Physical characterization of the asteroid (4660) Nereus

J. A. Mansour[1,2], M. Popescu[1], J. de León [3,4], D. Bertești eanu[5], D. Morate [3,4], O. Văduvescu [3,6], J.Licandro[3,4], B.A. Dumitru [1,7], G.N Simion[1,7], R. M. Gherase[1,9], V. Pinter[9,10,11], E. Tatsumi[3,12]

(1) Astronomical Institute of the Romanian Academy, 5 Cuțitul de Argint, 040557 Bucharest, România; (2) Tartu Observatory, Observatooriumi 1, 61602 Tõravere, Estonia (3) Instituto de Astrofísica de Canarias (IAC), C/Vía Láctea s/n, 38205 La Laguna, Tenerife, Spain; (4) Departamento de Astrofísica, Universidad de La Laguna, 38206 La Laguna, Tenerife, Spain. (5) Astroclubul București, Bulevardul Lascăr Catargiu 21, 010663 Bucharest, Romania, (6) Isaac Newton Group of Telescopes (ING), Apto. 321, E-38700 Santa Cruz de la Palma, Canary Islands, Spain (7) Institute of Space Science (ISS), 409, Atomistilor Street, 077125 Magurele, Ilfov, Romania (8) University of Amsterdam, Faculty of Science, 1090 GE Amsterdam, The Netherlands (9) Faculty of Sciences, University of Craiova, Craiova, Romania (10) Nordic Optical Telescope, Rambla José Ana Fernández Pérez 7, ES-38711 Breña Baja, Spain (11) Department of Physics and Astronomy, Aarhus University, Ny Munkegade 120, DK-8000 Aarhus C, Denmark (12) Department of Earth and Planetary Science, University of Tokyo, Tokyo, Japan

Abstract

The near-Earth asteroid (4660) Nereus represents an ideal candidate for future mission proposals and remains one of the key targets for space exploration. Its favorable apparition during the fall of 2021 and beginning of 2022 allowed us to observe the asteroid using various ground-based telescopes. We report the full light curve of Nereus based on which we determined its rotational period and absolute magnitude, and discuss the visible spectro-photometric and near-infrared spectral data. The Lomb-Scargle periodogram peaks at **P = 15.19 h.** Subsequently, we fit the asteroid's phase curve with the H-G model and obtain an absolute magnitude value of **H = 18.69 ± 0.18 and a slope parameter value G = 0.209 ± 0.06.** The average colors, obtained on multiple observing session with the 1.52m Telescopio Carlos Sánchez, are **(g-r) = 0.537 ± 0.048, (r-i) = 0.145 ± 0.012, (i-z_s) = 0.091 ± 0.017.** These values indicate that Nereus is an X-complex asteroid. This conclusion is supported by the near-infrared spectral data obtained with the 3.6 m Telescopio Nazionale Galileo (TNG)

Introduction

The asteroid with number 4600, Nereus (formerly know as 1982 DB) was discovered on February 28th, 1982 with the 1.2 m Schmidt telescope located at Palomar Mountain, California [1]. It is classified as an Apollo object due to its perihelion distance (0.952 A.U), and it also represents a potentially hazardous asteroid. It was deemed as one of the most accessible asteroids for a sample return mission gracefully to its orbital parameters and the delta-v budget required for such a spacecratf. It was proposed as a possible target for the NASA Near-Earth Asteroid Rendezvous (NEAR) and for JAXA Hayabusa mission.

The light-curve analysis and the radar shape modeling revealed a long rotational period of ~ 15.16 ± 0.04 h and a size of 510 (± 20) x 330 (± 20) x 241 (+80,-10) m [2, 4]. The radar [4] and thermal [9] observations report optical albedo values of 0.54 (-0.09, +0.03) and 0.55 ± 0.17 respectively. Nereus is classified as an E-type object in the Tholen taxonomy. This class has been associated with enstatite achondrite meteorites.

During the fall of 2021 (4660) Nereus had an apparent magnitude brighter than 18.5 V mag. for about 7 months. The peak brightness was 12.9 mag on the night of December 7, when it reached a geocentric distance of 0.030 A.U. Thus, we performed an extended observing campaign with the aim to determine its properties, namely the rotation, the shape, the size, and the surface composition.

Observations

The bright apparent magnitude of this near-Earth asteroid (NEA) allowed us to study it using various telescopes and techniques. First, we follow **the lightcurve** for eight nights using the T025-BD4SB, a 0.25 m aperture telescope located at the Bucharest Astronomical Institute. About 65 hours of observations were obtained during October 27 and November 25, 2021. These data were acquired using the QHY294M CMOS (complementary metal–oxide–semiconductor) camera.

Second, **the colors in the visible region** were determined using the MuSCAT2 instrument mounted on the 1.52 m Telescopio Carlos Sanchez (TCS) located on Teide Observatory, Tenerife. This instrument allows simultaneous images with the broad band filters g (0.40 - 0.55 µm), r (0.550 - 0.70 µm), i (0.70 - 0.82 µm), and z_s (0.82 - 0.92 µm). In order to search for surface heterogeneity, we gathered 12 hours of data during six nights of observations spread over October 02, 2021 until April 02, 2022. Additional photometry data was obtained using the 2.54 m Isaac Newton Telescope (Observatorio del Roque de los Muchachos, La Palma) equipped with Wide Field Camera. We obtained 6 hours of photometric observations using the B, V, R Johnson filters, and the r and z SDSS filters during the nights of March 2, and April 18, 2022.

The **near-infrared spectrum** was obtained using the 3.58 m Galileo National Telescope (Observatorio del Roque de los Muchachos, La Palma). We used the Near-Infrared Camera Spectrometer (NICS) with the AMICI prism and a 1.5 arcsec slit-width. This configuration allowed a resolving power of R = 50 and a spectral interval coverage of 0.8 - 2.45 µm.

Figure 1: *The instruments used for this study (from left to right): the 0.25m T025-BD4SB of Bucharest Astronomical Institute, the 1.52 m Telescopio Carlos Sanchez (TCS) located on Teide Observatory/Tenerife, the 2.54 m Isaac Newton Telescope, and the 3.58 m Galileo National Telescope both from Observatorio del Roque de los Muchachos / La Palma.*

Date	Time range(UTC)	Telescope	Filter	Δ[A.U.]	r[A.U.]	α[o]	V mag
2021-10-01	03:04 - 05:44	TCS	g,r,i,z	0.392	1.333	27.4	18.5
2021-10-15	01:01 - 01:58	TCS	g,r,i,z	0.285	1.257	21.5	17.5
2021-10-27	19:34 - 03:46	T025	-	0.202	1.188	15.2	16.4
2021-10-28	18:45 - 23:17	T025	-	0.197	1.182	14.7	16.3
2021-10-29	18:58 - 01:14	T025	-	0.191	1.177	14.3	16.2
2021-11-01	20:47 - 05:56	TCS	g,r,i,z	0.175	1.162	13.1	16.0
2021-11-10	23:27 - 02:06	T025	-	0.129	1.116	11.8	15.2
2021-11-20	16:40 - 00:23	T025	-	0.086	1.070	16.3	14.4
2021-11-21	15:42 - 03:37	T025	-	0.082	1.065	17.1	14.3
2021-11-24	16:16 - 03:30	T025	-	0.070	1.053	19.8	14.0
2021-11-25	16:24 - 03:49	T025	-	0.066	1.049	20.9	13.9
2022-03-03	04:14 – 04:44	INT	B,V,R,z	0.236	1.101	56.6	17.8
2022-04-18	20:19 – 03:28	INT	g,r	0.346	1.348	4.4	17.4
2022-04-21	01:02 – 01:44	TNG	NICS/AMICI	0.356	1.359	4.1	17.5

Table 1. *The observing circumstances, the observing dates and the time interval when the observations were performed, the telescope, the filter or the instrument used, the geocentric distance, the heliocentric distance, the phase angle and the apparent magnitude.*

References: [1] Helin et al 1984, Icarus [2] Y. Ishibashi et a 2000, Earth, Planets and Space; [3] Marina Brozovic et al, 2009, Icarus [4] Y. Ishibashi et al, 2000, Advances in Space Research [5] M. Colazo et al, 2022, Astronomy and Computing [6] Edward Bowell et al, 1989, Asteroids II [7] Francsca E. DeMeo et al. Icarus [8] Delbo et al 2003, Icarus [9] Binzel et al 2004, *Planetary and Space Science*

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Results

The obtained lightcurves were used to determine the rotation properties using the Lomb-Scargle Periodogram. Subsequently, we obtained the phase curve of the object and we computed its absolute magnitude (H) and the slope parameter (G). In order to quantify the YORP effect a longer observing time-span is needed.

We report the color indices obtained both with TCS/MuSCAT2 instrument and with INT/Wide Field Camera Telescope. These were used to obtain the taxonomic classification. The MuSCAT2 instrument allowed us to obtain simultaneous lightcurves in g, r, i and z_s filters for 12 hours of observations. The spectro photometric data is also compared with the spectral data. Finally we reviewed its taxonomic classification based on the new acquired near-infrared spectrum.

The Lomb-Scargle periodogram peaks at a value of 15.19 h. This value is in the range reported by [4] who used the least-squares frequency analysis and phase dispersion minimization to determine a period of 15.1±1.2 h. It is also compatible with the value obtained using radar data [3] of 15.16 ± 0.04 h. We estimated that the YORP effect can change the spin rate with one to four seconds for its orbital period in a range of 10 years. Unfortunately, the previous existing values for its rotation period have much larger uncertainties. The next favorable observing window is in 2060, when Nereus will be at geocentric distance of 0.008 a.u.

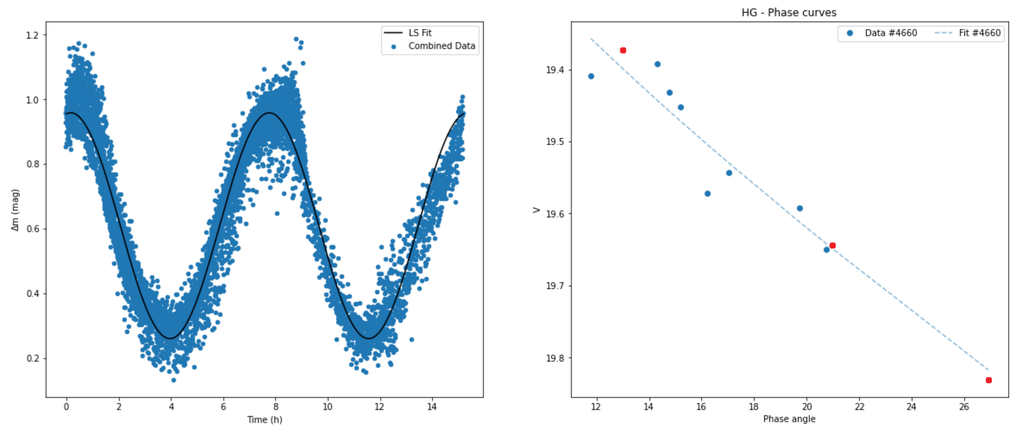

Figure 2: *Left: The folded lightcurve of (4660) Nereus obtained by combining the data from T025-BD4SB and TCS. The solid, black line represents the period fit using Lomb-Scargle periodogram. Right: Phase curve of (4660) Nereus. The red points are TCS observations while the blue ones are T025-BD4SB. The dotted line represents the H-G model fit..*

We determined the phase curve of the asteroid in order to obtain its absolute magnitude (Fig.2). In order to do this, we use the Pyedra software [5]. The algorithm allowed us to use the H-G model [6] in order to fit our phase curve. We obtained **the absolute magnitude (H = 18.69 ± 0.18) and the slope parameter (G = 0.209 ± 0.06).** For comparison, [4] reported a value of 18.58 ± 0.06.

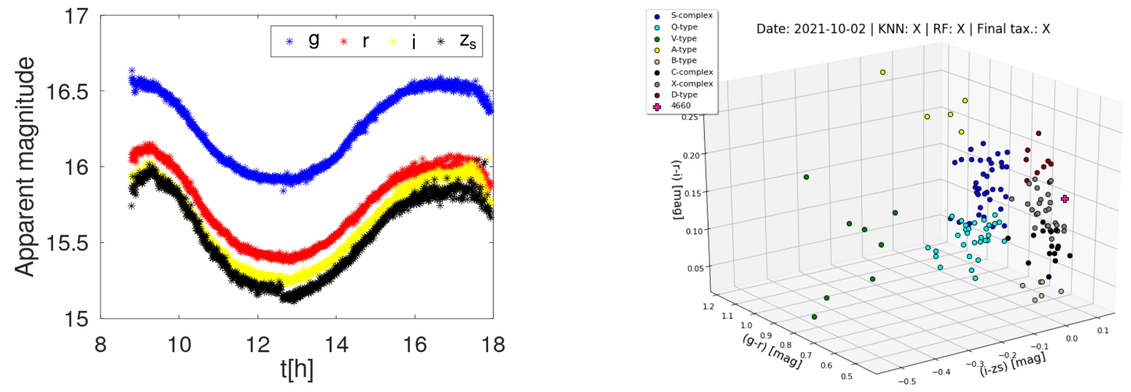

Figure 3: *The results obtained with TCS/MuSCAT instrument for Nereus. Left - the simultaneous observations in g, r, i, z_s bands performed during one night. Right: The color-color diagram of (4660) Nereus compared with the reference data-set (Popescu et al. 2022 - paper in preparation). The taxonomic types defined in [8] have been divided in three major composition groups: the Q /,S-complex (green and blue dots), the C-complex (black dots) and the X-complex (grey dots). Besides them, three end-member types are considered, A-, D- and V-type.60) Nereus and its taxonomic classification.*

The TCS/MuSCAT2 instrument allowed us to simultaneously obtain the light-curve in all four filters. We found **(g-r) = 0.537 ± 0.048, (r-i) = 0.145 ± 0.012, (i-z_s) = 0.091 ± 0.017**. In addition to these values by using the INT observations we obtained the (B-R) = 1.15 ± 0.05 mag, and (V-R) = 0.043 ± 0.03 mag colors. The average color values obtained with TCS/MuSCAT2 are compatible with an X-complex classification (Fig. 3). The classification is performed using K-Nearest Neighbors and Random Forest Classifier algorithms.

In Fig. 4 we show the combined spectral data obtained with the TNG/NICs instrument and the data obtained with TCS, which have been converted to reflectances. In the near-infrared, Nereus shows a mild slope increase with no absorption bands. Coupled with the lack of silicate absorption features, this is an indication of Nereus being part of the X complex. **The most plausible class for our data is Xe.**

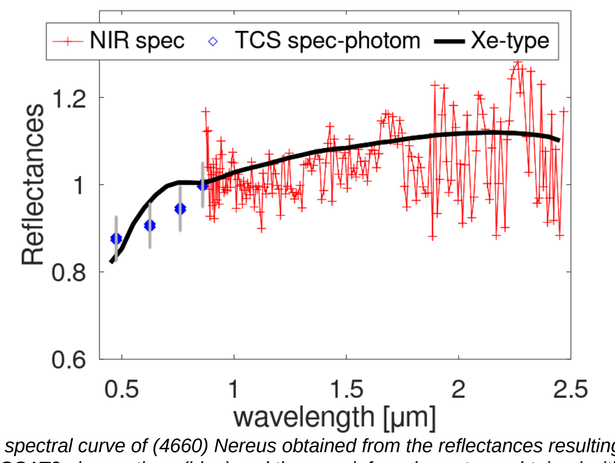

Figure 4: The spectral curve of (4660) Nereus obtained from the reflectances resulting from TCS/MuSCAT2 observations (blue) and the near-infrared spectrum obtained with TNG/NICS. The result is compared with the Xe-type (black).

Conclusions

- ✓ Report the full light curve of Nereus and determine its rotational period: **P = 15.19 h**
- ✓ Determine the phase curve and obtain the absolute magnitude and slope parameter: **H = 18.69 ± 0.18 & G = 0.209 ± 0.06**
- ✓ Determine the color indices in g, r, I and z_s filters: **(g-r) = 0.537 ± 0.048, (r-i) = 0.145 ± 0.012, (i-z_s) = 0.091 ± 0.017**
- ✓ Determine the color indices in the B, V and R Johnson filters: **(B-R) = 1.15 ± 0.05, (V-R) = 0.043 ± 0.03**
- ✓ Vis-NIR spectra compatible with the **Xe-complex**