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# Physical characterization of 2009 WN25: exploring the link with November i-Draconids meteor shower

S. Ieva <sup>1</sup>, <sup>1</sup>★ M. Micheli <sup>1,2</sup>, D. Perna, <sup>1</sup> M. Popescu <sup>3,4,5</sup>, E. Dotto, <sup>1</sup>  
 E. Mazzotta Epifani, <sup>1</sup> S. Antonucci, <sup>1</sup> D. Fulvio <sup>6</sup>, J. R. Brucato, <sup>7</sup> G. Poggiali, <sup>7,8</sup>  
 M. A. Barucci <sup>9</sup> and E. Perozzi <sup>10</sup>

<sup>1</sup>INAF - Osservatorio Astronomico di Roma, via Frascati 33, I-00078 Monteporzio Catone (Roma), Italy

<sup>2</sup>ESA NEO Coordination Centre, Largo Galileo Galilei, 1, I-00044 Frascati (RM), Italy

<sup>3</sup>Instituto de Astrofísica de Canarias (IAC), C/Vía Láctea s/n, E-38205 La Laguna, Tenerife, Spain

<sup>4</sup>Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain

<sup>5</sup>Astronomical Institute of the Romanian Academy, 5 Cuititul de Argint, 040557 Bucharest, Romania

<sup>6</sup>Departamento de Física, Pontifícia Universidade Católica do Rio de Janeiro, Rua Marques de São Vicente 225, 22451-900 Rio de Janeiro, Brazil

<sup>7</sup>INAF - Osservatorio Astrofisico di Arcetri, Largo E. Fermi 5, I-50125 Firenze, Italy

<sup>8</sup>Università degli Studi di Firenze, Dipartimento di Fisica ed Astronomia, I-50125 Firenze, Italy

<sup>9</sup>LESIA, Observatoire de Paris, PSL Research University, CNRS, Univ. Paris Diderot, Sorbonne Paris Cité, UPMC Univ., Paris 06, Sorbonne Université, 5 Place J. Janssen, Meudon Cedex F-92195, France

<sup>10</sup>Agenzia Spaziale Italiana, Via del Politecnico 1, I-00100 Rome, Italy

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## ABSTRACT

The distinction between active and inactive small bodies in the Solar System has become more blended in recent years, with the discovery of objects exhibiting a transient nature. The assumption of activity (past or present) for a small body can be achieved indirectly by its identification as the parent of a meteor shower. In this framework, the near-Earth object (NEO) 2009 WN25 represents an interesting case study. The target, recovered in 2015, is the likely progenitor of a complex stream of meteor shower, and its peculiar high-eccentricity, high-inclination orbit, with an aphelion as far as Jupiter, is responsible for the meteoroid long-term stability. We investigated the physical characteristics of 2009 WN25, by obtaining spectral observations from ESO-NTT and ESO-VLT to constrain its surface composition. We also compared the observed spectra with meteorite data present in the RELAB database and obtained from other laboratories. We found for 2009 WN25 a primitive D-type composition, in agreement with being a cometary progenitor. The low-albedo nature we derived implies a km-sized body, making it one of the few D-type NEOs in this size range. The two spectra we obtained have a similar spectral slope in the 0.5–0.9  $\mu\text{m}$  range, suggesting a possible homogeneous surface. Finally, by comparison with meteorite data we found an association with an unaltered sample of the rare meteorite Tagish Lake. All these evidences strongly support the association with the meteoroid stream.

**Key words:** methods: observational – techniques: spectroscopic – minor planets, asteroids: individual: NEO – minor planets, asteroids: individual: 2009 WN25 – minor planets, asteroids: individual: meteor.

## 1 INTRODUCTION

The classical distinction between asteroids and comets, with the first class being made of rocky and inactive objects and the latter made of icy ones, with a coma and a tail, has become blurry in the last years, with the discovery of transitional objects, like active asteroids (Jewitt, Hsieh & Agarwal 2015) and main belt comets (Hsieh &

Jewitt 2006). Active small bodies are usually identified as such using deep imaging (e.g. Mazzotta Epifani et al. 2017). However, the coma around an object can be hard to detect, particularly for faint/small objects. In this case, activity can be identified indirectly via one of its byproduct.

Ejecta produced by active asteroids or comets can be detected as meteor showers if the active small body moves on an Earth-crossing path. The study of an associated meteor shower can therefore put constraint on the past activity of the parent body. However, if these bodies have low and sporadic activity, the shower confirmation and

\* E-mail: [simone.ieva@inaf.it](mailto:simone.ieva@inaf.it)

parent identification could be challenging. While pioneering works (Jenniskens 2006) have tentatively linked some of these showers to objects in orbits like the Jupiter family comets, the advancement in near-Earth objects (NEOs) and meteor surveys has led to the identification of several meteoroid stream–NEO connections (see e.g. Ye 2018).

2009 WN25 is a NEO in a very peculiar high-inclination, high-eccentricity orbit, which is dynamically cometary but has been seen as inactive for both its 2009 and 2015 apparitions. However, Micheli, Tholen & Jenniskens (2016) have provided evidence that this object is convincingly linked to a complex radiant of meteoric activity, known as November i-Draconids (NID). The dynamics of dust ejected from 2009 WN25 behaves in a way that properly reproduces not just the location of the stream radiant, but also its complex two-dimensional structure, providing further proof of the association.

The dynamics of 2009 WN25 is also extremely interesting. The object is locked in a 2:1 mean motion resonance with Jupiter, which protects it from particularly close encounters with the planet at its aphelion. Only distant encounters can happen, usually in pairs separated by 140 yr. This dynamics is thought to be responsible for the long-term stability of the meteoroid stream, while the shallow pairs of encounters are likely the cause of the complex structure of the meteor radiant. This object is also one of the eight known near-Earth asteroids (NEAs) as of 2019 May<sup>1</sup> to have a Tisserand parameter with Jupiter  $< 2$ , compatible with a possible origin from the outer Solar system.

Over the past years an active effort has been made to recover this object, which culminated in successful recovery observations in August 2015. In the following months, the greater astrometric coverage was essential to improve the knowledge of its orbital dynamics, and the stream creation was simulated in greater detail (see Micheli et al. 2016, for details). This apparition also provided a unique opportunity to collect spectroscopic observations for the object, in order to obtain a complete physical characterization able to strengthen the link with the NID meteor shower. We observed 2009 WN25 at ESO-New Technology Telescope (NTT) with the EFOSC2 instrument, and at ESO-Very Large Telescope (VLT) using X-SHOOTER. With those instruments, we were able to characterize its ultraviolet, visible, and near-infrared wavelength range, with a proper wavelength coverage sufficient to confirm its cometary-like composition, as suggested by Micheli et al. (2016). This work is dedicated to the physical characterization of 2009 WN25. In Section 2, we report the observational conditions and the reduction procedures. In Section 3, we show our data analysis obtained through complementary techniques. Finally, in Section 4 we discuss our results and present our conclusions.

## 2 OBSERVATIONS AND DATA REDUCTION

### 2.1 EFOSC2

At NTT a visible spectrum was obtained using the EFOSC2 (ESO Faint Object Spectrograph and Camera 2) instrument, equipped with the Grism #1, covering the 0.32–1.09  $\mu\text{m}$  range, and the 2 arcsec slit, oriented along the parallactic angle. Data reduction followed standard procedures (e.g. Ieva et al. 2014): bias subtraction and flat-field correction, extraction of the monodimensional spectrum,

wavelength calibration, and extinction correction. The spectrum was normalized at 0.55  $\mu\text{m}$  and the final reflectance was obtained by dividing it by the solar analogue with the closest airmass to the object. Observational conditions are reported in Table 1.

### 2.2 X-SHOOTER

At VLT 2009 WN25 was observed with X-SHOOTER on a clear night. The instrument allowed us to simultaneously obtain a spectrum in the whole 0.4–2.2  $\mu\text{m}$  range, using its three separated arms (UVB, VIS, and NIR) equipped with three slits of 1.3 arcsec, 1.2 arcsec, and 1.2 arcsec width, respectively. Observations were carried out using the standard ABBA pattern, nodding along the slit, also oriented along the parallactic angle.

Data were reduced using the X-SHOOTER pipeline v.2.3.0 (Modigliani et al. 2010), which automatically performs all the calibration steps (bias and dark correction, flat fielding, distortion correction, sky subtraction, wavelength calibration, extinction correction) and finally provides a 2D spectral image for each arm. We extracted the monodimensional spectrum using a procedure specifically optimized for this pipeline in order to increase the SNR and better remove the sky contribution. Due to low instrumental efficiency after 2  $\mu\text{m}$ , particularly for faint targets, we decided to remove the NIR spectrum afterwards. Then, we used the ESO-MIDAS<sup>2</sup> package to compute the reflectance spectrum for each arm, dividing the spectrum of the object by the same monodimensional spectrum of the solar analogue with the closest airmass of the object (HIP22219). Finally, we combined the three arms making use of the overlapping part between two contiguous arms (UVB-VIS and VIS-NIR) for realignment. The spectrum was then normalized at 0.55  $\mu\text{m}$  and smoothed using a median-filtering technique inside a ten-pixel box. The final spectrum obtained at X-SHOOTER is shown in Fig. 1, while observational conditions for this run are also reported in Table 1.

## 3 RESULTS

### 3.1 Taxonomy and spectral slope analysis

Before our observations, there was no physical data available in literature for 2009 WN25. The visible parts of the two spectra we obtained at NTT and VLT are quite similar to each other (see Fig. 1), as supported by the agreement of their slopes in the 0.5–0.9  $\mu\text{m}$  range, reported in Table 1. Since there is no information on the rotational period of 2009 WN25, it is not possible to discriminate if we are sampling two different rotational phases. However, the similarity between the spectra suggests for this body a homogeneous surface.

The two featureless and reddish spectra are consistent with a primitive D-type classification, as suggested by their  $\chi^2$  comparison with all the template spectra portrayed in the DeMeo et al. (2009) taxonomy. For completeness, we also reported a possible match with other featureless and flat taxonomic classes (C- and X-complex). They both show a higher  $\chi^2$ , while they are not able to reproduce the general spectral behaviour, particularly in the visible region (Fig. 1b).

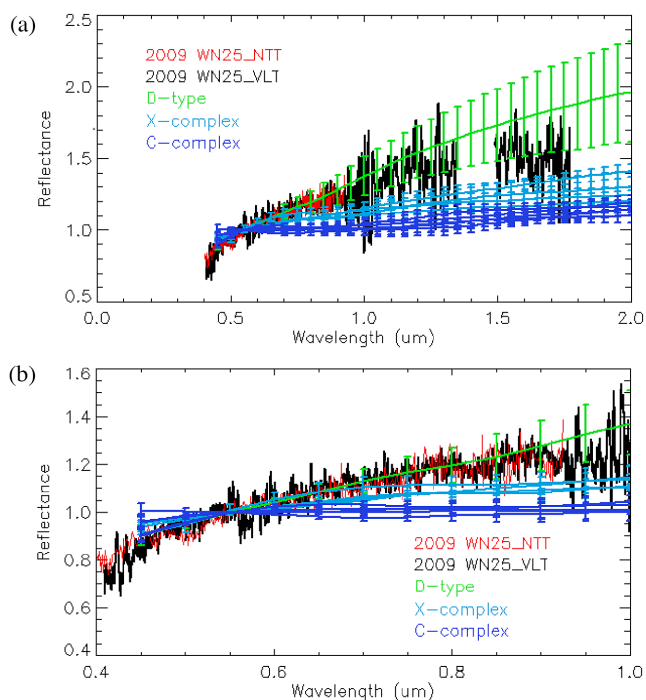
Furthermore, a spectral slope not significantly changing with the increase of phase angle (see Table 1) is compatible with a D-type nature, as Perna et al. (2018) recently found that this taxonomic

<sup>1</sup><https://echo.jpl.nasa.gov/~lance/tisserand/tisserand.html>

<sup>2</sup><https://www.eso.org/sci/software/esomidias/>

**Table 1.** Observational conditions for the two spectroscopic runs at NTT and VLT.

Telescope/ instrument	Date	UT start/end	$V_{\text{mag}}$	$T_{\text{exp}}$ (s)	Airmass	Solar analogue (airm)	Phase angle $\alpha$	Spectral slope (%/0.1 $\mu\text{m}$ )
NTT/ EFOSC2	2015 Nov 7	06:29–07:15	18.8	7 x 400	1.206–1.096	HD62558 (1.10)	61.2	$7.56 \pm 0.23$
VLT/ X-SHOOTER	2015 Dec 6	03:05–04:55	20.4	9 x 500 UV 9 x 600 VIS 9 x 600 NIR	1.555–1.476	HIP22219 (1.59)	52.3	$7.17 \pm 0.17$



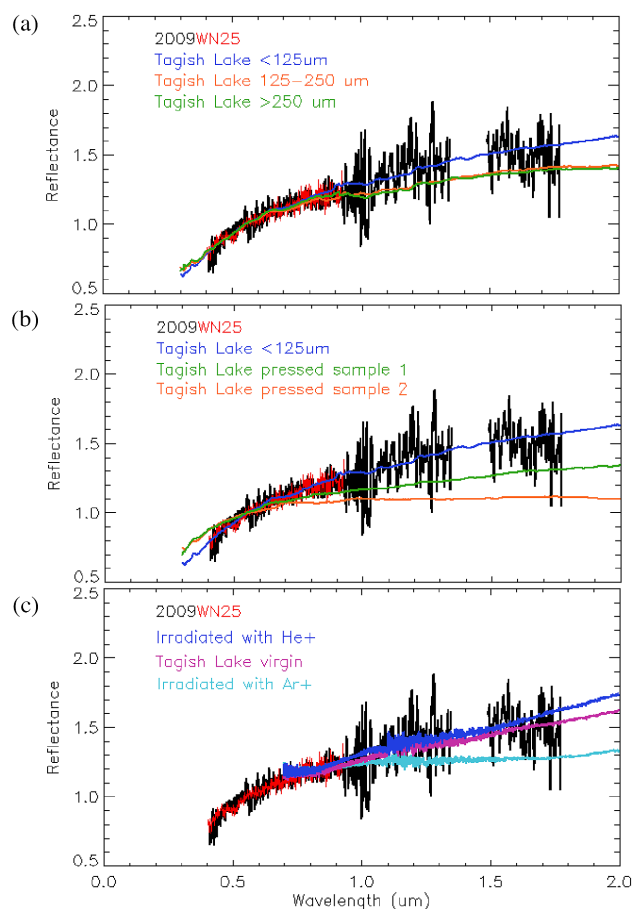
**Figure 1.** (a) The two spectra taken for 2009 WN25, from NTT and VLT, together with the template spectra (from top to bottom) for D-type objects, X- and C-complex objects considered in DeMeo et al. (2009). Spectral regions affected by strong atmospheric absorption or low instrumental efficiency have been cut out, while spectra has been normalized at  $0.55 \mu\text{m}$ ; (b) the same spectra considered above, focusing only in the visible ( $0.4\text{--}1.0 \mu\text{m}$ ) region. It is possible to appreciate that the D-type template, the one with the lowest  $\chi^2$  among the taxonomic classes ( $2.16 \times 10^{-4}$ ), is able to better reproduce the overall spectral behaviour of 2009 WN25.

class is not strongly affected by the so-called ‘phase reddening’. Assuming an average albedo for this taxonomic class (e.g. 0.067, from Ryan & Woodward 2010) we estimate for this target a diameter of about 1.1 km, making it one of the largest<sup>3</sup> D-type NEOs characterized, as of 2019 May.

### 3.2 Comparison with meteorites

We used the obtained spectra of 2009 WN25 to investigate the surface characteristics of the target, by means of a comparison with meteorite spectra obtained in laboratory. This method is typically affected by differences between the experimental conditions in the laboratory and in ground-based observations: for example,

<sup>3</sup><http://neo.ssa.esa.int/search-for-asteroids>



**Figure 2.** Comparison between the spectra obtained for 2009 WN25, and the best suitable meteorite found on the RELAB database, the Tagish Lake carbonaceous chondrite. (a) We shown here three powder samples of different grain sizes available on the RELAB database: from top to bottom  $< 125 \mu\text{m}$ ,  $125\text{--}250 \mu\text{m}$  and  $> 250 \mu\text{m}$ ; (b) we reported the unaltered sample with a grain size  $< 125 \mu\text{m}$ , together with two pressed samples of the Tagish lake meteorite; (c) we compared our data with spectra of Tagish Lake meteorite obtained before (in the middle) and after ion processing with  $\text{He}^+$  (top) and  $\text{Ar}^+$  (bottom), as reported in Vernazza et al. (2013).

laboratory spectra are usually taken at room temperature, while asteroids experience a whole range of different temperatures, which can produce a number of significant spectral effects (see e.g. Moroz, Schade & Wäsch 2000). Nevertheless, these effects generally produce a variation of the position and the depth of the absorption features possibly present in the spectrum, and in case of featureless asteroids (e.g. D-types) should only moderately affect the slope, which can be therefore considered diagnostic for a suitable meteorite comparison. Thus, we are confident that this

**Table 2.**  $\chi^2$  comparison between our spectrum and samples of the Tagish Lake meteorite from the RELAB database.

Spectrum	$\chi^2$	Sample ID	Filename
Tagish Lake < 125 $\mu\text{m}$	$1.75 \times 10^{-3}$	MT-MEZ-011	c2mt11
Tagish Lake 125–250 $\mu\text{m}$	$4.57 \times 10^{-3}$	MT-S1S-237B	c1mt237b
Tagish Lake > 250 $\mu\text{m}$	$4.69 \times 10^{-3}$	MT-S1S-237C	c1mt237c
Tagish Lake pressed sample 1	$5.07 \times 10^{-3}$	MT-TXH-025-L0	bkr1mto2510
Tagish Lake pressed sample 2	$1.34 \times 10^{-2}$	MT-TXH-025-L2	c1mt2512

kind of comparison can give us an indication of the composition of the asteroid surface.

Using the M4AST tool<sup>4</sup> we compared, through a  $\chi^2$  minimization method, our observed spectra with the whole sample of meteorite data considered in the RELAB<sup>5</sup> database, as of 2019 May. We took into consideration the meteorite spectrum that not only shows a lower  $\chi^2$  value, but is also able to better reproduce the overall spectral behavior of 2009 WN25. In particular, we focus on the visible part, the one confirmed from both our observations at NTT and VLT. The best meteorite match in the overall 0.4–2.0  $\mu\text{m}$  range is represented by a relatively unaltered sample of the Tagish Lake meteorite (Fig. 2). This ungrouped carbonaceous chondrite is one of the three meteorites extensively linked to D-type asteroids (see e.g. Barucci et al. 2018 and references therein), indirectly confirming the taxonomic classification we inferred for 2009 WN25.

We found a good agreement with a Tagish Lake powder sample of a grain size < 125  $\mu\text{m}$ , while spectra composed prevalently of larger grains available on the RELAB database (125–250  $\mu\text{m}$  and > 250  $\mu\text{m}$ , reported in Fig. 2a) show a lower reflectance in the VIS-NIR region and a higher  $\chi^2$  value (Table 2). This could imply that the surface of 2009 WN25 is prevalently composed of relatively unaltered material made of very small grain sizes. We also compared our spectra with Tagish Lake samples available in the form of pellet/pressed powder (Fig. 2b): the overall worse match respect to the unpressed sample (Table 2), particularly regarding the visible spectral slope, and the lower reflectance values in the NIR range, suggests that 2009 WN25 does not have a compacted surface (e.g. like the one present on Itokawa; Saito et al. 2006), but more probably it is covered by fine loose grains. Finally, in order to infer possible modification processes that happened on the asteroid surface, we compared our obtained spectra of 2009 WN25 with those of Tagish Lake reported in Vernazza et al. (2013), before and after ion processing simulating space weathering effects. As shown in Fig. 2(c), the spectrum of the virgin sample shows a better agreement with our target respect to the irradiated ones, especially when compared to the Tagish Lake sample strongly processed by Ar irradiation. This suggests that the surface of 2009 WN25 should not have suffered a great level of space weathering.

#### 4 DISCUSSION AND CONCLUSIONS

We obtained the physical characterization for the peculiar NEO 2009 WN25, which has been recently identified as the progenitor for the NID meteor shower. We observed it during two separated runs at NTT and VLT in 2015 November and December, obtaining a 0.4–1.0  $\mu\text{m}$  visible spectrum and a 0.4–2.0  $\mu\text{m}$  UVIS-NIR

spectrum. The two spectra are in good agreement with each other, showing a similar spectral slope in the 0.5–0.9  $\mu\text{m}$  range and a possible homogeneous composition, although the determination of its rotational period is necessary to confirm it.

Our physical analysis poses 2009 WN25 in the group of D-type NEOs. These bodies are mostly found in the outer main belt, in particular in the Jupiter Trojan population, and show colours and spectral behaviours similar to some Centaurs and Trans-Neptunian Objects (TNOs; Barucci et al. 2005). Moreover, Licandro et al. (2018) has recently proved that asteroids in cometary orbits (ACOs) are mostly classified as D-type objects. D-type NEOs are quite rare among physical surveys (Carry et al. 2016; Barucci et al. 2018), and they are widely believed to have formed in the outer Solar System, and then scattered inward. 2009 WN25 is even rarer, as it is one of the largest D-type NEOs discovered up to now.

D-types are also considered extremely primitives, being rich in organic compounds and volatiles (Brown 2016). They are crucial to investigate processes and materials that originated life on our planet. They are thought to have played a key role in the delivery of water (Izidoro et al. 2013) and organic material (de Marcellus et al. 2011) to the early Earth, contributing to the prebiotic reactions that ultimately lead to the emergence of life. The discovery of a large L-enantiomeric excesses on the Tagish Lake meteorite (Glavin et al. 2012) strongly supports this hypothesis.

Our meteorite comparison indicates that 2009 WN25 has a spectral behaviour that closely resembles a sample of the Tagish Lake meteorite with grain size < 125  $\mu\text{m}$ , suggesting an asteroidal surface covered by a loose layer of small grains. The relatively pristine condition of our target surface is also indicated by the absence of a great level of space weathering, suggested by our comparison with the spectra of Tagish Lake reported in Vernazza et al. (2013), before and after ion processing. It should be noted that only three small and rather fragile meteorites have been linked to D-type asteroids (Hiroi, Zolensky & Pieters 2001; Nakamura et al. 2013; Yamanobe, Nakamura & Nakashima 2018), indicating that D-types could be composed of particularly primitive material that difficultly survives to terrestrial atmospheric entry in large macroscopic samples. Moreover, two of these meteorite samples (Tagish Lake and WIS91600) show similar oxygen isotopic composition, carbon content and elemental composition (Yabuta et al. 2010), supporting the idea that these two meteorites are related and they could come from the same or a similar parent body.

Finally, the extreme fragility of those primitive meteorites is also suggested by the spectral match between D-type asteroids and interplanetary dust particles (IDPs; Vernazza et al. 2015). IDPs have a very fluffy aggregate nature, similar to that observed in the coma of comet 67P/Churyumov-Gerasimenko (Schulz et al. 2015). The fact that we found for 2009 WN25 a visible spectral slope comparable with values for inactive Jupiter Family Comets (JFC) nuclei ( $7.2 \pm 2.0$  per cent/0.1  $\mu\text{m}$ , Jewitt 2005) should be regarded

<sup>4</sup><http://m4ast.imcce.fr/>

<sup>5</sup><http://www.planetary.brown.edu/reldata/>



in the scenario of closely related origin for D-type asteroids and comets.

All our results strongly support the scenario of the association of 2009 WN25 with the NID meteoroid stream, depicted by Micheli et al. (2016). Further analysis on other meteoroid parent bodies (e.g. those listed in Kokhirova et al. 2018; Ye 2018) is desired, to better explore the association and the genetic link between primitive NEOs and meteoroid stream progenitors.

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