PHYSICAL CHARACTERIZATION AND SHAPE MODEL OF 1998 OR2 SHOWS ITS SURFACE IS HETEROGENEOUS M. Devogele[1], A. McGilvray[1], E. MacLennan[2], C. Monchinski[3], S. E. Marshall[1], D. Hickson[4], F. Venditti[1], L. Zambrano-Marin[1], A. Virkki[2], E. Jehin[5], M. Ferrais[1], Ph. Bendjoya[6], J.-P. Rivet[6], L. Abe[6], D. Vernet[7], A. Cellino[8]
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Introduction: The near-Earth object 1998 OR2 (hereafter OR2) was discovered by the Near-Earth Asteroid Tracking (NEAT) NASA program [1] in 1998. With an estimated absolute magnitude of $H = 16.04$ (according to the Minor Planet Center) it has an estimated diameter of 2km. OR2 is considered as a potentially hazardous object as it can performed close approaches to earth as close as 0.0087 au according to its current MOID(see table 1 for the OR2 orbital elements). With a $\delta_v = 6.5$ km/s, OR2 is also a good target for a space mission.

Table 1: Osculating orbital elements of OR2 at epoch 60000 MJD (2023-Feb-25) obtained with the JPL Horizons service.

a (au)	e	$MOID$ (au)	i (°)	ω (°)	Ω (°)
2.380	0.575	0.009	5.878	26.941	180.159

Observations: On April 29th 2020, OR2 experienced a close fly-by to Earth at a distance of 16.4 lunar distances (LD) (0.0420 au) and reached a V magnitude of 10.8. This is the closest and brightest apparition since its discovery and until April 16th, 2079 when it will get as close as 4.6 LD (0.01185 au). These are one of the closest approaches for such large asteroids as only Toutatis (D $\sim$ 5.4 km) has and will perform closer approaches to Earth in the near past or future and is larger than OR2.

Radar observations of OR2 in S-band (2380 MHz; 12.6 cm) were obtained with the 305-m radio telescope at the Arecibo Observatory for nine days between 2020 Apr 13 to 23. Optical polarimetric observations were obtained with the Torino Polarimeter (ToPol) in February and April 2020. Photometric observations were obtained during the close 2020 fly-by but also in 2021 and 2022. During those apparitions, it was observable at lower phase angles (i.e. the Sun-object-observer angle) than during the 2020 flyby and they allowed us to fine-tune the shape model with observations at different viewing geometries. During the 2021 apparition, it only reached a magnitude of $V = 21.0$, but was observable at a minimum phase angle of $\alpha = 0.7°$. During the 2022 apparition, it reached a magnitude of $V = 20.6$ with a minimum phase angle of $\alpha = 0.9°$. Our photometric campaign involved 22 different telescopes located at different observatories over a wide range of Earth longitudes.

Results:

We observed OR2 in polarimetry between a large range of phase angle from 30° to 80°. Such observations allowed us to construct a phase polarization-curve spanning the positive polarization branch. Since all of our measurements have been obtained in the positive polarization branch,i.e. with positive values of the $P_{\rm r}$ parameter, we are not able to get precise determination of the inversion angle. However, we still made use of the phase polarization curve to determine its albedo according to the relation linking the slope at the inversion angle with the albedo from [2]. We find an albedo for OR2 of $p_{\rm V} = 0.226^{+0.029}_{-0.034}$. This determination of the albedo should be taken with caution as we do not have any measurements at phase angle lower than the inversion angle.

We also observe that, in the case of OR2, the polarization displays variations that are correlated with its rotation phase. These variations should be triggered by heterogeneities of surface properties such as the albedo, composition, or grain size over the surface of OR2 as polarization is independent on the shape of the observed object.

We used the photometric and radar observations to determine a convex shape model of OR2. The

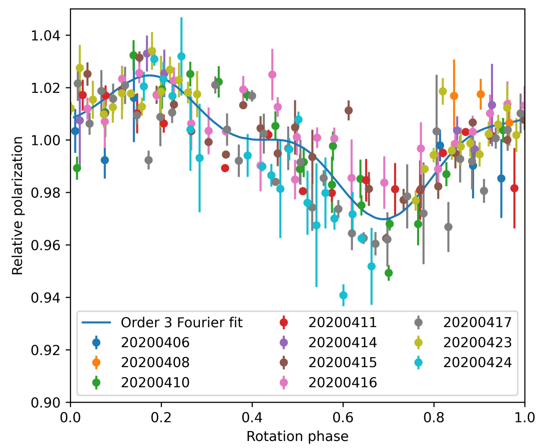

Figure 1: Plot of the relative polarization as a function of the rotation phase of 1998 OR2 (with the different colors corresponding to different nights). The blue continuous line represents the best Fourier fit of order 3.

parameters of the shape model are presented in Table 2. The shape model with example of radar delay-Doppler observations are presented in Fig. 2

Table 2: 1998 OR2 shape model characteristics. The effective diameter (D_{eff}) is the diameter of a sphere with the same volume as the shape model. DEEVE is the dynamically equivalent equal-volume ellipsoid (ellipsoid with the same volume and moment of inertia as the shape model).

Parameter	Value
Maximum dimensions (km)	$2.08 \times 1.93 \times 1.60$
Uncertainties (km)	± 0.10,± 0.10,± 0.03
D_{eff} (km)	1.78 ± 0.10
DEEVE (km)	$2.00 \times 1.87 \times 1.51$
Surface area (km^2)	10.67
Volume (km^3)	3.0 ± 0.5
Sidereal rotation period (hr)	4.10872 ± 0.00001
Ecliptic pole (λ, β)	$(332.3° \pm 5°, 20.7° \pm 5°)$

Discussion:

Spectroscopic observations showed that OR2 is displaying a slope-less spectrum that can be interpreted as belonging to the X-class in the Bus-DeMeo taxonomy [3]. However, [4] suggested that the spectrum of OR2 can be interpreted as an S-type with shock darkened surface or the presence of melts. In this work we find that OR2 is displaying a radar albedo of 0.29 ± 0.08. This value is too high for typical S-type asteroid as it imply that OR2 near surface bulk density is $\rho_{\mathrm{bd}} = 3.2 \pm 0.2$ g cm^{-3}. Such value is too high for a surface composed of silicaceous material with reasonable porosity. We are thus favouring the hypothesis that OR2 is an X-type asteroid with a metallic composition similar to the one of the asteroid (16) Psyche.

Psyche is an M-type asteroids that is believed to be of metallic compositions. However, recent studies suggest that fine-grained silicate are also present on its surface [5]. Several studies also showed that Psyche has an heterogeneous surfaces [6, 7] with region of higher metallic content and regions of higher silicate content. 1998 OR2 would thus be similar to the high silicate content region of Psyche rather than the high metallic ones.

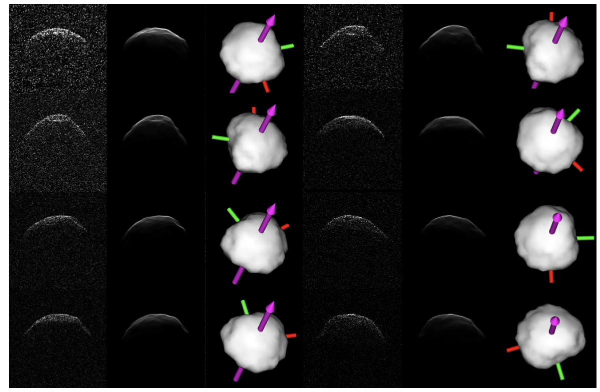

Figure 2: Example of delay-Doppler images for each day of observation of OR2. The left most figure shows the observations, the right most figure the best shape model as viewed during the observations, and the middle figure represents the modelled delay-Doppler image based on the shape model.

Conclusion: We obtained observations of the asteroid 1998 OR2 during its close fly-by to Earth on 2020, but also during its oppositions in 2021 and 2022. These observations showed that the surface of OR2 is heterogeneous and that its composition is similar to the one of the main belt asteroid (16) Psyche.

References: [1] S. H. Pravdo, et al. (1999) *The Astronomical Journal* 117(3):1616. [2] A. Cellino, et al. (2015) *Monthly Notices of the Royal Astronomical Society* 451(4):3473. [3] F. E. DeMeo, et al. (2009) *Icarus* 202(1):160. [4] A. Battle, et al. (2022) *The Planetary Science Journal* 3(9):226. [5] Z. A. Landsman, et al. (2018) *Icarus* 304:58. [6] S. Cambioni, et al. (2022) *Journal of Geophysical Research: Planets* 127(6):e2021JE007091. [7] M. K. Shepard, et al. (2021) *The Planetary Science Journal* 2(4):125.