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Spectral properties of Mars-crossers and near-Earth objects

Results of the S^3OS^2 survey⋆

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Abstract. We present the results concerning Mars-crossing and Near-Earth asteroids of our Small Solar System Objects Spectroscopic Survey – S^3OS^2, carried out at the ESO (La Silla, Chile). Thirty-four objects, twenty-two Mars-crossing and twelve NEAs, have been observed from November 1996 through September 2001 in the wavelength range of 4900-9200 Å. Most (twenty-seven out of thirty-four) of the objects of our sample fall in the "S-complex", including the S, Sa, Sk, Sl, Sq and A classes, as introduced by Bus (1999). The spectra of these objects resemble that of some ordinary chondrite meteorites. In spite of the small number of objects, we found also in our sample members of the C, Ld, V and X classes.

Key words. minor planets, asteroids – solar system: general

1. Introduction

In recent studies, Mars-crossers and Near-Earth objects have been recognized as potential sources of the meteorites recovered on Earth. Near-Earth asteroids are divided into three classes, following their orbital parameters: the Atens have semimajor axes smaller than that of the Earth, the Apollos have orbits that cross the Earth's orbit (they are sometimes called *Earth-crossers*), and the Amors pass inside the Mars orbit but do not cross the Earth one. Nowadays, it is widely accepted that Near-Earth asteroids are fragments of larger objects of the main belt that, probably after a collision, were injected into a resonance. Later encounters with the terrestrial planets could then remove these bodies from the resonances and convert them into Near-Earth asteroids. On the other hand, an asteroid is a Mars-crosser when its current osculating perihelion distance is greater than 1.3 AU and its orbit intersects that of Mars. The Mars-crossing population has unstable orbits and can, through close encounters with the planet, evolve to Earth-crossing orbits. Recent dynamical works (Migliorini et al. 1998; Michel et al. 2000) suggested that the Mars-crosser population can account for an important fraction of the multikilometer Near-Earth asteroids. As the relationships among these classes of bodies are not at present completely understood, the study of these objects from a spectral reflectance point of view can help us to impose additional constraints on the origin of these populations.

In order to increase our knowledge about the compositional distribution of these objects, we observed 22 Mars-crossers and 12 Near-Earth asteroids. We obtained fifty-seven reflectance spectra for the Mars-Crossers and twenty-seven for the Near-Earth objects, as part of our Small Solar System Objects Spectroscopic Survey (Lazzaro et al. 2001). We also present a spectrum obtained for the largest Near-Earth asteroid, 1036 Ganymed, whose rotational spectra have been published by Mothé-Diniz et al. (2000).

In Sect. 2 we describe the observing and reduction procedures and in Sect. 3 we present the obtained results. In Sect. 4 we make a brief discussion and present some conclusions.

2. Observations and data reductions

The data presented here were obtained at the European Southern Observatory at La Silla (Chile) using a 1.5 m telescope equipped with a Boller and Chivens spectrograph and a CCD 2048 × 2048 with a readout noise of ±7 electrons. A 225 gr/mm grating with a dispersion of 330 Å /mm in the first order was used. The CCD has a square 15 μm pixel, that gives a dispersion of about 5 Å/pixel in the wavelength direction. The spectral range is about $4900 < \lambda < 9200$ Å with a *FWHM* of 10 Å. The spectra were taken through a 5 arcsec slit oriented in the East-West direction, in order to eliminate possible loss of light due to atmospheric differential refraction. All of the observations were made as near as possible to the meridian.

The observations have been carried out between November 1996 and September 2001, and the observational circumstances are listed in Table 1 for the Mars-Crossers and in Table 2 for the Near-Earth objects. These tables show the date of observation, the number of exposures in each night, the heliocentric and geocentric distances, the solar phase angle and the visible magnitude for each asteroid, as well as the solar analog star used to obtain the final spectrum of each asteroid. Whenever more than one spectrum was available, the least noisy one was chosen to represent the referred asteroid, and the night when

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⋆ Based on observations made with the 1.52 m telescope at the European Southern Observatory (La Silla, Chile) under the agreement with the CNPq/Observatório Nacional (Brazil).

Table 1. Observational circumstances for the Mars-crossers.

Asteroid	UT Date	Exp.	R(AU)	Δ (AU)	α	m_v	Solar analog
323 Brucia	1997/07/08*	2	2.313	1.300	2.94	12.4	HD144585
	1997/07/14	3	2.292	1.286	4.8	12.5	HD144585
391 Ingeborg	1997/12/23*	2	2.484	1.781	18.8	14.3	HD44594
	1997/12/31	1	2.505	1.750	17.3	14.2	HD44594
699 Hela	1999/06/18	1	1.636	0.971	35.5	14.2	HD144585
1139 Atami	1997/12/21	2	1.506	0.589	21.7	13.3	HD44594
	1997/12/26*	2	1.516	0.594	20.7	13.3	HD44594
1656 Suomi	2001/01/20	2	1.649	0.822	26.5	14.3	HD76151
	2001/01/27*	2	1.651	0.823	26.4	14.3	HD76151
1660 Wood	1997/01/03	2	1.800	1.023	25.6	14.4	HD44594
1747 Wright	1997/12/27	1	1.810	1.022	25.0	15.8	HD44594
1750 Eckert	1997/03/16	2	2.086	1.337	22.6	16.4	HD44594
2074 Shoemaker	1996/11/19	1	1.667	0.955	31.5	16.3	HR2290
2204 Lyyli	1996/11/17	1	1.549	0.789	33.2	14.5	HR1405
2577 Litva	1997/12/22	1	1.812	1.624	32.7	16.9	HD44594
3198 Wallonia	2000/09/30	1	2.205	1.308	15.1	15.4	HD1835
	2000/10/05*	1	2.191	1.278	13.9	15.3	HD196755
	2000/10/06	1	2.188	1.273	13.8	15.3	HD196755
3267 Glo	2001/09/20*	2	1.847	0.991	22.4	15.5	HD1835
	2001/09/21	1	1.844	0.990	22.5	15.5	HD1835
3343 Nedzel	2000/05/25	2	1.724	0.785	18.8	14.9	HD144585
	2000/05/26*	1	1.721	0.788	19.4	14.9	HD144585
3635 1981WO1	1998/12/14	1	1.645	0.973	33.0	17.2	HD44594
	1998/12/15*	2	1.645	0.966	32.8	17.2	HD44594
3873 Roddy	1997/12/26	3	1.804	0.893	16.8	13.9	HD44594
4276 Clifford	1998/12/22	1	1.626	0.980	34.2	16.7	HD44594
	1998/12/23*	1	1.625	0.986	34.4	16.7	HD44594
4558 Janesick	1998/12/13*	1	2.028	1.063	7.6	14.4	HD44594
	1998/12/14	2	2.033	1.066	7.1	14.4	HD44594
5230 1988EF	1998/12/10*	2	1.525	0.683	28.9	14.7	HD44594
	1998/12/11	1	1.524	0.682	29.0	14.7	HD44594
5870 Baltimore	1997/12/23	1	1.643	0.901	30.7	15.1	HD44594
	1998/01/02*	3	1.659	0.916	30.3	15.1	HD44594
7002 Bronshten	2000/09/30*	1	1.594	0.641	17.4	15.8	HD1835
	2000/10/04	1	1.600	0.662	19.4	15.9	HD1835
	2000/10/06	1	1.602	0.673	20.4	16.0	HD196755
1994 NL2	2001/05/29	2	1.806	0.840	14.4	15.0	HD144585

it was obtained is indicated in these tables by an asterisk. In Table 2 we give in addition the orbital classification of each Near-Earth asteroid as an Apollo, Amor or Aten object.

The spectral data reduction was performed using the Image Reduction and Analysis Facility (IRAF) package. Pixel-to-pixel variations were removed by subtracting the bias level from each frame and dividing it by a "flat field". The IRAF apsum package was used to sum the pixel values within a specified aperture and to subtract the background level. Wavelength calibration was performed using a He-Ar lamp and the spectra were corrected for airmass through the mean extinction curve of La Silla (Tüg 1977). Solar-type stars (Hardorp 1978) have been observed in order to compute reflectivities and to estimate the quality of the night. All asteroid spectra are normalized around 5500 Å by convention.

3. Results

Tables 3 and 4 show the physical and dynamical parameters for the Mars-crossing and the Near-Earth asteroids, respectively. Columns 2 and 3 of both tables show, for each asteroid, the diameter and the albedo, Cols. 4 to 6 show the osculating semi-major axis, eccentricity and inclination, and Cols. 7 to 9 show the taxonomic classification according to Tholen (1989) (*a*), Bus (1999) (*b*), and the present work (*c*). The values of the diameters were taken either from IRAS (Tedesco et al. 2002) for those indicated by an asterisk, or were calculated through the relation ($D = 10^{((6.259-0.4H-\log p)/2)}$) (Bowell et al. 1989) using the absolute magnitude H and an average visual albedo p. The adopted value of the albedo is the median value for each class, as defined by Bus (1999): 0.21 for A and S asteroids, 0.07 for B asteroids, 0.06 for C asteroids, 0.23 for V asteroids, and 0.10 for X asteroids. In Table 4, the values of the diameter and albedo of 1685 Toro and 1943 Anteros are from Veeder et al. (1989), and those for 1980 Tezcatlipoca are from Harris & Davies (1999).

The obtained reflectance spectra for the Mars-crossing and Near-Earth objects are shown in the Appendices A and B, respectively. The classification of the spectra has been made following the taxonomic system developed by Bus (1999) and implemented by our group (Carvano 2002). Twenty-four asteroids of our whole sample (thirteen Mars-crossers and eleven

Table 2. Observational circumstances for the NEAs.

Asteroid	Orbit	UT Date	Exp	R(AU)	Δ (AU)	α	m_v	Solar analog
1036 Ganymed	Amor	1998/12/10	2	1.712	0.844	22.3	11.1	HD44594
1685 Toro	Apollo	1997/03/16*	2	1.707	0.772	17.1	15.7	HD144585
		1997/03/19	1	1.719	0.773	15.5	15.7	HD144585
1943 Anteros	Amor	1997/01/11	1	1.283	0.715	49.5	17.4	HD44594
1980 Tezcatlipoca	Amor	1997/12/22	1	1.329	0.490	37.1	14.5	HD44594
		1997/12/26*	2	1.349	0.533	37.8	14.7	HD44594
3352 McAuliffe	Amor	1998/12/17	1	1.309	0.396	29.4	15.7	HD44594
		1998/12/18	1	1.306	0.396	30.2	15.7	HD44594
		1998/12/19*	1	1.302	0.396	30.9	15.7	HD44594
3753 Cruithne	Aten	2000/10/01*	1	1.265	0.554	49.8	16.2	HD20630
		2000/10/06	1	1.234	0.517	51.6	16.0	HD196755
4055 Magellan	Amor	1998/12/12*	1	1.895	1.070	21.7	17.4	HD44594
		1998/12/14	1	1.903	1.081	21.7	17.4	HD44594
		1998/12/15	1	1.907	1.087	21.8	17.4	HD44594
4954 Eric	Amor	1997/03/20	1	2.259	1.264	1.5	15.1	HD144585
4957 Brucemurray	Amor	1997/01/05*	1	1.607	0.722	23.0	16.5	HD44594
		1997/01/08	1	1.615	0.747	24.2	16.6	HD44594
5751 Zao	Amor	1997/12/28*	1	1.484	0.636	29.7	16.0	HD44594
		1998/01/04	2	1.449	0.633	33.3	16.0	HD44594
7480 Norwan	Amor	1997/01/05	1	1.313	0.366	22.1	16.7	HD44594
		1997/01/08*	1	1.326	0.385	23.0	16.8	HD44594
7482 1994PC1	Apollo	1997/01/03	2	1.064	0.204	61.6	15.7	HD44594

Table 3. Physical and dynamical parameters for the Mars-crossers.

Asteroid	D (km)	Alb.	a (AU)	e	i (deg.)	Class[a]	Class[b]	Class[c]
323 Brucia	35.8*	0.18*	2.38	0.30	24.22	S		S
391 Ingeborg	28.1		2.32	0.31	23.17	S	S	Sl
699 Hela	11.7		2.61	0.41	15.30	S	Sk	Sk
1139 Atami	16.9		1.94	0.25	13.09	S	S	Ch
1656 Suomi	7.9*	0.16*	1.88	0.12	25.06	S		Sl
1660 Wood	12.2		1.39	0.30	20.55		S	Sl
1747 Wright	6.4*	0.20*	1.71	0.11	21.42	AU:	Sl	Ld
1750 Eckert	6.9		1.93	0.17	19.08	S		S
2074 Shoemaker	4.7		1.80	0.08	30.08		S	Sa
2204 Lyyli	25.2*	0.02*	2.59	0.41	20.53		X	X
2577 Litva	6.8		1.90	0.14	22.90	EU		Sl
3198 Wallonia	10.2		2.18	0.24	17.98		S	Sk
3267 Glo	7.0		2.33	0.30	23.98			S
3343 Nedzel	6.4		2.35	0.31	25.09			Sl
3635 1981WO1	3.2		1.79	0.08	19.22		S	Sl
3873 Roddy	11.7		1.89	0.13	23.36		S	Sa
4276 Clifford	7.5		2.01	0.20	21.03		Cb	Ch
4558 Janesick	10.7		2.20	0.36	22.18		S	S
5230 1988EF	6.1		2.40	0.37	20.70		S	Sl
5870 Baltimore	7.5*	0.22*	2.79	0.42	28.95			B
7002 Bronshten	3.2		2.36	0.33	4.58			S
1994NL2	6.4		2.31	0.35	21.33			S

Near-Earth objects) have also been observed by SMASS (Small Main Belt Asteroid Spectroscopic Survey). The results of the SMASS survey are available in numerous publications, whose references are grouped in Binzel et al. (2001). In what follows we will use always the acronym SMASS to refer to any of these publications. Only minor differences are observed, in general, between our spectra and the SMASS ones. A curious case is that of the Mars-crosser 1139 Atami, which will be discussed later.

Most of our observed objects (27 out of 34) have been classified as belonging to the S-complex (including the S, Sa, Sk, Sl, Sq and A classes), as introduced by Bus (1999), but some asteroids of the C complex (Ch and B classes) are also present, in addition to the Ld, V and X classes, showing the diversity present in a such small sample.

In the following subsections we present the results by grouping the asteroids in the several taxonomic classes.

3.1. Asteroids classified in the S-Complex

Ten asteroids have been classified as S-type: six Mars-crossers – 323, 1750, 3267, 4558, 7002 and 1994NL2 – and four NEAs – 1036, 1685, 4954 and 7480. Among these asteroids, one Mars-crosser, 4558 Janesick, and all four NEAs have already been observed by SMASS, and both classifications agree, as can be seen in Tables 3 and 4. The Mars-crossers 323 Brucia and 1750 Eckert, and the NEA 1036 Ganymed have been previously classified in the Tholen taxonomy (Tholen 1989) also as S-type asteroids.

Nine objects of our sample have been classified as Sl – Mars-crossers 391, 1656, 1660, 2577, 3343, 3635 and 5230, and NEAs 1943 and 4957. Among them, five objects – Mars-crossers 391, 1660, 3635 and 5230, and NEA 4957 – had already been classified by SMASS as S-types. Three objects had also been classified by Tholen (1989), two in the S class, 391 Ingeborg and 1656 Suomi, and one in the EU class (2577 Litva). Regarding the NEA 1943 Anteros, the classification by SMASS is as a L-type, but our spectrum shows an indication of the 1 μm absorption band (see Appendix B), which places this object in better agreement with a Sl-type.

We have classified three objects of our sample as Sa: Mars-crossers 2074 and 3873, and NEA 7482. All three objects have been classified as S-type by SMASS. Two objects of our sample have been classified as Sk, the Mars-crossers 699 Hela and 3198 Wallonia. The SMASS classifications are Sk-type for the first object and S-type for the second one. All our three spectra of 3198 Wallonia, obtained on three different nights, are better matched by a Sk-type.

Only two objects have been classified as Sq-type in our sample. Both are NEAs – 3352 McAuliffe and 3753 Cruithne – that have been previously classified by SMASS as A-type (3352) and Q-type (3753). Both objects had already been observed by Lazzarin et al. (1997), whose spectra were also compatible with a classification in the S class. For 3352 McAuliffe, all our three spectra are much less red than the template of the A class. In addition, in the spectra of the object 3753 Cruithne we observe the presence of a 0.6 μm band (see Appendix B).

Finally, one object of our sample has been classified as A-type, the NEA 1980 Tezcatlipoca, already classified as SU by Tholen (1989) and as Sl by SMASS. Concerning this object, all our three spectra are much redder than the template of the Sl class and are more compatible with a classification in the A class.

We compared, in the visible range, our spectra of the S-complex asteroids (Mars-crossers and NEAs) with the spectra of some ordinary chondrite meteorites measured by Gaffey (1976). From Fig. 1 we see that most of the asteroid spectra are significantly redder than the OC spectra. In Fig. 1b, the spectra situated in the extreme lower part of the S-complex distribution are that of the Sq-types (3352 McAuliffe and 3753 Cruithne), which show the better spectral matches with the spectra of the OC meteorites. The correction factor of +0.025 μm is applied to the original spectra of Gaffey (1976) in order to take into account a calibration offset (Gaffey 1984).

With the adopted values of albedo, the diameters of the asteroids classified in the S complex range from 1.1 km to 35.8 km, both for NEAs and Mars-crossers. No relations were found between the reflectivity gradients of the spectra and the diameters of these asteroids.

3.2. Asteroids classified in the C-Complex

All objects classified in the C complex are Mars-crossers. Among the two asteroids classified as Ch, one is 1139 Atami, already mentioned above. This object has been classified as S-type by Tholen (1989) and by SMASS, but all our four spectra are compatible with a classification in the C class. This object had, at the time of our observations, a magnitude $V = 13.3$, and its field in the sky was not crowded of stars, so we conclude that this is not a case of an observational mistake. Therefore, the reasons for the differences between our spectra and that of SMASS, producing the disagreement in the classifications remain to be found.

The other asteroid classified as Ch is 4276 Clifford, classified as a Cb-type by SMASS. Our classification comes from the 0.7 μm absorption feature, present in the spectra (see Appendix A). The B-class has been attributed to one object, 5870 Baltimore, never classified before. It must be noted, however, that the IRAS albedo for this asteroid is 0.22, a quite high value for a B-type, while in the Bus taxonomy the median albedo value for the B-class is 0.07.

The largest object of our sample classified in the C complex is 1139 Atami, with a computed diameter of 16.9 km. The other objects have an even smaller computed diameter of 7.5 km, for both 5870 Baltimore and 4276 Clifford.

3.3. Asteroids classified in other classes

One Mars-crosser (1747 Wright) has been assigned to the Ld class. The Ld is, along with the L class, a newly defined class by Bus (1999), and the Ld classification places the objects between the L and D classes. Our classification does not agree with the previous classification by SMASS, that classified this asteroid as a Sl-type. From the analysis of 1747 Wright we observe that our spectrum is much redder than the template of the Sl class, being in better agreement with a Ld-type. This object has been classified also in the Tholen taxonomy as a AU: type.

We have classified two X-type objects, one Mars-crosser (2204 Lyyli) and one NEA (5751 Zao), both already classified as X-types by SMASS. Following the Tholen taxonomy and considering the low albedo of 0.02 given by IRAS for this asteroid, it would be classified as a P-type. Only one object had the V-class attributed to it, the Amor asteroid 4055 Magellan, previously classified as V-type by Tholen (1989). The Mars-crosser 2204 Lyyli has an IRAS diameter of 25.2 km, but all the other three asteroids have computed diameters smaller than 7 km.

Table 4. Physical and dynamical parameters for the NEAs.

Asteroid	D (km)	Alb.	a (AU)	e	i (deg.)	Class[a]	Class[b]	Class[c]
1036 Ganymed	31.7*	0.29*	2.66	0.54	22.64	S	S	S
1685 Toro	3.4!	0.31!	1.37	0.44	9.37		S	S
1943 Anteros	1.8!	0.22!	1.43	0.26	8.70		L	Sl
1980 Tezcatlipoca	6.7#	0.15#	1.71	0.36	26.85	SU	Sl	A
3352 McAuliffe	2.0		1.88	0.37	4.77		A	Sq
3753 Cruithne	2.8		1.00	0.51	19.81		Q	Sq
4055 Magellan	3.1		1.82	0.33	23.23	V		V
4954 Eric	8.9		2.00	0.45	17.47		S	S
4957 Brucemurray	2.8		1.56	0.22	35.01		S	Sl
5751 Zao	4.7		2.10	0.42	16.06		X	X
7480 Norwan	1.1		1.57	0.32	9.45		S	S
7482 1994PC1	1.3		1.35	0.33	33.49		S	Sa

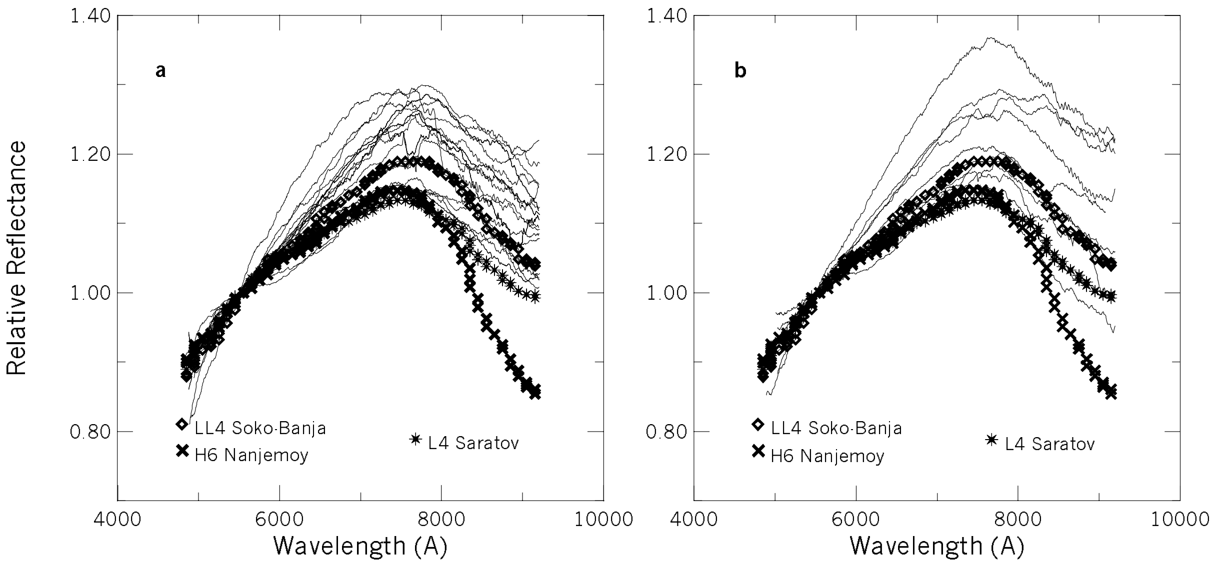

Fig. 1. Spectra of the Mars-crossers **a)** and NEAs **b)** classified in the S-complex compared with three ordinary chondrites' spectra Saratov (L4), Soko-Banja (LL4) and Nanjemoy (H6) (Gaffey 1976). The spectra are normalized around 5500 Å and are fitted by a polynomial for clarity.

4. Discussion and conclusions

In this work we confirm the previous classification of several asteroids, as well as attribute a taxonomic class, according to the more recent taxonomic system developed, to some other objects never classified before. Fifty-seven spectra have been obtained for Mars-crossing asteroids and twenty-seven for Near-Earth asteroids in the visible wavelength. In this region only part of the absorption features due to olivine and/or pyroxene are in evidence. Therefore, to better characterize the mineralogy of the observed objects we would need observations in the near-infrared region.

Differences between our spectra and the SMASS ones, when observed, are small, with only one exception, the Mars-crosser 1139 Atami. The disagreements in the classifications are, in most cases, due to differences in the slope (or redness) of the spectra, which can be due to atmospheric and/or instrumental conditions. On the other hand, several NEAs of our sample have been observed at large solar phase angles (see Table 2), which could lead to a "phase reddening effect", as discussed by Luu & Jewitt (1990). However, due to the small temporal coverage of our observations it is not possible to precisely quantify this reddening, if it exists at all. Future work is needed in order to clarify this effect and the way in which it operates on asteroids.

No relations were found between reflectivity gradients and asteroid diameters in the studied set of asteroids. In spite of the small sample, with the spectra presented in this work we give an additional example of the variety of taxonomic classes and, probably, mineralogies, present in the Mars-crossing and NEA populations. Through the comparison of the Mars-crossing and NEA spectra versus OC spectra we show, once more, that objects resembling this class of meteorites are present in both these populations. Additional studies are needed to better quantify these populations and their relationships.

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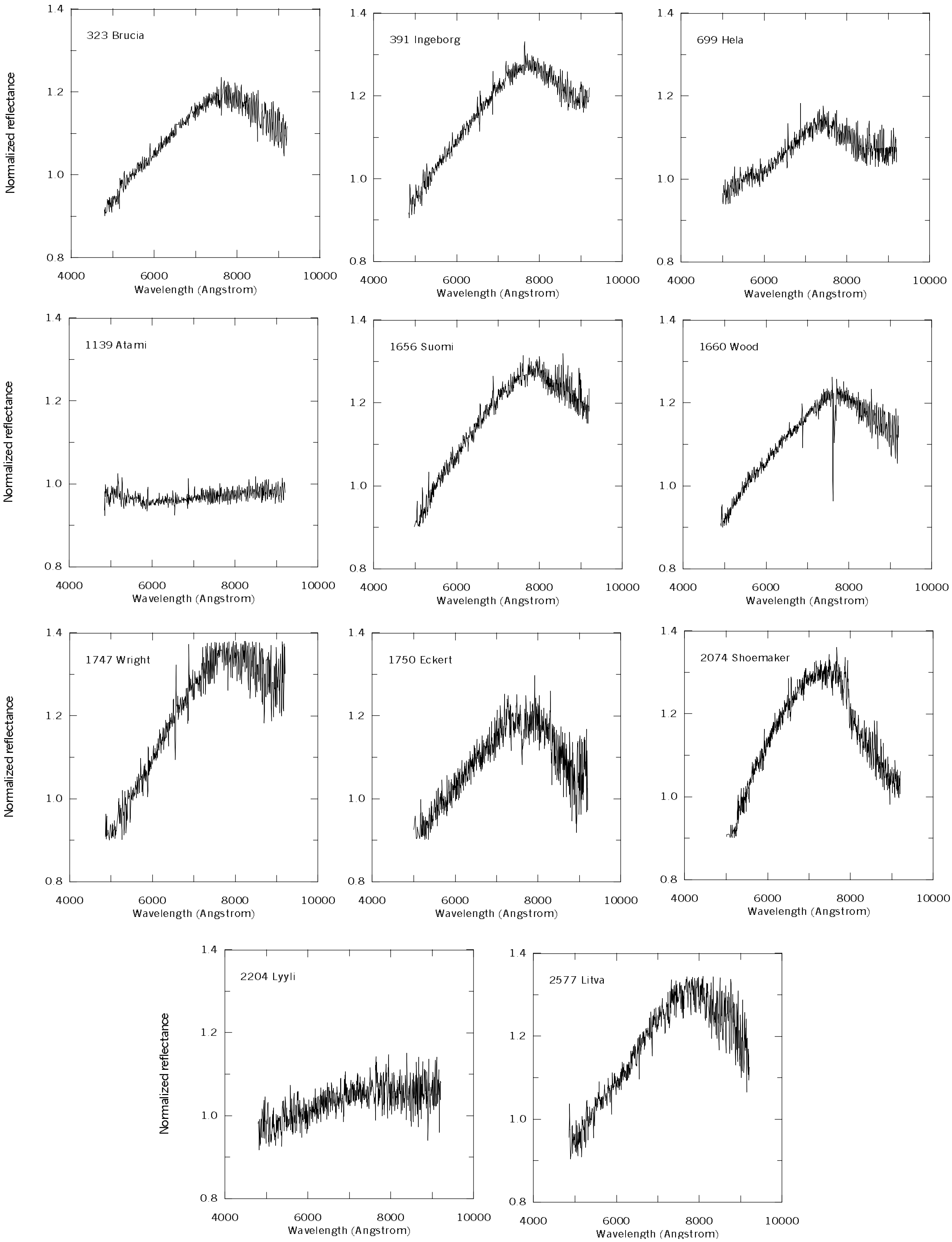
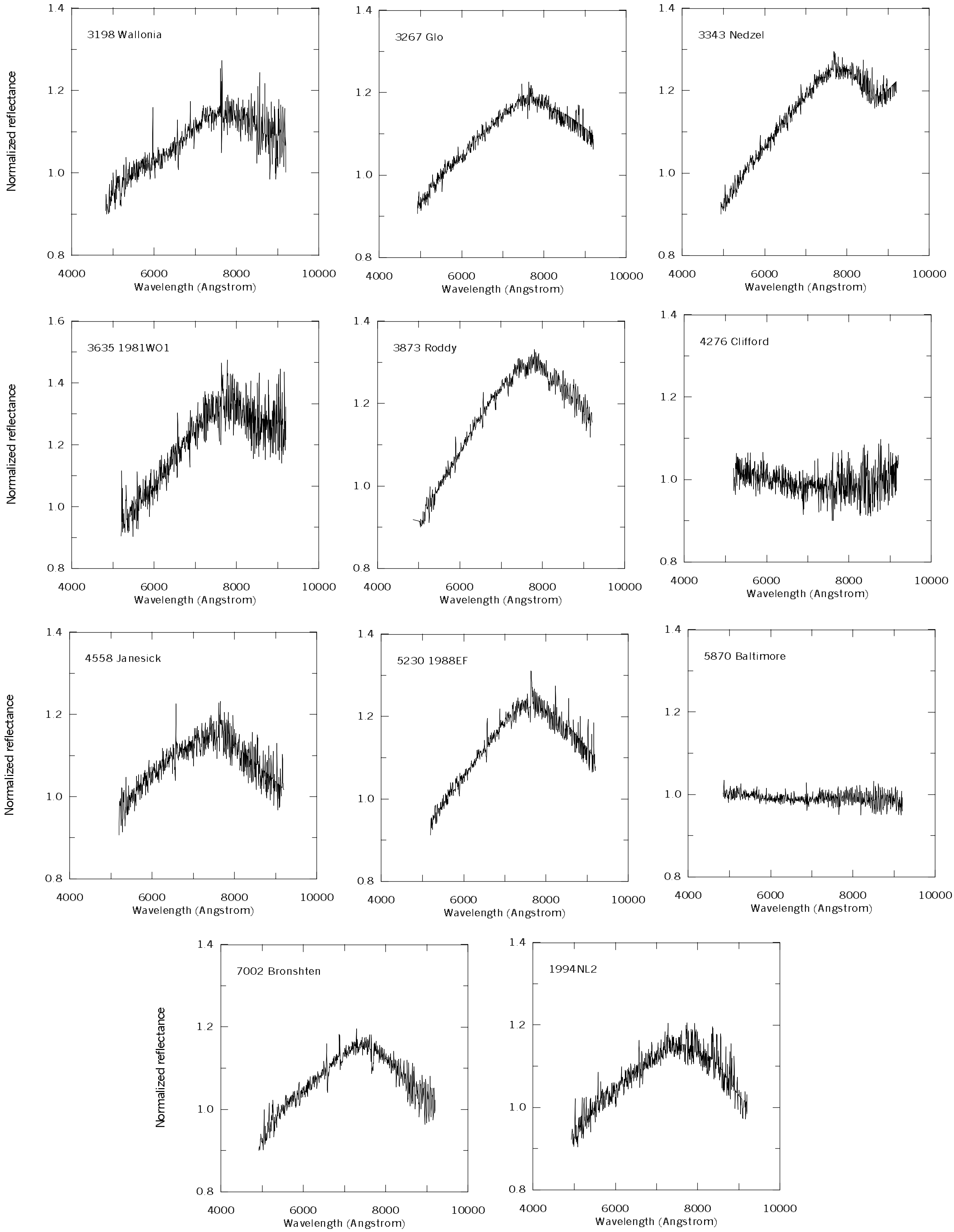
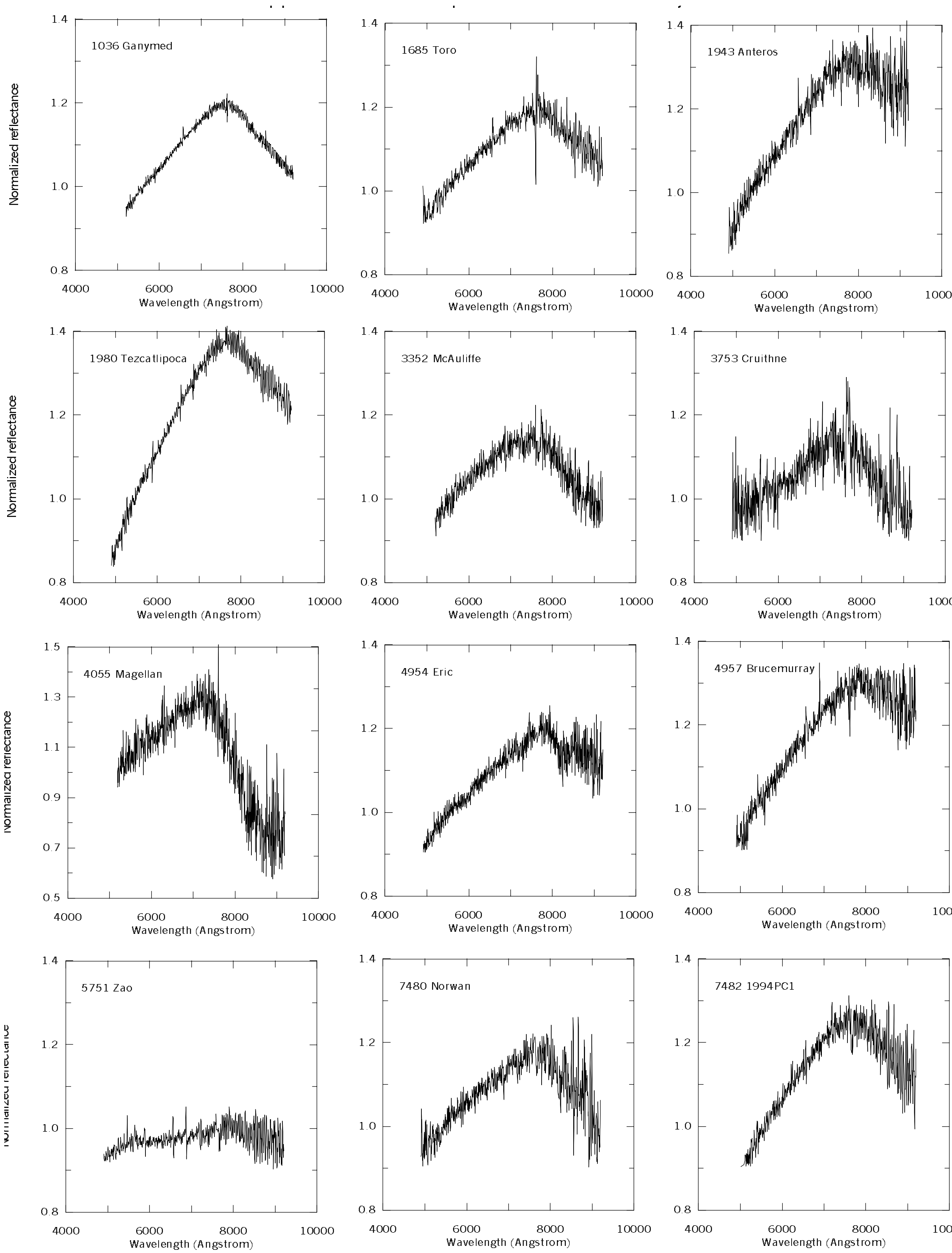
Appendix A: Visible spectra for Mars-crossing objects




3198 Wallonia
3267 Glo
3343 Nedzel
3635 1981WO1
3873 Roddy
4276 Clifford
4558 Janesick
5230 1988EF
5870 Baltimore
7002 Bronshten
1994NL2
Normalized reflectance
Wavelength (Angstrom)
0.8
1.0
1.2
1.4
1.6
4000
6000
8000
10000

Appendix B: Visible spectra for Near-Earth objects



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