the rotation period was known or unknown at the time of observations. If already known, the period values are compared with the Small-Body Database (SBDB) of the NASA Jet Propulsion Laboratory (JPL), which collects information from the ALCDB and peer-reviewed publications. The letter B or T next to the asteroid name stands for BFOSC or TANDEM. The presence of a question mark indicates an uncertain outcome for the rotation period and an application of the amplitude-phase relationship beyond the phase-angle limit.

NEA	Rotation Period (h)	U	A (mag)	H_V (mag)	D (km)	$a/b \geq$	Note
(415029) 2011 UL ₂₁ (T)	-	-	-	16.4 ± 0.3	1.5 ± 0.3	-	Period of about 2.5 h (radar)
(415029) 2011 UL ₂₁ (B)	-	-	-	16.3 ± 0.3	1.6 ± 0.4	-	
2024 MK (T)	0.521 ± 0.003	2	1.2	22.4 ± 0.5	0.10 ± 0.03	1.60 (?)	Period unknown
2015 RG ₃₆ (B)	0.31 ± 0.01	1	0.05	20.7 ± 0.4	0.21 ± 0.05	1.04	Period unknown
(488693) 2003 WW ₈₇ (B)	4.676 ± 0.005	3	0.11	17.0 ± 0.3	1.1 ± 0.3	1.07	Period unknown
(154589) 2003 MX ₂ (B)	2.3 ± 0.2	2	0.04	16.7 ± 0.3	1.3 ± 0.3	1.03	Uncertain period of about 1.6 h
2024 WB (B)	0.302 ± 0.006	1	0.03	21.1 ± 0.3	0.30 ± 0.1	1.03	Period unknown
(618350) 2021 PS ₂ (B)	0.27 ± 0.02	1	0.06	19.8 ± 0.4	0.5 ± 0.2	1.04	Period unknown
(9058) 1992 JB (B)	7 (?)	1	> 0.34	18.3 ± 0.3	0.6 ± 0.1	-	Period unknown
(812769) 2005 VO ₅ (B)	1.065 ± 0.001	2	0.23	—	—	1.20	Period unknown.
(333284) 1999 PJ ₁ (B)	—	-	—	18.4 ± 0.2	0.5 ± 0.1	-	Period known, 6.2013 h
(152664) 1998 FW ₄ (B)	—	-	—	19.7 ± 0.3	0.5 ± 0.2	-	Period known, 17.38 h
2025 FA ₂₂ (B)	13.1 ± 0.2	2	0.60	21.4 ± 0.3	0.2 ± 0.1	1.50	Period unknown
(138205) 2000 EZ ₁₄₈ (B)	4.981 ± 0.002	3	0.17	15.5 ± 0.2	2.4 ± 0.5	1.14	Period unknown
(843079) 2016 CB ₃₂ (B)	(?)	-	> 0.04	18.9 ± 0.3	0.7 ± 0.3	-	Period unknown
(52340) 1992 SY (B)	3.1485 ± 0.0005	3	0.10	18.3 ± 0.2	0.5 ± 0.1	1.05 (?)	Period unknown

The cohesionless spin-barrier for asteroids



Why exist the spin-barrier? The rubble pile model

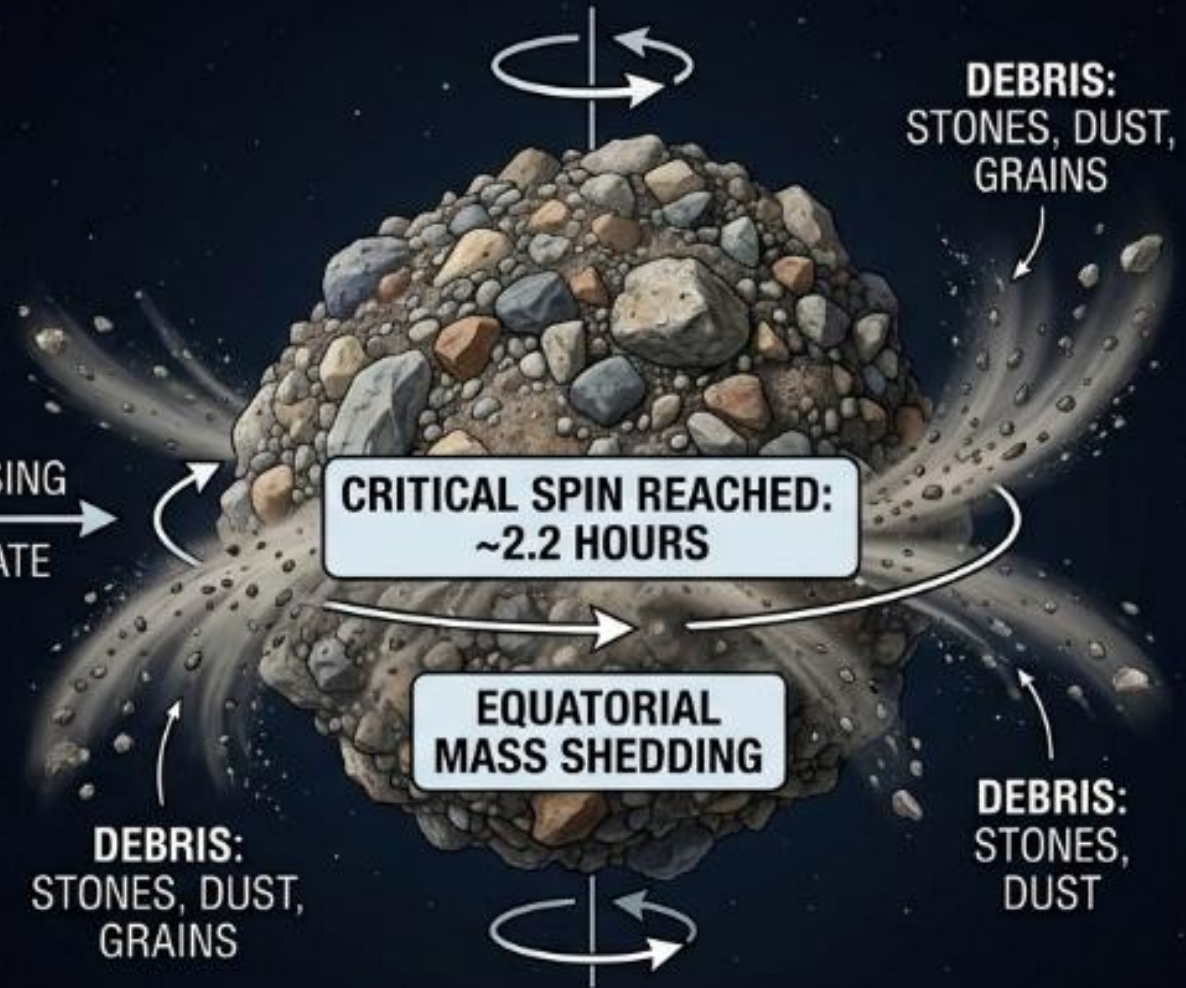
STABLE RUBBLE PILE ASTEROID (BELOW LIMIT)



STABLE CONFIGURATION:
GRAVITY > CENTRIFUGAL FORCE

INCREASING
SPIN RATE

UNSTABLE RUBBLE PILE ASTEROID (SPIN BARRIER LIMIT)



INSTABILITY:
CENTRIFUGAL FORCE OVERCOMES GRAVITY

Why exist the spin-barrier? The rubble pile model

STABLE RUBBLE PILE ASTEROID (BELOW LIMIT)

UNSTABLE RUBBLE PILE ASTEROID (SPIN BARRIER LIMIT)

But the **cohesive force (strength)** between the dust, stones, and block that form a rubble pile asteroid can be sufficiently high to **overcome the spin barrier**: the asteroid with a rubble pile structure can have a rotation period inferior to the classical spin barrier value. In this case, we speak of a **super-fast rotator** or a **large super-fast rotator** if the dimension is larger than about 300 m.

STABLE CONFIGURATION:
GRAVITY > CENTRIFUGAL FORCE

DEBRIS:
STONES, DUST,
GRAINS

INSTABILITY:
CENTRIFUGAL FORCE OVERCOMES GRAVITY

DEBRIS:
STONES, DUST,
GRAINS

DEBRIS:
STONES,
DUST

EQUATORIAL
MASS SHEDDING

CRITICAL SPIN REACHED:

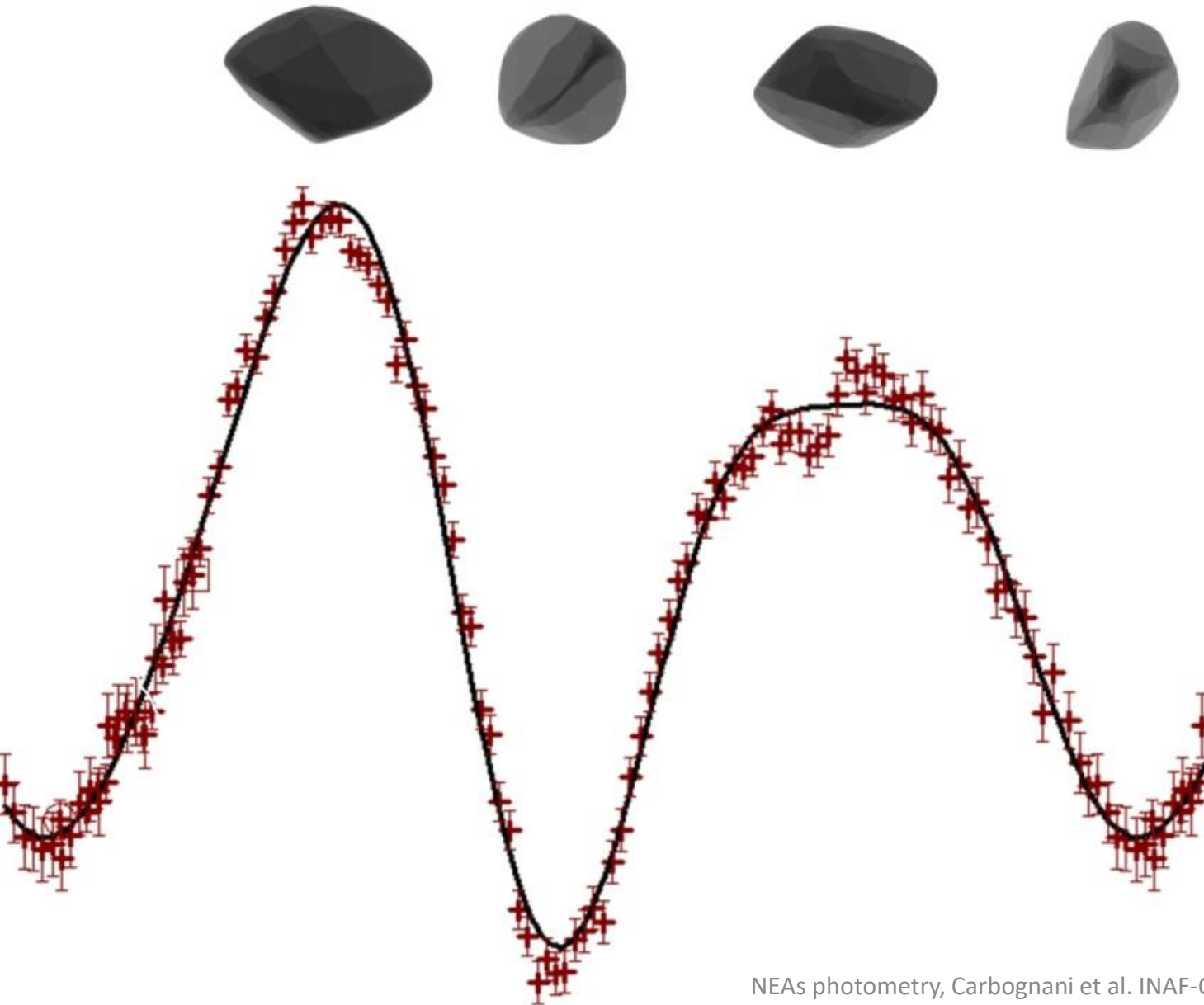
~ 2.2 HOURS

SPIN PERIOD: ~ 4 HOURS

INCREASING

SPIN RATE

Lightcurve and rotation period

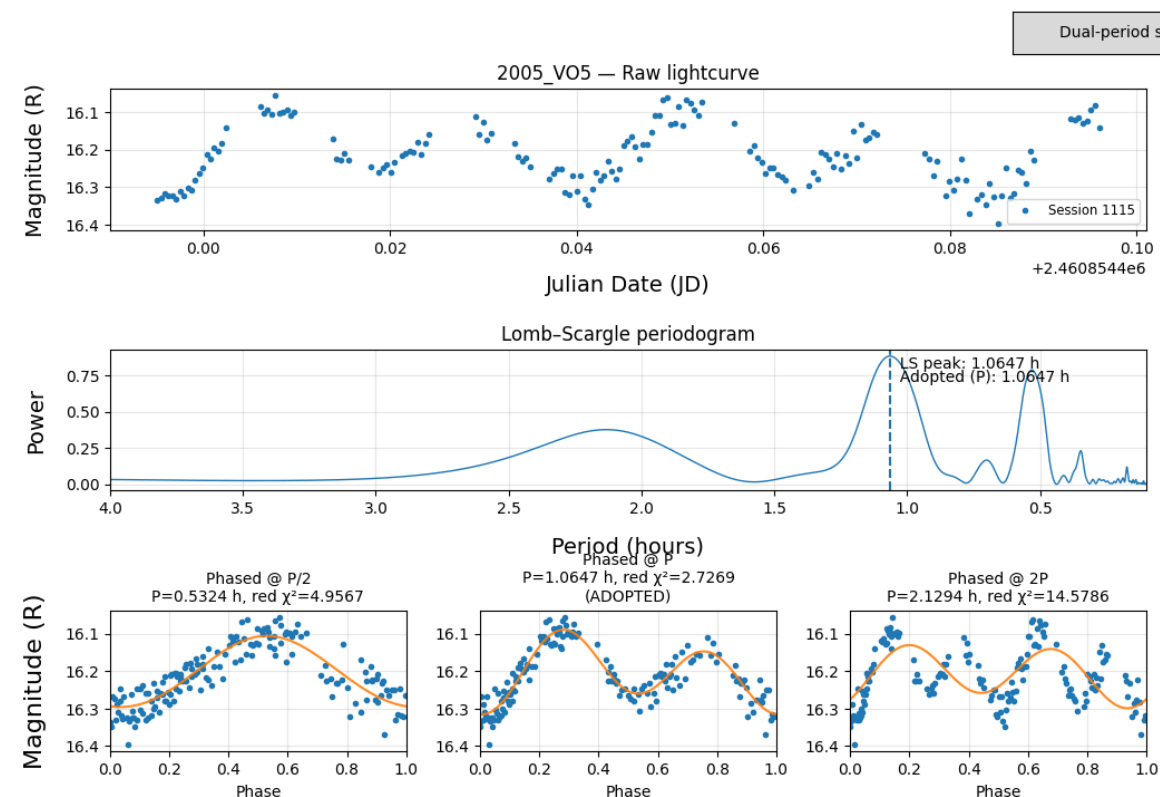
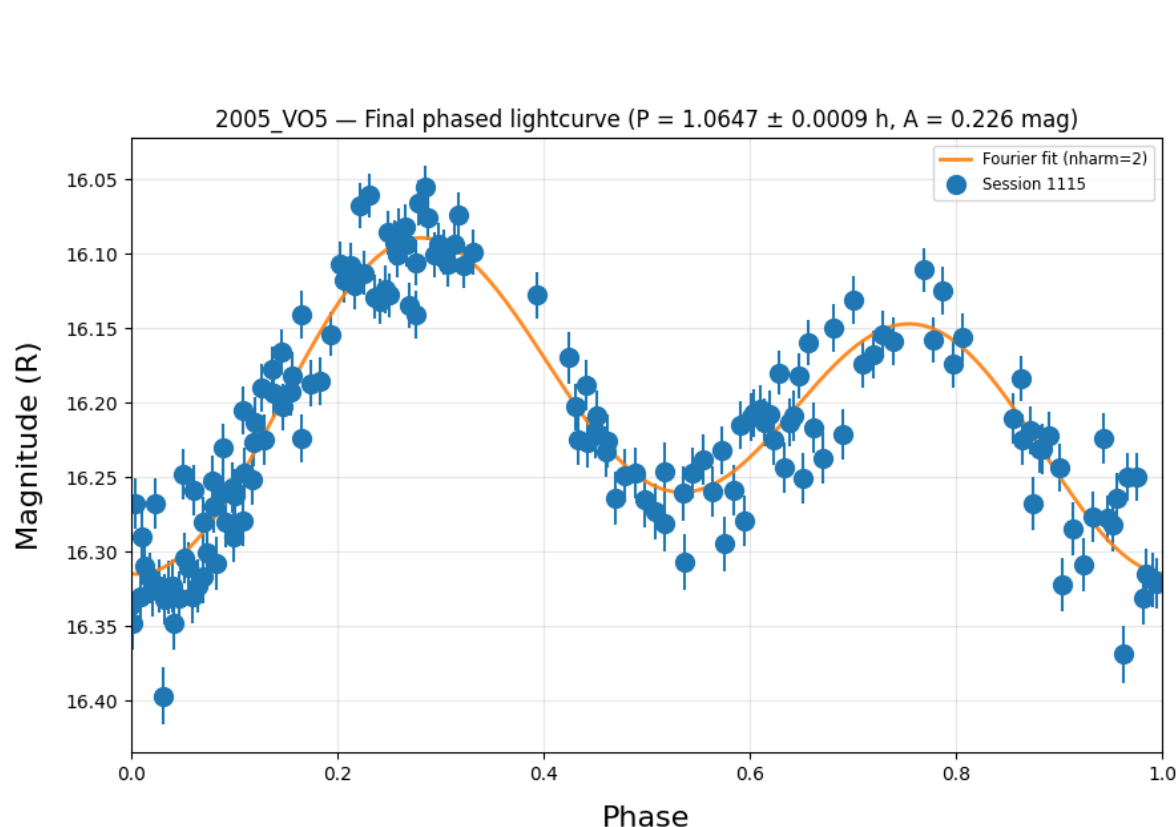


Dense photometric sessions, about 1-2 h long, were carried out with the *Rc* filter. The photometric observations were reduced using the **MPO CANOPUS software package**, which implements the classical **FALC algorithm** (Harris et al., 1989) for period determination from the observed sessions' lightcurves.

For asteroids observed in a single session, we analyzed the reduced photometric data using homemade Python software to search for periods using the **Lomb-Scargle algorithm**, widely used for detecting and characterizing periodicity in unevenly sampled time series.

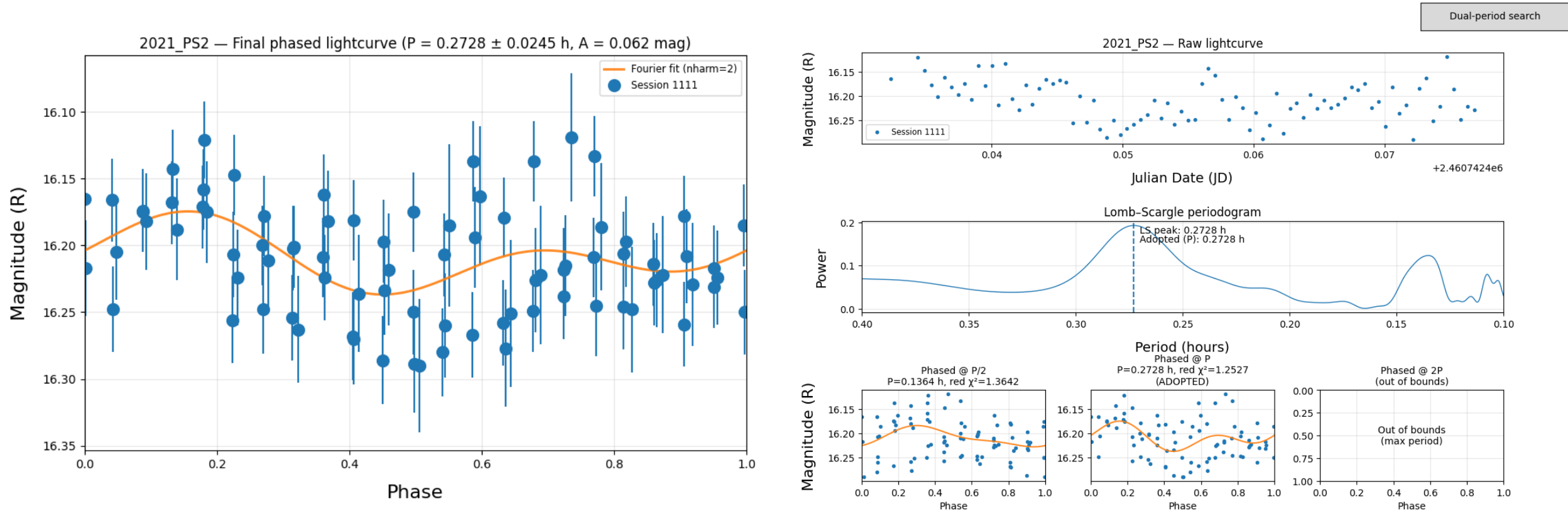
NOTE: Knowing an asteroid's rotation period can be important for **planning a mission to its surface**: if rotations are too rapid, **centrifugal acceleration can exceed gravitational acceleration**, making it difficult for a lander to descend to the surface, as in the case of 2022 OB5.

Apollo [NEO, PHA] (812769) 2005 VO5



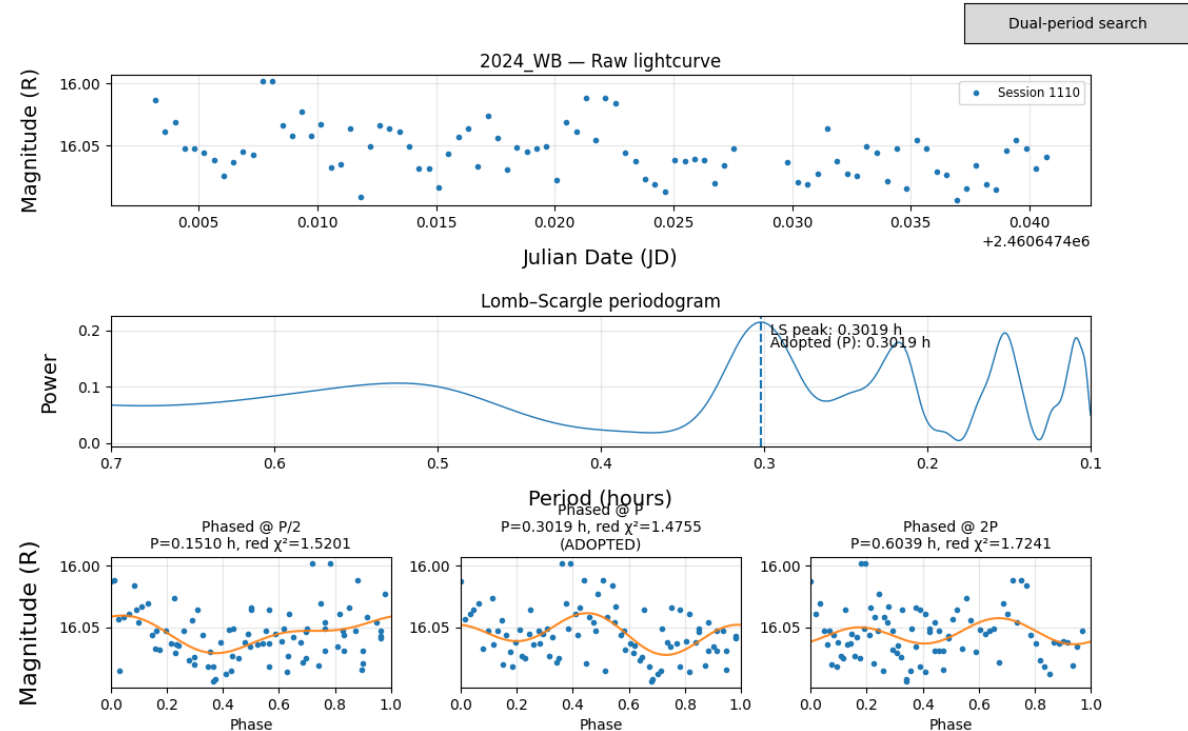
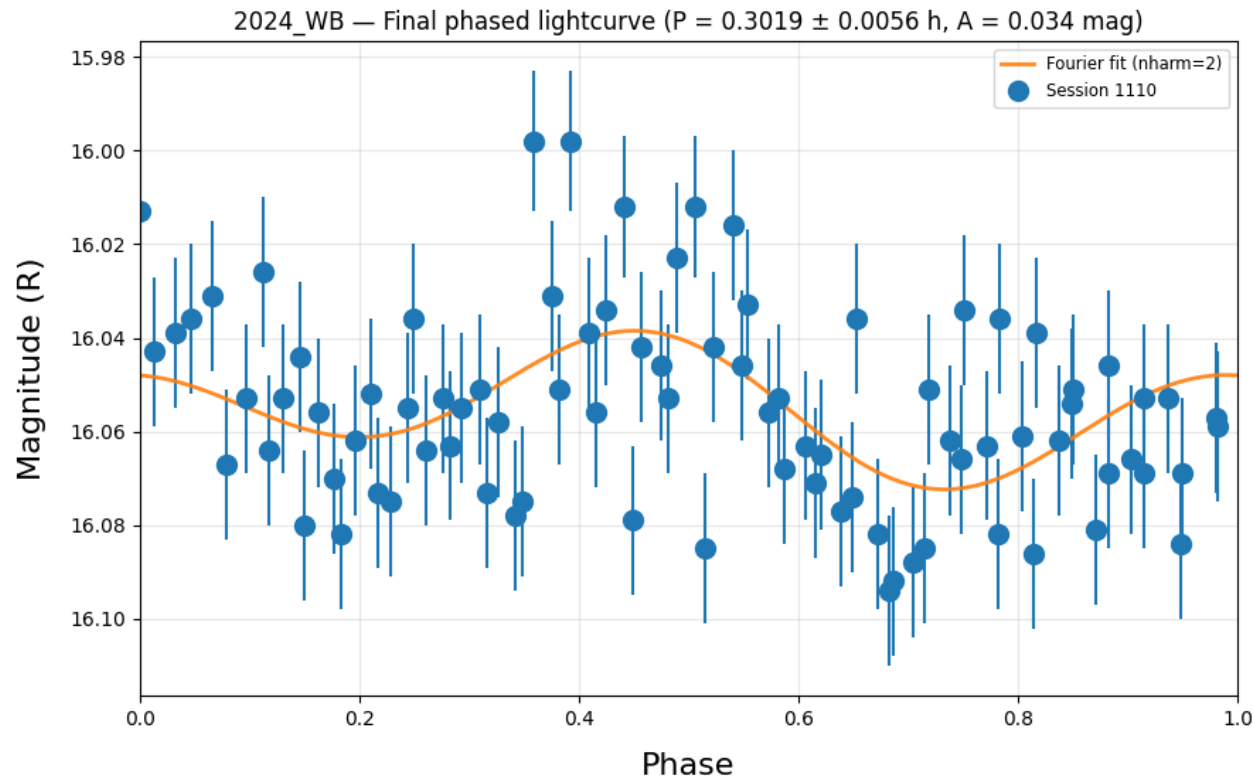
For this asteroid, no taxonomic classification is available, but based on absolute mag from the Minor Planet Center, the **estimated dimensions are between 0.3 and 0.6 km**, so it can be considered a «large» asteroid. The best rotation period is about 1 h and is a candidate large super-fast rotator.

Apollo [NEO, PHA] 618350 (2021 PS2)



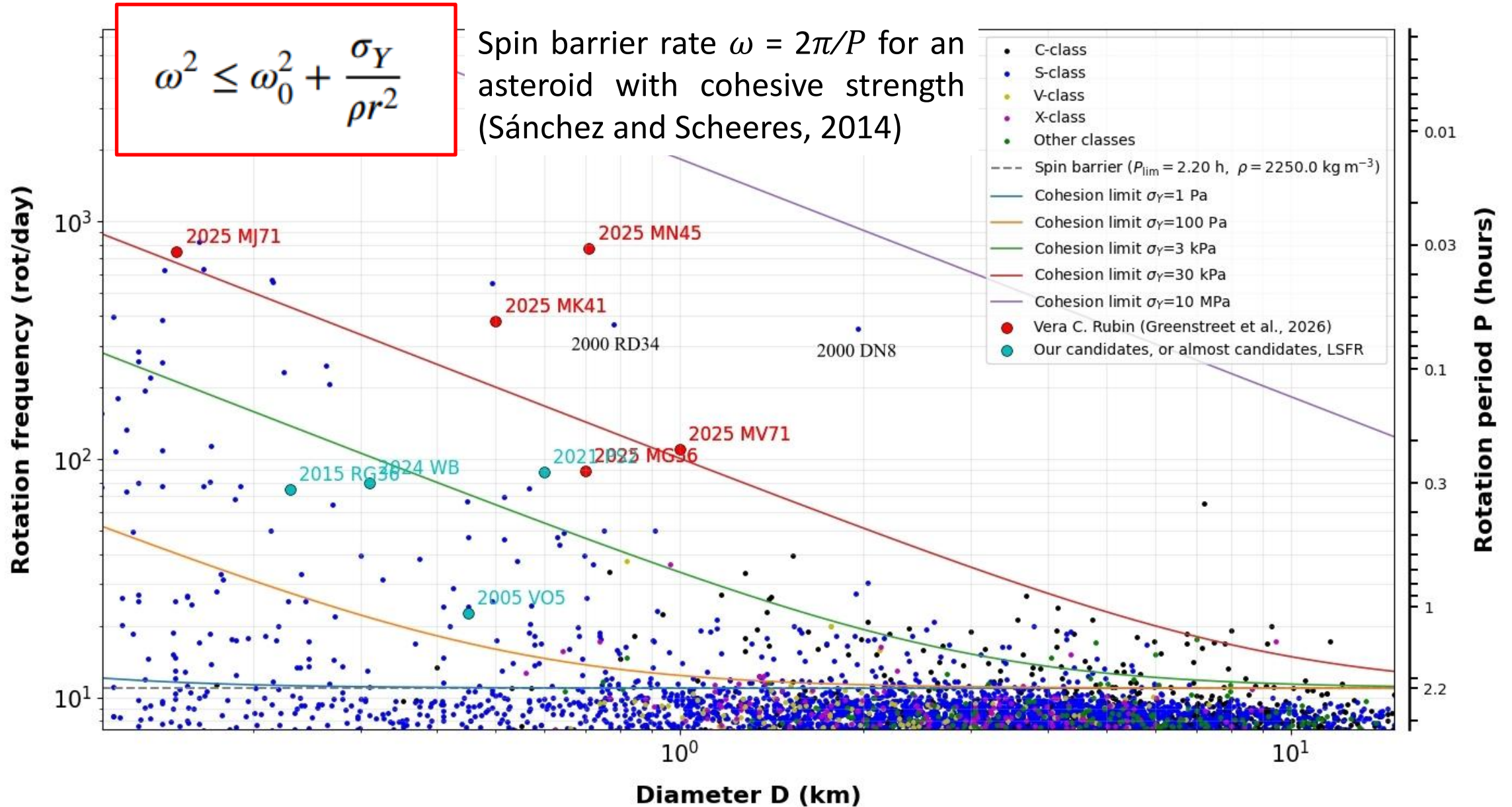
The NEA 2021 PS2 is a C-complex with an estimated diameter of about 0.5 ± 0.2 km and a possible rotation period of about 0.3 h. Candidate large super-fast rotator.

Apollo [NEO, PHA] 2024 WB



The NEA 2024 WB was a C-complex asteroid with an estimated diameter of 0.3 ± 0.1 km and a rotation period of about 0.3 hour.

Candidate super-fast rotators and cohesive strength



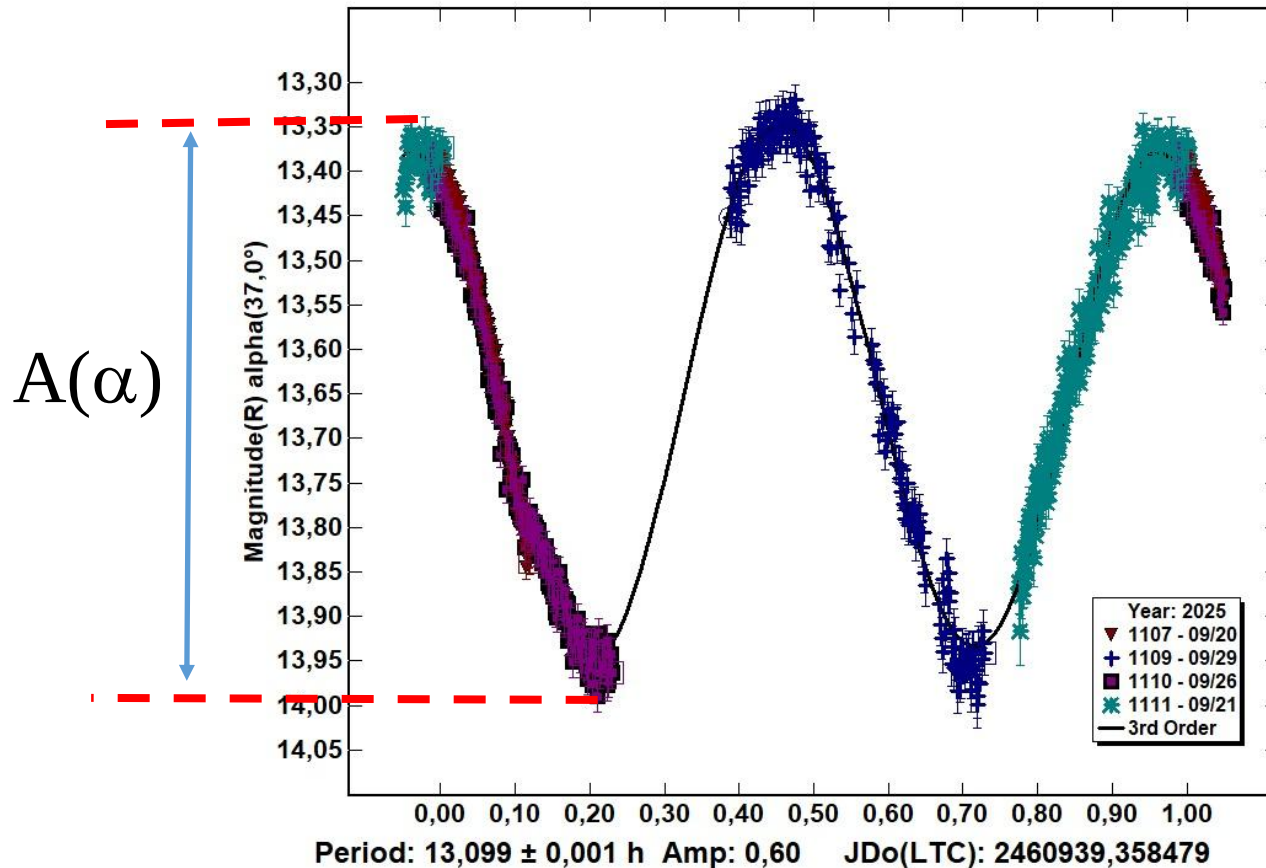
Conclusions

1. We determined color indices and **taxonomic classifications**, and constrained the **rotational properties** and **diameter** of a sample of NEAs that had never been studied before.
2. Color measurements were obtained for almost all targets, with typical uncertainties that allow a **first-order taxonomic classification using the reflectance-curve fitting**. The sample is dominated by **S-complex asteroids**, with additional representatives of the **C-complex**, **X-complex**, and **V-type**. This distribution is broadly consistent with previous photometric and spectroscopic surveys of the NEA population.
3. Rotation periods were determined or constrained for most objects in the sample. **Some asteroids are candidates to rotate faster than the classical cohesionless spin barrier**.
4. A **cohesive rubble-pile model** provides a plausible explanation for the observed rapid rotation, and modest **cohesive strengths of order 10^2 – 10^4 Pa** are sufficient to account for the observed rotation rates.

**Thank you for your
attention**

Shape estimate

When the lightcurve amplitude is determined, we have estimated the lower limit of the ratio between axes of the asteroid, which is supposed to be an ellipsoid shape:



$$a/b \geq 10^{0.4\bar{A}(0)}$$

$$A(0) = \frac{A(\alpha)}{(1 + m\alpha)}$$

Amplitude-phase relationship
 $m \sim 0.014 \text{ deg}^{-1}$