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Compositional properties of Near-Earth Asteroids: spectroscopic comparison with Ordinary Chondrite Meteorites

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Abstract. Some years ago we started a spectroscopic survey, in the visible region, of Earth-approaching asteroids to investigate their compositional nature in order to improve the comprehension of their origin. To date we have obtained low-resolution spectra, in the range 0.5-1.0 μm, of 1 Aten (3753 *1986 TO*), 4 Apollo (1864 *Daedalus*, 5786 *Talos*, *1989 JA*, 2063 *Bacchus*), and 3 Amor (3352 *McAuliffe*, 4954 *Eric*, 5836 *1993 MF*). Most of them show spectra similar to those of the S taxonomic class; Bacchus only has a spectrum which resembles those of more primitive objects (C-type).

It has not been possible to definitively distinguish to which S-subclass the observed objects belong because the spectra we obtained do not cover the necessary spectral range to make this investigation as described by Gaffey et al. (1993). Nevertheless four of the observed objects have visible spectra similar to those of ordinary chondrites meteorites suggesting a strong relation between the two classes of objects.

Moreover 5836 *1993 MF* shows an absorption feature near 6000 Å probably due to the presence of aqueous altered materials.

Key words: asteroids – meteroids

1. Introduction

Near-Earth Asteroids (NEA) represent one of the most peculiar classes of objects in the Solar System. Their orbits can approach or even intersect the terrestrial one. More than 360 NEAs have been discovered to date. The largest object of this population has a diameter of 38 km, two others are about 20 km in size, the remaining have diameters less than 10 km, and about 3/4 of them are smaller than 3 km. According to the more recent estimate (Rabinowitz et al., 1994; Muinonen et al., 1995), NEAs with diameter $\geq$1 km are about 2000, and at present we know the orbits of only about 7% of them.

The population of NEA is extremely heterogeneous in all the aspects of their physical properties. Available data show that shapes, rotation rates and albedos of NEAs are on the average practically the same as those of main-belt objects. However, among NEAs there are objects with unusual shapes (very elongated, dumb-bell like and possibly binary), with very complex non-principal axis rotation (*tumbling* asteroids) and with peculiar mineralogical compositions. Recent radar observations allow to assume that a substantial part of NEAs could be binary systems. In the NEA population all the taxonomic types have been identified, except the B and the P classes, even though the most numerous classes observed are S and C respectively.

The discovery of the very dark (albedo about 0.03) and reddish D-type Amor asteroid 3552 *Don Quixote* has been rather unexpected because most of the asteroids belonging to this class are located in the outermost parts of the main belt (Trojan and Hilda groups) and they represent the most primitive objects among asteroids. The variety of taxonomic classes discovered among NEAs indicates that this population is heterogeneous in origin and composition.

The importance to study NEAs is connected to several reasons:
a) the impacts by these objects are the principal cause of the craterization of the Earth and the Moon, at least in the last 3.8 Gyr (Wetherill and Shoemaker, 1982). The discovery of the majority of the possible "dangerous" objects and the knowledge of their physical properties are two of the main research lines to be followed in order to solve the problem of "asteroid hazard".
b) They could be the sources of chondritic and achondritic meteorites (Wetherill, 1976; Di Martino et al., 1995);
c) It is likely that a good number of these objects represent the final evolutionary state of comets, that is a devolatilized nucleus.
d) They could be potential sources of metals and other raw materials in the neighbourhood of the Earth space. At present we know two M-type asteroids (3554 *Amun* and 6178 *1986 DA*) and the results of radar observations leave no doubts about the

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Send offprint requests to: Monica Lazzarin metallic nature of them (Tedesco and Gradie, 1987; Ostro et al., 1991).

Anyway, one of the most interesting aspects in the study of NEA is to understand their origin. In fact, their dynamical lifetimes are shorter than the age of the Solar System. Moreover, owing to the constant craterization of the inner Solar System bodies from their formation, it is believed that the population of NEA is practically constant in number. So, it has to be continuously supplied by some sources and/or mechanisms which have been identified in: (i) the dynamical evolution of the fragments coming from catastrophic collisions in the main belt (Greenberg and Nolan, 1989), and in (ii) extinct or dormant comet nuclei (Weissmann et al., 1989; Binzel et al., 1992).

An example of the latest case is comet P/Encke, a low active comet on an Apollo-like orbit. On the other hand, some NEA have been discovered on cometary-like orbits as 2201 *Oljato* (McFadden et al., 1993, Lazzarin et al., 1996) or dynamically connected with meteor streams, that are believed to be cometary in origin (Asher et al., 1994).

The most striking evidence of this connection is the Apollo object 4015 *1979 VA*, discovered as an asteroid and then recognized as the non active comet Wilson-Harrington.

Another important aspect of NEAs is that they are very likely the principal sources for meteorites, in particular for ordinary chondrite (OC) meteorites. The OC are considered the remnants of the primitive solar nebula: they have been scarcely thermally processed during the evolutionary stages of the Solar System.

Binzel et al. (1996) have recently found a quite clear relationship between OC and some NEAs. If the idea that part of NEAs could be the parent bodies of OC is confirmed, it would help to understand the origin of part of these objects: they would have been injected into near-Earth orbits from the main-belt reservoir.

In order to try to answer to all these open questions we started a long term spectroscopic survey of NEAs, which preliminary results we present in this paper.

2. Observations and data reduction

The low-resolution spectra we present in this paper have been obtained during different observing runs between 1993 and 1996 (Table 1). The observations have been performed at the European Southern Observatory (ESO, La Silla, Chile) and at the Asiago Observatory (Italy). At La Silla we used the 1.5 m telescope equipped with a Boller & Chivens spectrograph and a type Ford CCD (2048×2048 pixels) detector. The grating used was a 225 gr/mm with a dispersion of 330 Å/mm in the first order. The CCD has a 15 μm square pixel, yielding a dispersion of 5 Å/pixel in the wavelength direction. The spectral range covered is about $0.5 < \lambda < 1$ μm with an instrumental FWHM of 10 Å.

At the Asiago Observatory we used the 1.82 m telescope equipped with a Boller & Chivens spectrograph and a Thomson CCD (430×600 pixels) as detector. The grating was a 150 gr/mm with a dispersion of 340 Å/mm in the first order. The CCD has 23 μm square pixels giving a dispersion of about 7.8 Å/pixel in the wavelength direction. The spectral coverage is about $0.5 < \lambda < 1$ μm with an instrumental FWHM of 15.6 Å.

The reduction of the spectra has been performed using standard procedures of data reduction using the softwares MIDAS, IRAF and IDL. In order to calibrate the observational data, bias, flat-field, calibration lamp, spectrophotometric standard star and solar analog (Hardorp, 1978) spectra were secured at different intervals throughout each night. After bias subtraction, flat-field correction, cosmic-rays removal, wavelength calibration, airmass correction, flux calibration, division by the solar analog spectrum, we obtained the reflectivity spectra of the objects. The standard stars and the solar analogs were observed at airmasses similar to those of the asteroids with differences less than 0.2 in each case. In Table 1 we report the circumstances of the observations.

3. Results

The reflectance spectra of the eight asteroids, normalized at 1 around 5500 Å, are shown in Fig. 1 to Fig. 3. The objects we observed are: 1 Aten (3753 *1986 TO*), 4 Apollo (1864 *Daedalus*, 5786 *Talos*, *1989 JA*, 2063 *Bacchus*), and 3 Amor (3352 *McAuliffe*, 4954 *Eric*, 5836 *1993 MF*).

For each object an indication of the diameter is given (Tholen, 1995). Some of the spectra show some shallow spurious features which are probably due to the division by the solar analog spectrum, that is a non perfect elimination of the solar features, or also to a non perfect cancellation of the atmospheric O_2 bands at 7612 Å and 6880 Å.

3753 *1986 TO*

This is the only Aten object we have observed and no spectral information was available before for this asteroid. The spectrum we obtained (Fig. 1) shows the typical trend of the objects belonging to the S-class, but it is different from the spectra of OC assemblages.

The estimated diameter of this asteroid is about 5 km and its rotational period $P_{syn}= 18^h.14$ (Hoffmann et al., 1993).

4954 *Eric*

This rather large asteroid, with a diameter of about 12 km, has a rotational period of about 11 hours (Wisniewski et al., 1996). Barucci et al. (1994) obtained the near infrared spectrum of this object (1.0-2.5 μm) and the coupling with that obtained in the visible (Fig. 1) suggests the belonging of this object to the S taxonomical class. No similarity with ordinary chondrite spectra has been identified.

1989 JA

This Apollo asteroid has an estimated diameter of about 1.5 km. Also the spectrum of this object shows the typical S-type trend, but again different from the ordinary chondrite ones (Fig. 1).

Table 1. Observational characteristics of the NEAs.

ASTEROID	DATE [UT]	OBSERV.	TEL.	r [AU]	Δ [AU]	m_v	SOLAR ANALOG
1864 Daedalus	1994/04/17	ESO	1.50m	1.596	0.638	15.8	HD 44594
2063 Bacchus	1996/05/20	ESO	1.50m	1.279	0.374	16.3	HD144585
3352 McAuliffe	1994/04/18	ESO	1.50m	1.579	0.584	16.0	HD 44594
3753 1986 TO	1993/09/25	ESO	1.50m	1.341	0.578	15.5	Hyades 64
4954 Eric	1994/04/18	ESO	1.50m	2.100	1.396	16.0	HD 44594
5786 Talos	1996/10/16	ESO	1.50m	1.123	0.309	16.6	HD 28099
5836 1993 MF	1993/09/14	Asiago	1.82m	1.251	0.308	13.8	16 Cyg B
1989 JA	1996/10/17	ESO	1.50m	1.272	0.377	16.9	HD 28099

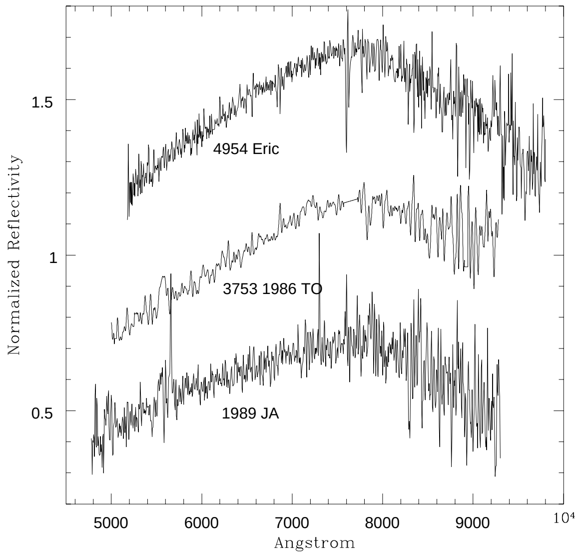

Fig. 1. Reflectance spectra of the near-Earth Asteroids *1989 JA*, 3753 *1986 TO*, 4954 *Eric*. The spectra have the typical trend of the S-types.

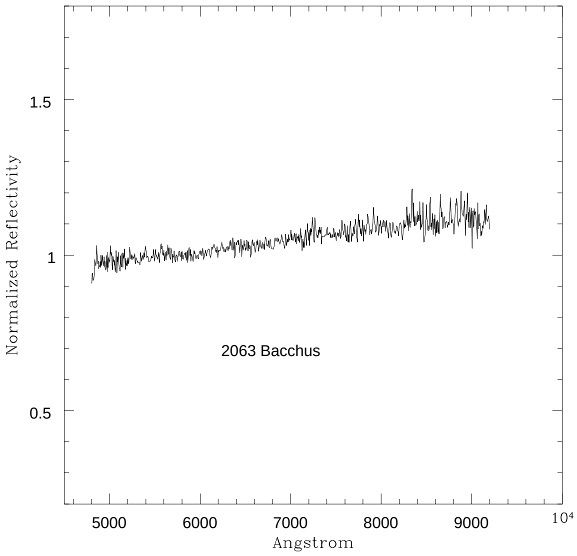

Fig. 2. Reflectance spectrum of the near-Earth object 2063 *Bacchus*.

2063 Bacchus

This Apollo object has an estimated diameter of about 2 km. It shows a spectrum (Fig. 2) different from all the other near-Earth objects here presented. It is redder than the solar spectrum and resembles that of the more primitive C-type asteroids. Its reflectance slope is 3.7±0.1 %/10^3 Å in the spectral range 5000÷7500 Å, which is consistent with the reflectance slopes of C-type objects more than with those of D-types (lower limit of the reflectance slopes of D objects is about 7%/10^3 Å).

1864 *Daedalus*

This Apollo asteroid has been classified as an SQ-type by Tholen (1989). Its rotational period, P_{syn} = 8.57 hours, has been determined by Gehrels et al. (1971) and this object shows a large amplitude (0.85 mag) of the lightcurve, which implies a very elongated shape. The estimated diameter is about 3 km. No previous spectral information is available on this asteroid and the spectrum we obtained (Fig. 3) shows a trend similar to that of S-type asteroids. Anyway, in this case, as reported in Fig. 3, there is a good match between the spectrum obtained and the laboratory spectra of L4-type OC.

5786 *Talos*

This Apollo asteroid has an estimated diameter of 1.7 km. Also the optical spectrum of Talos is similar to that of OC, in particular to H6-type (Fig. 3).

3352 *McAuliffe*

No physical information was available on this Amor asteroid, except the diameter, that has been estimated in about 3 km. The S-type spectrum obtained (Fig. 3) is very similar to that of H4-type OC.

5836 *1993 MF*

This object, with an estimated diameter of about 6 km, has a rotational period of 4.959 hours (Mottola et al., 1995 and Wisniewski et al. 1996). The spectrum of this asteroid that we obtained (Fig. 3) shows an absorption feature centered around

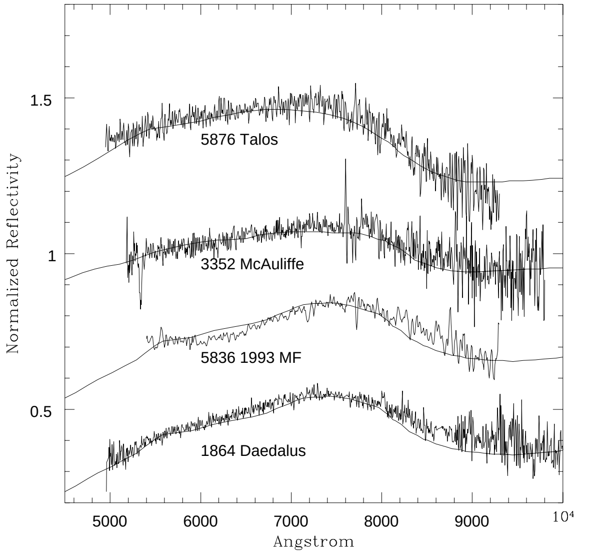

Fig. 3. Spectra of near-Earth asteroids compared with laboratory spectra of ordinary chondrites assemblages. Averaged L4-subtype OC spectrum is superimposed to 1864 *Daedalus* and 5836 *1993 MF*; averaged H4-subtype OC spectrum is compared with 3352 *McAuliffe* and averaged H6-subtype OC spectrum is superimposed to the spectrum of 5876 *Talos*.

6000 Å which is suggestive of the presence of aqueous altered materials and found in some C and S asteroids also by Vilas et al. (1992, 1994) and Hiroi et al. (1996). This feature is even more evident when we compare the spectrum of 1993 MF with that of L4-type OC (Fig. 3): there is a good match between the two except around 6000 Å where there is the absorption band.

4. Discussion and conclusion

A better investigation of the spectra obtained and a consequent clearer classification of the objects here presented would require near-infrared data. In fact, this could allow a more detailed comparison with the spectra of OC and also a comparison with the S-subclasses as designed by Gaffey et al. (1993). Nevertheless, the results obtained are suggestive of some conclusions.

Among the eight observed objects, only one, 1864 *Daedalus*, had been previously classified as an SQ-type and we confirm the belonging to the S class. All the others show the typical trend of S-type objects, except 2063 *Bacchus* which spectrum has the typical behaviour of C-type objects. Four of the observed objects (1864 *Daedalus*, 5836 *1993 MF*, 3352 *McAuliffe* and 5876 *Talos*) show a spectrum that, within the errors, match quite consistently the laboratory spectra of OC. So these objects are potential parent bodies for these meteorites and this could suggest: a main-belt origin and a surface formed by undifferentiated mineral assemblages. The differences between the four objects similar to the OC and the other three typical S type asteroids could be due to space weathering effects: different ages of the objects are probably responsible of different surface reflectance characteristics (Chapman, 1996). The asteroids which composition is closer to OC would be those with "younger" surfaces (Binzel et al. 1996).

The asteroid 5836 *1993 MF*, besides its similarity to OC assemblages, shows also an absorption band centered around 6000 Å suggestive of the presence of aqueous altered materials.

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