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Small D-type asteroids in the NEO population: new targets for space missions

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ABSTRACT

In the framework of the Near Earth Objects (NEOs) observational campaign carried out within the NEOShield-2 project, we identify nine new small D-type asteroids with estimated diameter less than 600 m. The link with meteorites for this class of asteroids is weak and the best fit obtained is with the Tagish Lake meteorite for seven of them. D-type asteroids are believed to contain the most pristine material of the Solar system and could have delivered the pre-biotic material to the Earth. Our results double the known sample of the D-types in the NEO population and triple the candidates of this class for a sample-return mission (at very low ΔV). Our finding increases considerably the number of targets for sample-return mission. A sample-return mission to a D-type asteroid will provide a major progress in understanding the early history of the Solar system and to investigate the origin of life on the Earth.

Key words: techniques: spectroscopic – minor planets, asteroids: general.

1 INTRODUCTION

D-type asteroids, considered the most primitive among the asteroid population, are supposed to contain organics and volatiles. This type of asteroids are the most abundant beyond the outer edge of the main belt, in particular in the Trojan population (L4 and L5 Lagrangian points of Jupiter), and are rarely detected in orbits close to the Sun. Their colour indexes and spectral slope and albedo are very similar to part of the Centaurs and the trans-Neptunian object population (Barucci et al. 2005) and to those of comets (including the comet 67P/Churyumov–Gerasimenko; Fornasier et al. 2015). They are supposed to be formed in a region of the solar nebula rich in frozen volatiles, possibly as far as the trans-Neptunian objects, and have been subsequently captured in their present locations as a consequence of the migration of the giant planets (Levison et al. 2009). From dynamical models it appears clearly that the current position of the D-type asteroids does not directly relate to where they formed.

The most widely accepted models (e.g. Morbidelli et al. 2005) invoke the capture of Trojans from a primordial trans-Neptunian disc. Following the 'Grand Tack' model (Walsh et al. 2011), the planetary migrations early in the history of the Solar system allowed to mix the small bodies so that those that formed at large heliocentric distance can be now closer to the Sun. Vokrouhlický, Bottke & Nesvorný (2016), on the basis of their simulations, predicted the capture of trans-Neptunian planetesimals (as D-type asteroids) in the asteroid main belt. According to Fernández, Sheppard & Jewitt (2003) the surfaces of D-types are probably more like those of active and post-active comets. Water ice was undetected in the spectra of Trojan D-types even if they are believed to be formed in a region rich in frozen volatiles (Dotto et al. 2008): spectral features indicate that D-types contain abundant organic materials and fine anhydrous minerals, but no spectral features related to the presence of ices are present. In the last years water ice was detected in few asteroids like Themis (Campins et al. 2010; Rivkin & Emery 2010), Cybele (Licandro et al. 2011), and Ceres (Combe et al. 2016; De Sanctis et al. 2016). Only recently Brown (2016) was able to detect in part of the Trojan population, the 3.1 µm absorption band associated with N–H stretch features and some others bands to organics.

The interpretation of these red spectra is difficult and only three meteorites [Meteorite Hills (MET) 00432, Wisconsin Range (WIS) 91600, and Tagish Lake] have been proposed to originate from D-type asteroids (Brown et al. 2000; Hiroi, Zolensky & Pieters

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Table 1. Log of observations for the D-types observed by the NEOShield-2 survey. The asteroid designation, the orbit type (AT-Aten, AM-Amor, and AP-Apollo), semimajor axis, eccentricity, inclination, mid-UTC of observation, the apparent magnitude (V), the phase angle (α), the airmass, the total integration time (Exp.), and the corresponding used solar analogue are presented.

Designation	Orbit	a (au)	e	i (°)	UTC	V_{mag}	α (°)	Airmass	Exp. (s)	Solar analogue
420262	AP	1.587	0.42	17.1	2015-06-09T00:31	20.2	30	1.02	2 × 1050	Land 1021081
467352	AT	0.949	0.33	23.9	2015-06-09T02:40	19.9	32	1.07	2 × 900	Hip 056139
2009 CV	AP	1.116	0.15	0.9	2016-06-29T00:26	19.2	49	1.03	1 × 800	Hip 52311
2009 DL46	AM[a]	1.461	0.31	7.9	2016-06-30T04:03	19.5	36	1.24	2 × 1200	HD 146997
2013 YE38	AP	2.066	0.63	34.2	2016-11-30T08:19	18.1	57	1.10	1 × 900	HD 20926
2015 LN21	AM	2.092	0.49	8.6	2015-07-19T09:22	20.0	54	1.43	2 × 1200	Land 115271
2016 WL7	AP	1.057	0.19	10.0	2016-11-29T02:06	18.9	64	1.11	2 × 900	HD 6400
2016 WZ8	AP	1.502	0.34	4.1	2016-11-30T04:59	19.1	6	1.46	1 × 600	HD 20926
2017 DL34	AM	1.345	0.25	8.2	2017-02-28T05:22	20.1	9	1.15	2 × 1600	HD 91640

Note. [a]Potentially hazardous asteroid.

2001; Nakamura et al. 2013). Vernazza et al. (2015), with the additional analysis of the infrared (IR) spectra, found the best spectral match of D-type asteroids with those of chondritic porous interplanetary dust particles (CP-IDPs; Bradley et al. 1996).

These tiny dust particles, particularly rich in carbon, are widely considered the most primitive materials currently available. The similarity with CP-IDPs supports the hypothesis that D-type asteroids consist of very primitive carbon-rich friable material originated from cold outer solar nebula or interstellar medium (Alexander et al. 2007, 2010; Yabuta et al. 2010) and very poorly sampled in available ground collections.

The study of these most primitive asteroids is not only relevant for our understanding of the origin of the Solar system, and how it evolved, but also to investigate the key processes and materials that shaped the origin of life on the Earth. Current exobiological scenarios for the origin of life invoke an exogenous delivery of matter capable of triggering the pre-biotic synthesis of biochemical compounds on the early Earth. Altwegg et al. (2015) reported the deuterium-to-hydrogen (D/H) ratio of the comet 67P to be about three times the terrestrial value supporting models advocating that primitive asteroids could be the origin of the oceans on the Earth and the terrestrial atmosphere. The origin of life is essentially still unknown and vividly debated. The inner Solar system was heavily bombarded from around 4.6 to 3.8 billion years ago by comets and asteroids, which may have brought pre-biotic organic molecules to the early Earth (e.g. Schidlowski 1988; Chyba & Sagan 1992). This coincides when life could have emerged in the early Earth ∼4 to ∼3.5 billion years ago (Schopf 1993; Rosing 1999; Westall et al. 2011). Therefore, in order to assess the possible contribution of extraterrestrial organics to the origin of life it is crucial to determine the origin, diversity, and complexity of organic species in a primitive asteroid for an in-depth understanding of organic chemistry processes in space and their evolutionary time-scales.

For their supposed content of primitive organic, and their importance on the origin of life on Earth, D-type asteroids are considered to be the most appealing targets for space missions. *Lucy* space mission by NASA on Discovery Program (Levison & Lucy Science Team 2016) will be launched on 2021 October to Trojan D-type asteroids and many other projects of sample-return missions have been studied in Europe (Barucci et al. 2012; Barucci 2014; Franchi et al. 2017) or are under study in China (Liao et al. 2017).

Near Earth Objects (NEOs) are an evolving population with a lifetime of about few million years and are continuously replenished from major small bodies reservoirs (Morbidelli et al. 2002). We concentrate this work on nine new detected D-type asteroids observed in the NEO population. The results presented in this work are part of the NEOShield-2 project for which 147 NEOs of small size have been observed by spectroscopy and taxonomy classified (Perna et al. 2018).

2 NEOSHIELD-2 OBSERVATIONS AND ANALYSIS

In the framework of the NEOShield-2 observational campaign we present in this paper new spectra of nine asteroids in Table 1. The orbital elements (a, e) of the observed asteroids are reported in Fig. 1. The NEOShield-2 project has been funded by European Commission (2015–2017) in the framework of the EU H2020 programme following the first NEOShield (2012–2015) that principal aim was to investigate the most promising mitigation techniques of an asteroid impact risk. One of the main objectives of the NEOShield-2 project (Barucci et al. 2017b; Perna et al. 2018) was to characterize, by complementary techniques, a large number of small NEOs to provide physical and compositional characterization giving priority to potential space-mission targets.

Our team obtained a GTO program at ESO with an allocation of 30 observing nights at the 3.6-m New Technology Telescope in the La Silla (Chile) to characterize the composition of the small population of near-Earth asteroids. Priority has been given to small asteroids and to potential space-mission targets, optimized for mitigation or exploration missions.

The observations were obtained using the ESO Faint Object Spectrograph and Camera version 2 (EFOSC2) instrument with the Grism#1 diffraction element covering the spectral interval

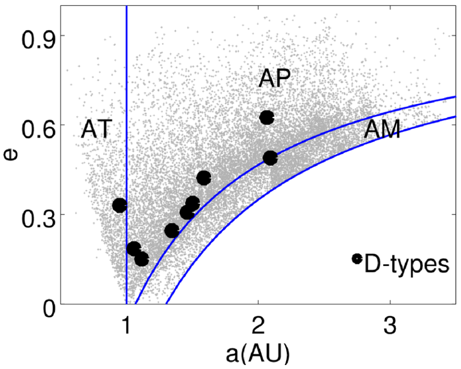

Figure 1. The detected NEOShield-2 observed D-type asteroids in (a, e) representation of NEOs (a is the semimajor axis and e the eccentricity). The continuous lines are the limits of different orbital classes (AM-Amor, AP-Apollo, and AT-Aten).

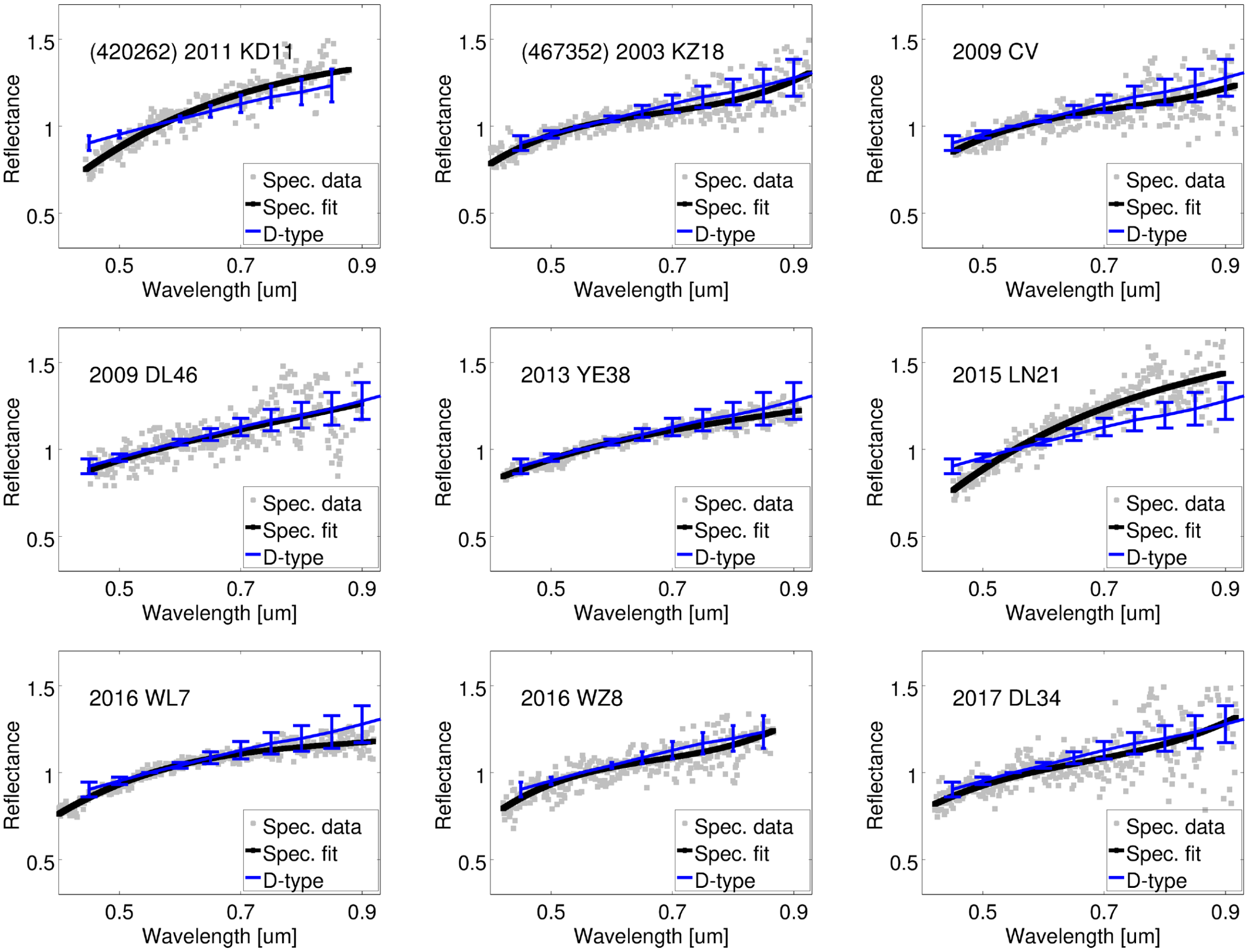

Figure 2. Visible spectra of (420262) 2011 KD11, (467352) 2003 KZ18, 2009 CV, 2009 DL46, 2013 YE38, 2015 LN21, 2016 WL7, 2016 WZ8, and 2017 DL34 are shown in grey. All spectra are normalized to 0.55 μm. A splinefit function (piecewise third-order polynomial fit) of the data is shown in black. The D taxonomic mean spectrum and its standard deviation defined by DeMeo et al. (2009) are shown in blue for comparison.

0.4–0.92 μm with a resolution of $R \approx 500$. On each night we observed several G2V solar analogues at similar airmasses of the observed asteroids to avoid artefacts caused by solar analogue selection. The data reduction followed the standard procedure and is described in detail in Perna et al. (2018). The details of observations of the new D-type observed objects are presented in Table 1 as well the used solar analogues for the reported spectra.

The D-types are easily distinguishable by the red featureless spectrum that is almost linear with the steepest slope compared with X-complex and C-complex types. Nevertheless, each object has been classified by performing curve matching with the visible part of the template spectra defined by Bus–DeMeo scheme (DeMeo et al. 2009) using the M4AST online tool (Popescu, Birlan & Nedelcu 2012). In this paper we report those for which the least mean square differences between the observed spectra and the taxonomic templates correspond to the D-type. The choice for Bus–DeMeo schema was motivated by the fact that it better describes the reflectance range for the D class in the visible part as for defining it, DeMeo et al. (2009) used spectra over visible and near-infrared ranges.

The D and T classes were recognized also by previous taxonomies (e.g. Tholen 1984; Barucci et al. 1987; Tholen & Barucci 1989). Thus, for additional check, we also compared the observed objects with the taxonomy by Tholen & Barucci (1989).

3 RESULTS

We identified nine new D-type asteroids as a by-product of the NEOShield-2 survey. We doubled the sample of D-types in the whole NEO population already observed. The spectra of the observed asteroids with the typical mean D-type class and relative standard deviation are reported in Fig. 2.

For comparison, the EARN[1] data base (which contains published data, including major surveys, for all known NEOs and the corresponding bibliographic references) reports taxonomic classification for 739 NEOs (as of 2018 January). In this sample they report five D-types and four T-types. The sample of objects with $H \geq 20$ is of 118, and contains only two D-types (2001 SG286, 2002 AT4). By using Sloan Digital Sky Survey (SDSS), Carry et al. (2016) classified 230 NEOs having absolute magnitudes between 12 and 23. They found six D-types in their sample.

A distribution by taxonomic classes is strongly affected by selection biases in favour of high albedo objects (e.g. Jedicke, Larsen & Spahr 2002). Because of the small sample (about ~270 objects including our NEOShield-2 data) of NEOs with $H \geq 20$ any attempt to debias is strongly affected by the poor statistics.

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[1] http://earn.dlr.de/nea/

Table 2. The *H* magnitude, estimated diameter (assuming a mean albedo of 0.048), spectral slope measured in per cent/0.1 μm, and the mean squared distance from D-types from DeMeo et al. (2009) are reported.

Designation	*H*	Diam. (m)	Slope	SlopeErr	Dist.
420262	20.1	580	13.02	0.37	1.7E-03
467352	21.3	330	6.79	0.29	2.7E-04
2009 CV	24.3	80	7.29	0.35	1.9E-04
2009 DL46	22.0	240	8.82	0.46	1.2E-05
2013 YE38	20.1	580	7.55	0.15	1.6E-04
2015 LN21	23.0	150	15.35	0.37	3.4E-03
2016 WL7	24.3	80	7.18	0.17	5.7E-04
2016 WZ8	28.4	10	6.85	0.36	2.1E-04
2017 DL34	25.9	40	8.92	0.50	4.1E-04

In order to confirm our newly discovered D-types we computed the spectral slope (Table 2) and we compared the slopes defined over the visible region with the literature data. These slopes correspond well to the D-type asteroids (which is about 8.09%/0.1 μm for D class) as shown in Fig. 2. For comparison, the average slopes measured by Fornasier et al. (2010), about 3.77 ± 1.20 per cent/0.1 μm, and Neeley et al. (2014), about 4.66 ± 1.68 per cent/0.1 μm, for M-type asteroids are significantly lower than the values shown in Table 2. One asteroid (2015 LN21) shows visible spectra even more red than typical D-type. As discussed in Barucci et al. (2017a) and Perna et al. (2018), the phase reddening, a physical process that increases the visible spectral slope with the increasing phase angle, is less significant for D-type asteroids than for other asteroid types. This has been confirmed, even if in the analysis of only few data, by Lantz, Binzel & DeMeo (2018). This latter work, analysing also the effect of space weathering (SpWe), argued that SpWe can make the spectral slopes less red for this type of objects, decreasing the capability to detect members of the D-type population.

The equivalent diameters, reported in Table 2, are computed by taking into account the mean albedo (0.048) of the assigned taxonomic class (Mainzer et al. 2011) and the measured absolute magnitude. From our analysis, we observed an excess of presence of D-type for small objects, considering also the bias effect on observing these very low albedo objects and consequently much fainter. Our observations double the number of the D-type objects among the NEOs, increasing in particular the number of D-types of small size. To increase the consistency of the interpretation we compared the spectra of these nine D-type objects with those of meteorites present in the RELAB data base. The best matches have been computed and reported in Table 3. We compare all the data with the Tagish Lake samples (see details in Table 3) that represent the best matches for seven of them, while in two cases other carbonaceous chondrite meteorites seem to match slightly better. The samples that best match the spectra are reported in Fig. 3.

In this new set of data, we select all the targets classified as D-type and with low ΔV. We identify six D-type asteroids with $\Delta V < 7$. We complemented our set using the data existing in the EARN data base and two other objects already presented by Perna et al. (2017, 2018). We searched for asteroids unambiguously classified as D or T types and with low albedo (when it was available). The T-type was included because the D-type reflectance range (as defined by DeMeo et al. (2009) in the visible region covers also this taxonomy. We report in Table 5 these new objects with those available in literature. We note that near-infrared data are available only for two of these candidates (52381) 1993 HA (Perna et al. 2017) and 2001 SG286 (Popescu et al. 2011), which confirm their classification. Compared with EARN data base, our sample increases in an important way the existing number of D/T types mission candidates. Among these, 2009 CV, 2016 WZ8, 2017 DL34, and 2009 DL46 presented in this paper, (52381) 1993 HA (Perna et al. 2017) and 2011 AM24 (Perna et al. 2018) require a ΔV below 5.5 km s^{-1} making them the best candidates currently known for a sample-return mission to a D-type primitive asteroid. An accurate orbit computation of the new discovered objects (such as 2016 WL7, 2016 WZ8, and 2017 DL34) requires additional astrometric observations, as we observed them just after their discovery.

4 DISCUSSION AND CONCLUSION

We identified nine new asteroids, in the NEO population, classified as D-type with very small diameter (estimated to be less than 600 m in diameter). The number of the total found D-type objects in the sample observed in the framework of NEOShield-2 project is about 7 per cent of the observed population (Perna et al. 2018). These asteroids were considered relatively rare within NEOs and are believed to be the most primitive ones in the Solar system. By comparing the obtained spectra with the RELAB data base we found that the spectral curves of Tagish Lake are the best matches for seven objects and second match for another two (Table 3). The good analogy found with Tagish Lake meteorite for the visible spectra is however not sufficient to strongly constrain the composition.

Our results double the known sample of the D-types in the NEO population, and suggest that D-types are much more

Table 3. Comparison with spectra of carbonaceous chondrites from RELAB data base. The asteroid designation, the distance between the spectra in terms of mean squared differences (Dist.), the sample ID, the file name corresponding to RELAB spectrum, the sample name, the size of the grains of the meteorite sample, and the origin of the meteorite are provided. The best matches are shown. In two cases a sample of Tagish Lake meteorite was the second match – these are shown for comparison.

Asteroid	Dist.	Sample ID	File name	Sample name	Size (μm)	Origin
420262	3.1E-03	MP-TXH-050	C1MP50	PCA91084 8	<125	Pecora Escarpment Antarctica
	3.4E-03	MT-TXH-024	BKR1MT024	Tagish Lake heated at 100° C	<125	Tagish Lake Canada
467352	3.1E-03	MT-MEZ-011	C2MT11	Tagish Lake ET01-B	<125	Tagish Lake Canada
2009 CV	1.5E-03	MT-MEZ-011	C2MT11	Tagish Lake ET01-B	<125	Tagish Lake Canada
2009 DL46	8.7E-03	MT-TXH-024	BKR1MT024	Tagish Lake heated at 100° C	<125	Tagish Lake Canada
2013 YE38	5.7E-04	MT-MEZ-011	BKR2MT011	Tagish Lake ET01-B	<125	Tagish Lake Canada
2015 LN21	4.7E-03	MT-TXH-020	BKR1MT020	Tagish Lake ET01-B heated at 300° C	<125	Tagish Lake Canada
2016 WL7	7.9E-04	MA-ATB-063	BKR1MA063	Migei 4c 125–200 μm	125–200	Russia
	9.1E-04	MT-MEZ-011	LAMT11	Tagish Lake ET01-B	<125	Tagish Lake Canada
2016 WZ8	3.2E-03	MT-MEZ-011	BKR2MT011	Tagish Lake ET01-B	<125	Tagish Lake Canada
2017 DL34	1.1E-02	MT-TXH-024	BKR1MT024	Tagish Lake heated at 100° C	<125	Tagish Lake Canada

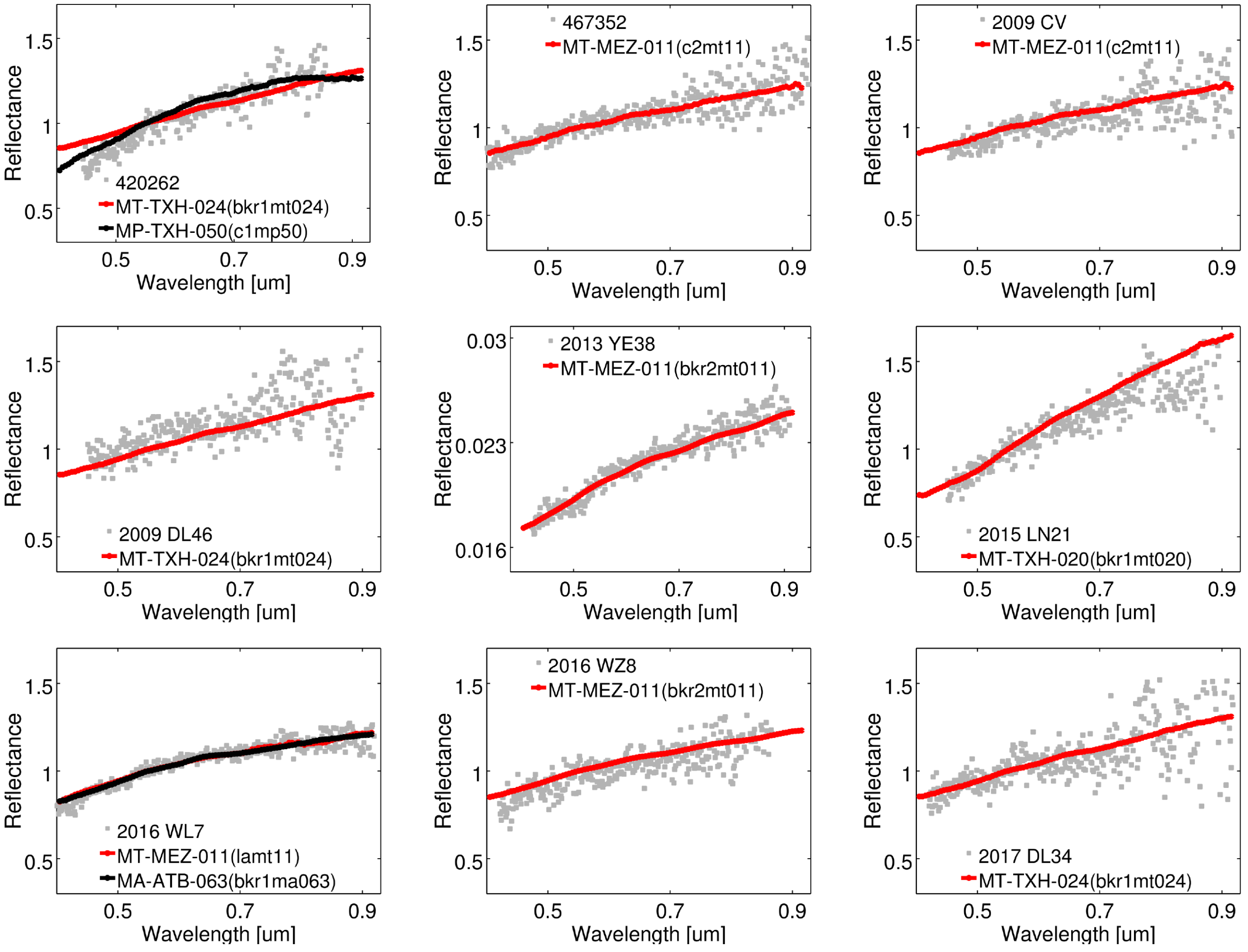

Figure 3. Plot of the asteroid spectra versus the best matched spectrum of carbonaceous chondrites from RELAB data base. The asteroid is identified by its designation and is plotted in grey, the RELAB spectrum corresponding to Tagish Lake is shown in red and it is referenced by its sample ID and file name. For the two cases were the best match was a different meteorite we plot their spectrum in black. See Table 3 for additional details. All spectra are normalized to 1 at 0.55 µm.

abundant than observed by previous surveys of NEOs and main belt asteroids. This difference can be explained as (i) limitation on the interpretation of the visible spectra (peculiar cases of the asteroids 2015 LN21 and/or 420262, even if no other classifications are possible); (ii) there is a higher fraction of D-types among small asteroids; and (iii) preferential dynamical delivery of D-types to near-Earth orbits, possibly due to recent breakup event(s) of large D-type asteroid(s). The excess found in the NEO population of D-type objects with small diameters is in fact in good agreement with the weakness of the material of this type of asteroids (Granvik et al. 2016).

Our results support those of Vokrouhlický et al. (2016) who predicted that D-type asteroids found in the near-Earth on low ΔV orbit with Earth are possible surviving relics from the same population source of trans-Neptunians objects, suggesting that Tagish lake meteorite is likely a fragment of trans-Neptunian object population. However this meteorite has experienced considerable aqueous alteration, and therefore is likely distinct from anhydrous D-type material. Questions remain about the composition of D-type asteroids and the link with existing meteorites.

In order to derive a complete characterization of these objects more observations are required at large wavelength range, and in particular the albedo determination. Unfortunately, the opportunities to observe these types of objects are rare. To obtain additional spectroscopic and albedo data, the approximative observational opportunities for the next 10 yr (2018–2028) are reported in Table 4, assuming an apparent V magnitude brighter than 20.0.

Table 4. Approximative opportunities for observing low ΔV D-types during the next 10 yr (2018–2028). A cut-off of V brighter than 20.0 is considered for the apparent magnitude. The dates when the object is observable and the brightest magnitude (V_b) is provided.

Asteroid	Dates	V_b (mag)
52381	2019 Mar. 22–2019 May 16	19.2
	2025 Jul. 21–2025 Sep. 06	19.5
162998	2025 Sep. 03–2026 May 10	18.6
2001 SG286	2020 Sep. 11–2020 Nov. 06	18.6
	2028 Apr. 04–2028 May 26	16.8
2011 AM24	2020 Feb. 05–2020 Mar. 07	19.6
	2024 May 08–2025 Jan. 16	16.1

A sample-return mission to a D-type asteroid will provide the key for understanding the early history of the Solar system and the processes that led to the formation of planetary systems (Barucci et al. 2012). The selection of good candidates for asteroid sample-return space mission is difficult as there are very few asteroids classified

Table 5. The D/T type candidates for a space-mission rendezvous. The asteroid number and provisional designation, the orbit type (AM-Amor and AP-Apollo), the ΔV budget (in km s^{-1}), the spectral interval (Vis – visible region; NIR – near-infrared region), the taxonomic classification, the absolute magnitude (H), the equivalent diameter (in m) assuming a mean albedo of 0.048, and the minimum orbital intersection distance (MOID) with the Earth is provided.

Number	Name	Orbit	ΔV (km s^{-1})	Spectra	Taxon	H (mag)	Diam. (m)	MOID (au)	References
–	2009 CV	AP	4.26	Vis^a	D	24.3	80	0.01154	
–	2016 WZ8	AP	4.81	Vis^a	D	28.4	10	0.01147	
–	2017 DL34	AM	4.96	Vis^a	D	25.9	40	0.04691	
–	2011 AM24	AM	5.02	Vis^a	D?	20.4	505	0.00989	(1)
–	2009 DL46	AM	5.08	Vis^a	D	22.0	240	0.01233	
52381	1993 HA	AM	5.30	Vis+NIR^a	D	20.0	607	0.16887	(2)
–	2002 AT4	AM	5.55	Vis	D	21.2	349	0.04220	(3), (4)
162998	2001 SK162	AM	5.57	Vis	T/D	17.9	872	0.03005	(3), (4), (5), (6)
–	2001 SG286	AP	5.60	Vis+NIR	D	20.9	401	0.00512	(3), (4), (7)
–	2001 YE1	AP	5.84	Vis	T	20.8	449	0.05938	(4)
–	2016 WL7	AP	6.05	Vis^a	D	24.3	80	0.01488	
–	2015 LN21	AM	6.35	Vis^a	D	23.0	150	0.07002	

Note. ^{a}The data obtained by NEOShield-2 survey.

References: (1) Perna et al. (2018); (2) Perna et al. (2017); (3) Binzel et al. (2004a); (4) Binzel et al. (2004b); (5) Thomas et al. (2014); (6) Ye (2011); and (7) Popescu et al. (2011).

as D/T types among NEO population for a cheap space mission, which satisfy the $\Delta V < 7$ km s^{-1} requirements for an easy/short space mission (Binzel et al. 2004a). The results presented in this paper triple the number of NEOs classified as D-types that satisfy the ΔV requirements for sample-return missions and will be of great support on the selection of targets for future space missions. Moreover, as shown in Table 5, we report the minimum orbital intersection distance (MOID) with the Earth. Few objects have very small MOID ($<$0.015 au) making them also good candidates for mitigation mission purposes.

As current exobiological scenarios for the origin of life invoke an exogenous delivery of this matter capable of triggering the prebiotic synthesis of biochemical compounds on the early Earth, a sample-return mission to a D-type asteroid has to be the next step in the future planetary exploration not only to better investigate the origin of Solar system, but also more importantly the emergence of life on the Earth. Carbon is a key element in the evolution of prebiotic material (Henning & Salama 1998) and organic molecules provide important constraints on the emergence of life on the Earth and possibly elsewhere (Ehrenfreund & Charnley 2000).

The *Rosetta* mission by ESA has returned a treasure trove of information (Barucci & Fulchignoni 2017) and revolutionize our understanding on comets, but we still do not know which are the complex organic dark materials present on the nucleus surface of the comet 67P/Churyumov–Gerasimenko. Moreover limitations in what can be achieved so far from the Earth have highlighted deficiencies in our knowledge, particularly with respect to detailed and high precision isotopic information, and on the real composition of the dark material. The complex mixture of present materials on these dark primitive objects with the mix of very fine-grained minerals demands high sensitivity and high precision analytical capability and therefore requires return of sample to the Earth for detailed investigation. At present, two asteroid sample-return missions dedicated to primitive asteroids are in journeys: *OSIRIS-REx* by NASA to the asteroid Bennu (B-type) and *Hayabusa2* by Japan Aerospace Exploration Agency (JAXA) to the asteroid Ryugu (C-type). To complete the inventory on the primitive materials of the Solar system, the next step in its exploration must include a sample return from a D-type asteroid, which will provide fundamental information on our origin.

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