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Physical Investigation of the Potentially Hazardous Asteroid (144898) 2004 VD17 *

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*Based on observations carried out at the European Southern Observatory (ESO), Chile, ESO run ID 276.C-5057
Running head: Nature of (144898) 2004 VD17

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Abstract

In this paper we present the observational campaign carried out at ESO NTT and VLT in April and May 2006 to investigate the nature and the structure of the Near Earth Object (144898) 2004 VD17. In spite of a great quantity of dynamical information, according to which it will have a close approach with the Earth in the next century, the physical properties of this asteroid are largely unknown. We performed visible and near-infrared photometry and spectroscopy, as well as polarimetric observations. Polarimetric and spectroscopic data allowed us to classify 2004 VD17 as an E-type asteroid. A good agreement was also found with the spectrum of the aubrite meteorite Mayo Belwa. On the basis of the polarimetric albedo \( p_v = 0.45 \) and of photometric data, we estimated a diameter of about 320 m and a rotational period of about 2 hours. The analysis of the results obtained by our complete survey have shown that (144898) 2004 VD17 is a peculiar NEO, since it is close to the breakup limits for fast rotator asteroids, as defined by Pravec and Harris (2000). These results suggest that a more robust structure must be expected, as a fractured monolith or a rubble pile in a “strength regime” (Holsapple 2002).

Keywords: Near-Earth Objects – Asteroids, composition – Asteroids, rotation – Photometry – Spectroscopy – Polarimetry
1 Introduction

The asteroid (144898) 2004 VD17 is a Near Earth Object (NEO) belonging to the Apollo group, discovered by the LINEAR asteroid survey on the 7th of November, 2004. Its orbital parameters are summarized in Table 1. It will encounter the Earth several times during the next 100 years: in 2032, 2041, 2067 and 2102. Between February and May 2006, the available astrometry did not exclude the possibility of an impact with the Earth at the last encounter of the sequence, the one taking place in early May 2102. This impact was rated 2 on the Torino Scale (TS, Binzel 2000) and in excess of −0.30 on the Palermo Scale (PS, Chesley et al. 2002). Further observations have reduced these values to TS=0 and PS< −3.

Although we have a lot of dynamical information, up to now the physical properties of (144898) 2004 VD17 are very poorly known. These characteristics are very important to constrain its mineralogical composition, albedo and density, allowing us to deduce the internal structure.

In order to investigate the nature of this NEO and to assess its impact hazard, in April and May 2006 we carried out photometric, spectroscopic and polarimetric observations at the European Southern Observatory (ESO, Chile).

2 The Observational Campaign and Data Reduction

[TABLE 2]
The observational campaign was performed in the framework of a Director’s Discretionary Time Program (Run ID 276.C-5057). The aim of this survey was to carry out visible and near-infrared photometry and spectroscopy together with polarimetric measurements of (144898) 2004 VD17.

In particular, our aim was:

i) to determine the albedo by analysing the polarimetric data in order to constrain size and taxonomic classification. Due to the faintness of our target at the time of observations ($m_v \simeq 19.2$ mag), polarimetry was the only way to estimate its albedo and thus its real size;

ii) to investigate the surface composition, looking for spectral evidence of minerals and mixtures present on its surface, to perform the taxonomic classification and to investigate the possible link with the known meteorite classes;

iii) to investigate the rotational status, by analysing the periodicity and the shape of its lightcurve;

iv) to reveal a possible satellite or companion and to check for the presence of cometary activity;

v) to investigate the internal structure (bulk density and internal tensile strength), crosscorrelating all the obtained results.

In Table 2 an overview of the observations is presented. For each run, telescopes, instruments and relative adopted techniques are presented, together with the observational circumstances.
2.1 Polarimetry

Polarimetric observations of (144898) 2004VD17 were carried out at ESO-Paranal in service mode with the telescope VLT–UT2 Kueyen, equipped with the FORS1 instrument (see http://www.eso.org/instruments/fors1) in polarimetric mode, from April 16 to May 30, 2006, for a total of 4 observing runs (Table 2).

Linear polarimetry was obtained in the Bessel V filter at 4 angles of the $\lambda/2$ retarder plate ($0^\circ$, $22.5^\circ$, $45^\circ$ and $67.5^\circ$ with respect to celestial coordinate system), covering the phase angle range from $26^\circ$ to $77^\circ$. For each retarder plate position, 3 images were acquired with exposure time of 300 s each, for a total exposure time on the target of 1 hour during each run.

The observing procedure included the acquisition of several flat field images, taken on twilight time without polarimetric optics in the light path, and of at least one unpolarized standard star (taken from the ESO list at http://www.eso.org/instruments/fors/tools/FORS Std/FORS1 Std.html) to calibrate the instrumental polarization. The zero point of the position angle was taken from the FORS1 user manual (http://www.eso.org/instruments/fors/doc).

The data reduction and polarimetric parameters evaluation have been performed following the procedure described in Fornasier et al. (2006a). The observing conditions and the final results on the degree of polarization $P$ and on the position angle $\theta$ of the polarization plane, together with the polarimetric quantities $P_r$ ($P_r = P \times \cos(2\theta_r)$) and $\theta_r$ ($\theta_r = \theta - (\phi \pm 90^\circ)$, where $\phi$ is the position angle of the scattering plane), are reported in Table 3.
2.2 Visible photometry and spectroscopy

Visible photometric and spectroscopic data were acquired in service mode during three different nights (see Table 2) at ESO-La Silla, using the 3.58 m NTT (New Technology Telescope). The telescope was equipped with the instrument EMMI (ESO Multi-Mode Instrument) in RILD mode (Red Imaging and Low Dispersion Spectroscopy) (http://www.ls.eso.org/lasilla/sciops/ntt/emmi/index.html). This instrument was equipped with a detector mosaic of two thin, back-illuminated, AR coated MIT/LL CCDs, with an image size of 2048 x 4096 pixels each one, a field of view, in total, of 9.1 x 9.9 arcmin and a resolution of 0.1665 arcsec/pixel.

For photometry the $B, V, R,$ and $I$ Johnson filters in $2 \times 2$ binning mode were used. The exposure times were 180 and 90 sec in B and V filters, respectively, and of 60 sec in R and I filters. These measurements span a time interval of about four hours for the night of 1st May and about two hours in the nights of 21st and 22nd May. Biases and sky flat-fields were also acquired at the beginning and at the end of each night.

The photometric data were reduced with the software packages IRAF, MIDAS and IDL using the standard procedure (see, e.g., Dotto et al. 2006). The raw data were corrected subtracting the bias contribution and dividing by a median flat-field. The instrumental magnitude was then computed using aperture photometry, with an integration radius of about three times the average seeing. The sky contribution was estimated using an annulus 5-10 pixels wide around the asteroid and then removed. The final magnitude cali-
bration was performed using several standard stars (Landolt 1992) observed during each night, with the exception of the night of 22nd May, that was clear but not photometric. For images acquired during this last night, a differential magnitude analysis was performed.

The visual inspection of the images does not show the presence of companions of 2004 VD17, nor cometary activity. The obtained single night lightcurves corrected for light-time are shown in Fig. 1. The $B-V$, $V-R$ and $V-I$ colors are reported in Table 4.

For spectroscopy was used the grism #1 (150 gr/mm), covering the wavelength range $4100 \div 9400 \, \text{Å}$, with a dispersion of $3.1 \, \text{Å/pix} \, (200 \, \text{Å/mm})$ at the first order. The slit of 5 arcsec was oriented along the direction of the asteroid’s motion. To reduce the possibility that the target went out of the slit during the exposure, each spectrum was divided into 2–3 parts, with a total exposure time of 20–30 minutes (see Table 5). The asteroid position in the slit was checked before each spectrum.

The obtained spectra were calibrated in wavelength, using a helium-argon lamp as reference. Then the object’s spectra were divided by the spectrum of a solar analog star observed just before and after the target, at a similar airmass (Table 5). All the obtained visible spectra, shown in Fig. 2, are flat and featureless. They exhibit very similar behaviors and have the same spectral slope of $(0.03 \pm 0.01) / 10^3 \text{Å}^{-1}$, computed between 0.55 and 0.75μm.

2.3 Near-Infrared photometry and spectroscopy
The near-infrared observations were carried out at ESO-Paranal in service mode, during two nights (24th and 25th of May), using the 8.2 m VLT–UT1 Antu, equipped with the infrared-cooled grating spectrometer ISAAC (Infrared Spectrometer And Array Camera) (http://www.eso.org/instruments/isaac) and with a Rockwell Hawaii 1024×1024 pixel Hg:Cd:Te array.

Photometric $J$, $H$, and $K_s$ measurements (centered at 1.25, 1.65, and 2.16 $\mu m$) have been obtained before each spectrum, with an exposure time of 120 s, 180 s and 240 s respectively. The calibration was performed by the observation of several faint infrared standard stars from Persson et al. (1998). The observations were carried out with the jitter imaging technique and data analysis was performed using the jitter routine from the ECLIPSE package. The data processing routines are described in Dotto et al. (2003) and Romon et al. (2001). The obtained $V-J$, $V-H$ and $V-K$ colors are reported in Table 4.

Near-infrared spectroscopic observations were performed in the SW mode (1 to 2.5 $\mu m$ wavelength range). The ISAAC low resolution spectroscopic mode, with a 2 arcsec wide slit and the grating at two different central wavelengths corresponding to J and K bands, was used (Table 5). The observations were done by nodding the object along the slit by 10 arcsec between two positions A and B. The two averaged A and B images in each spectral range were subtracted from each other. The A–B and B–A images were flat-fielded, corrected for spatial and spectral distortion and finally combined with a 10-arcsec offset. The spectra were extracted from the resulting combined images, and wavelength calibration was performed using a xenon–
argon lamp. The telluric absorption correction and the removal of the solar contribution were obtained by dividing the spectra of the asteroid by the spectrum of a solar analog star, observed just before and after the object and at similar airmass. The resulting spectra are shown in Fig. 3.

3 Data analysis

1. Polarimetry

It is well known that asteroids exhibit a well defined trend of the linear polarization versus the phase angle (Fornasier et al. 2006b, and references therein). Two different empirical relations make it possible to determine the asteroid albedo thanks to the knowledge of the minimum of the polarization curve ($P_{\text{min}}$) or/and of the slope of the polarization curve near the inversion angle. Primitive low albedo asteroids (e.g., C-types) present a higher value of $P_{\text{min}}$ and a smaller inversion angle, as compared for example to medium-high albedo objects (e.g., S- or E-types). Polarimetric albedos up to now available for the asteroid population are in agreement with data derived from other techniques, including direct measurements such as occultations and space missions.

To estimate the slope of the polarization phase curve at the inversion angle in the V band, a linear fit to our data, weighted according to their errors, was used (see Fig. 4). The use of a linear fit is reasonable because of the small curvature of the ascending branch of the asteroid polarization phase dependence (e.g., Zellner and Gradie 1976). The obtained slope is of
0.037±0.001 (%/deg) in a good agreement with the mean slope of 0.041±0.007 (%/deg) for the other four E-type asteroids observed so far (Zellner and Gradie 1976, Kiselev et al. 2002, Fornasier et al. 2006a). The relatively small value of positive polarization degree of 2.35% measured at phase angle of 76.8° is another indication that the asteroid belongs to the E class. (144898) 2004 VD17 is the second E-type NEO, together with (33342) 1998 WT24 (Kiselev et al. 2002), for which polarimetric data are available. Comparison of their polarimetric measurements is shown in Fig. 4, which also includes the available observations of some main belt E-type asteroids (Zellner and Gradie 1976; Rosenbush et al. 2005; Fornasier et al. 2006a,b). Both NEOs and main belt asteroids show similar polarization-phase angle dependences, suggesting similarity of their microscopic surface properties. Our observations of (144898) 2004 VD17 are well supplement to the available data, covering gaps in the composite phase dependence of E-type asteroids shown in Fig. 4, and constraining a lower limit of the polarization maximum. The data obtained for (144898) 2004 VD17 provides a maximum value of polarization $P_{\text{max}} \geq 2.35\%$, higher than that one of (33342) 1998 WT24 (Kiselev et al. 2002). The phase angle of the polarization maximum for (144898) 2004 VD17 is $\alpha_{\text{max}} \geq 80^\circ$, while for (33342) 1998 WT24 is $\alpha_{\text{max}} \geq 75^\circ$. This discrepancy is likely connected with incertainties in polarimetric measurements rather than with differences in surface properties of the observed NEOs. To estimate the albedo of 2004 VD17, the empirical correlation of polarimetric slope vs. albedo, as described in Fornasier et al.
(2006a) for asteroid 2867 Steins was used. These asteroids have exactly the same values of the polarimetric slope assuming the same albedo. The corresponding albedo is 0.45±0.10, where the error accounts both for the uncertainties on the slope and on the constants in the slope-albedo relation.

2. Photometry and Spectroscopy

[FIGURE 5]
The visible and near-infrared colors reported in Table 4 were transformed in reflectance and used to combine V, J, and K spectra. Fig. 5 shows the entire spectrum of (144898) 2004 VD17, from about 0.50 μm to about 2.4 μm. It appears featureless and almost flat, and compatible with the typical E-type asteroids spectrum.

In order to investigate the surface composition of this NEO, its spectrum was compared with a large sample of meteorite spectra taken by the RELAB Public Spectroscopy Database (http://www.planetary.brown.edu/relab/). The comparison was carried out by means of an automatic χ²-test. As shown in Fig. 5, a good match was found with the Mayo Belwa aubrite meteorite. This result gives a further confirmation to our taxonomic classification of (144898) 2004 VD17, since aubrites are widely believed to be the meteorite analogs of the E-type asteroids. As the aubrite meteorites are mainly composed by enstatite, the found match confirms the enstatitic nature of our target.

3. Lightcurves
To determine the synodic rotational period of (144898) 2004 VD17, a Fourier analysis of our photometric data set, as described in Harris et al. (1989) was performed. The rotational period of 2004 VD17 resulted \( P_{\text{syn}} = 1.99 \pm 0.02 \) hours. The obtained V and R lightcurves are shown in Figures 6 and 7 respectively. Their behaviors make it possible to exclude a binary nature.

The lightcurve amplitude is \( 0.21 \pm 0.02 \) mag, giving a lower limit of the semimajor axis ratio of \( a/b \geq 1.21 \pm 0.02 \). On the basis of these results, 2004 VD17 is a fast rotator asteroid (FRA) with an ellipsoidal shape: this makes it a peculiar object since it is widely believed that fast spin rates are coupled with quite spheroidal structures (Pravec and Harris 2000). It could be speculated that the repeated recent close encounters with the terrestrial planets (Scheeres et al. 2004) and/or the non gravitational perturbations (e.g. Yorp effect, Lowry et al. 2007), related to its non spherical shape and small semimajor axis, brought the spin rate of our target to the present high value.

In the Fig. 6 the coverage of the three visible spectra shown in Fig. 2 is reported. Since we found the same spectral behavior for about the 75% of the whole rotational phase, we can argue that (144898) 2004 VD17 has a quite homogeneous surface composition.
4 Discussion

We applied the Bowell et al. (1989) procedure to our V photometric data together with all the astrometric V magnitudes, archived from 1st March 2006 to 1st June 2006 in the NEODyS\footnote{http://newton.dm.unipi.it/cgi-bin/neodys/neoibo} database (http://newton.dm.unipi.it/cgi-bin/neodys/neoibo), to estimate the absolute magnitude of (144898) 2004 VD17, obtaining $H = 18.9$. Hence, we estimated the diameter of our target using the empirical relationship

$$D = \frac{1329 \cdot 10^{-H/5}}{\sqrt{p_v}}$$  \hspace{1cm} (1)

with a visual albedo of $p_v = 0.45$, obtaining a diameter of $D \sim 320$ m.

Using the measured synodic period ($P_{\text{syn}}$) and the obtained lightcurve amplitude ($\Delta m$), from the Eq. (7) of Pravec and Harris (2000):

$$\rho \simeq \left( \frac{3.3}{P_{\text{syn}}} \right)^2 \cdot (1 + \Delta m)$$  \hspace{1cm} (2)

we can estimate the density of (144898) 2004 VD17 assuming a body with no tensile strength (rubble pile). The resulting value is $\rho \sim 3.36 \text{ g/cm}^3$, that would be an extremely large value with respect to the currently known asteroids’ densities. Note that our target, with its non negligible ellipsoidal shape, would lie slightly beyond the border between “rubble-piles” and “monolithic” bodies, as shown in Fig. 8 of Pravec and Harris (2000). Following their analysis, with $D \sim 320$ m, $a/b \sim 1.2$ and $P_{\text{syn}} \sim 2$ hours, (144898) 2004 VD17 would be a peculiar, quite large fast rotator, with a larger-than-average nonspherical shape, calling for a very high density value to withstand the rotational accelerations. Moreover, with about 12 revolutions per day, in the
classical plot “Diameter vs. Spin rate”, our target would lie above the so-called “rubble-pile spin barrier”, but to the right of the 0.2 km line, usually discriminating between “small monoliths” and “rubble-piles”. This seems to suggest a more robust structure. (144898) 2004 VD17 could be a monolith, maybe partially fractured (Richardson et al. 2002), even if the lack of any information about its porosity does not make possible to constrain its nature. On the other hand, recent works by Holsapple (2002, 2003) pointed out the possible role of cohesive forces in determining the strength of an asteroid. In particular, for asteroids of the size of our target where the gravitational pressures are small, the cohesion forces could become important so that we could speak about a “strength regime” (as it is customary in impact cratering studies). Note that an extremely low cohesion (compared to terrestrial rocks), of the order of a few parts in $10^4$, is enough to hold a non-spherical fast rotating body, such as (144898) 2004 VD17, together. An asteroid model with a low cohesion gives a bound on spin rate above the classical barrier, leading to a smooth transition between the data from small fast rotators to the larger bodies (where the gravity pressure dominates). E.g., in Fig. 3 of Holsapple (2003), (144898) 2004VD17 would fall within the new spin limits set by the $5 \times 10^4$ dyne/cm$^2$ curve. In other words, it is not necessary to refer to the category of “monoliths” to account for the fast rotation rate of our target, and a rubble pile structure with a negligible strength would suffice.

Considering diameter and density of our NEO, we can obtain an estimation of the impact energy, $E_{imp}$ (Chapman and Morrison 1994; Chesley et al. 2002). The impact velocity for the 2102 encounter is evaluated as
$V_{imp} = 21.36$ km/s (see, e.g., NEODyS). Assuming a range of densities from $\rho = 2$ to $\rho = 3.36$ g/cm$^3$, $E_{imp}$ varies from $\approx 7.8 \times 10^{18}$ J to $\approx 1.3 \times 10^{19}$ J, corresponding to 1871 and 3143 MT, respectively. Note that these values, while 4.5 to 7.5 times lower than those used by NEODyS to assess the risk, are still about two orders of magnitudes larger than the Tunguska event.

We rerun, with the methods of Milani et al. (2005), the impact risk estimation for the 2102 possible impact of (144898) 2004 VD17, which still has a small but non negligible probability, estimated at $4.2 \times 10^{-7}$ on the NEODyS risk page. We have used as mass value the upper limit of the range estimated above, rather than the mass computed on the basis of an “average” NEO albedo, as it is done when no data are available (Chesley et al. 2002).

If the risk is measured as expected impact energy (impact energy times probability), the value changes from 5.9 KT to 1.3 KT, in proportion to the mass. The other useful value is given by the Palermo Scale. The PS value has changed with the revised mass by $-0.52$ (corresponding to a factor 3.3 in the probability ratio); this factor is somewhat smaller than the one for the mass because the background probability does not scale in inverse linear relationship with the impact energy. The PS change was from $-3.52$ to $-4.04$, thus this case is now beyond the “psychological barrier” set at PS $= -4$ by the warnings posted on the NEODyS risk page. Nevertheless, because the orbit is now very well determined and no radar observations are possible for a long time, (144898) 2004 VD17 could remain on the “risk pages” of NEODyS and of the corresponding JPL Sentry system, although
with a low risk level, for decades.

The results we obtained for 2004 VD17 suggest some comments on our estimation of the impact risk and on the discovery completeness of the NEO population. Recent observations made possible to measure the albedo of the two NEOs with most stable Virtual Impactors, (99942) Apophis (Cellino et al. 2007) and, in this work, (144898) 2004 VD17. The measured albedos are much larger than the mean value of 0.1 usually adopted to convert the observed magnitudes in sizes. This resulted in an initial size overestimation, with a corresponding overestimation of the expected impact energy and Palermo Scale. This overestimation could occur systematically for Virtual Impactors, that are usually quite small (the impact probability of large objects is by far smaller). It is evident that, at a given magnitude cut-off, discovery surveys detect a larger fraction of higher albedo bodies, with respect to the fraction of bodies in the population corresponding, for the average albedo, to a given size. Therefore, the NEOs having virtual impactors could be biased in favour of high albedo objects.

5 Conclusions

During April and May 2006, a visible and near–infrared photometric and spectroscopic survey, as well as polarimetric observations of the NEO (144898) 2004 VD17, were carried out at the ESO-Chile telescopes.

With our survey, a complete analysis of (144898) 2004 VD17 was obtained:
i) on the basis of our polarimetric data an albedo of $p_v \sim 0.45 \pm 0.10$ was computed and a diameter of about $D \sim 320$ m was estimated;

ii) from the visible photometry the rotational period of $1.99 \pm 0.02$ hours was computed. The lightcurve analysis gave a lower limit of the semimajor axis ratio $a/b \geq 1.21 \pm 0.02$. 2004 VD17 is therefore a fast rotator object with an unexpected ellipsoidal shape;

iii) photometric images and lightcurve analysis found no companions nor cometary activity;

iv) visible spectra obtained at different rotational phases are very similar each other, suggesting an homogeneous surface composition for this object;

v) from the flat and featureless visible and near–infrared spectra, (144898) 2004 VD17 was classified as an E-type asteroid and analogies with the spectra of the aubrite meteorites were found. Our taxonomic classification has been confirmed also by the high value of the polarimetric albedo.

On the basis of our results, (144898) 2004 VD17 is therefore a very peculiar object. According to its density, diameter and rotational period, it is close to the limit estimated for the disruption of the “rubble-pile” structure, making hard to distinguish it as an aggregate, a monolith or a fractured monolith. The rubble pile structure is still possible if a strength regime is considered with a cohesion of a few times $10^4$ dyne/cm$^2$ (Holsapple 2002, 2003). Further
investigations on the porosity and the relative tensile strength are needed to better constrain the internal structure of this object.

(144898) 2004 VD17 has still a possibility of impacting the Earth (in the year 2102), compatible with the available astrometry. This risk cannot be easily removed by additional astrometry. Thus it was important to reduce the risk estimate by a factor 4.5 in the expected impact energy and by a factor 3.3 in the ratio of the probability of this event to the probability of an event of the same energy from the background population. Besides its scientific interest, (144898) 2004 VD17 is a dangerous object. Observing it had the additional value of contributing to decrease the estimated risk.

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Tables

Table 1: Orbital parameters of (144898) 2004 VD17

| Parameter                     | Value     |
|-------------------------------|-----------|
| Perihelion Distance (AU)      | 0.6203    |
| Aphelion Distance (AU)        | 2.3960    |
| Eccentricity                  | 0.5887    |
| Inclination (degree)          | 4.223     |
| Ascending Node (degree)       | 224.239   |
| Argument of perihelion (degree)| 90.686   |

Table 2: Observational circumstances: heliocentric and geocentric distances ($r$ and $\Delta$) and phase angle ($\alpha$) are referred at 0UT of each night.

| Date       | Telescope | Instrument | Range | Technique(s) | $r$ (AU) | $\Delta$ (AU) | $\alpha$ (degree) |
|------------|-----------|------------|-------|--------------|----------|---------------|-------------------|
| 16 Apr 06  | VLT-UT2   | FORS1      | Vis   | Polarimetry  | 1.426    | 0.497         | 26                |
| 23 Apr 06  | VLT-UT2   | FORS1      | Vis   | Polarimetry  | 1.365    | 0.485         | 35                |
| 01 May 06  | NTT       | EMMI       | Vis   | IMG + SPC    | 1.292    | 0.476         | 44                |
| 21 May 06  | NTT       | EMMI       | Vis   | IMG + SPC    | 1.098    | 0.460         | 67                |
| 22 May 06  | NTT       | EMMI       | Vis   | IMG + SPC    | 1.088    | 0.459         | 68                |
| 24 May 06  | VLT-UT1   | ISAAC      | NIR   | IMG + SPC    | 1.068    | 0.456         | 71                |
| 25 May 06  | VLT-UT1   | ISAAC      | NIR   | IMG + SPC    | 1.057    | 0.454         | 72                |
| 25 May 06  | VLT-UT2   | FORS1      | Vis   | Polarimetry  | 1.057    | 0.454         | 72                |
| 28 May 06  | VLT-UT2   | FORS1      | Vis   | Polarimetry  | 1.018    | 0.448         | 77                |
Table 3: Results for the (144898) 2004 VD17 polarimetric observations in the V filter. The position angles of the scattering plane ($\phi$) were taken from the JPL ephemeris service (http://ssd.jpl.nasa.gov/cgi-bin/eph).

| Date      | UT$_{start}$ | $\phi$ (°) | P (%)  | $\theta$ | $P_r$ (%) | $\theta_r$ (°) |
|-----------|--------------|------------|--------|----------|-----------|----------------|
| 16 Apr 06 | 02:09        | 105.1      | 0.53±0.11 | 14.1±5.9 | +0.53±0.11 | -1.1±5.9       |
| 23 Apr 06 | 01:27        | 107.8      | 0.76±0.08 | 21.0±3.0 | +0.76±0.08 | 3.1±3.0        |
| 25 May 06 | 00:05        | 109.9      | 2.21±0.18 | 22.0±2.3 | +2.21±0.18 | -0.2±2.3       |
| 28 May 06 | 23:32        | 109.6      | 2.35±0.13 | 20.0±1.6 | +2.35±0.13 | 0.4±1.6        |

Table 4: (144898) 2004 VD17 colors

| B-V  | V-R  | V-I  | V-J  | V-H  | V-K  |
|------|------|------|------|------|------|
| 0.76±0.03 | 0.40±0.03 | 0.75±0.03 | 1.16±0.04 | 1.15±0.08 | 1.56±0.06 |

Table 5: Observational circumstances for visible and near-infrared spectroscopy

| Date      | UT$_{start}$ | Grism | Slit (arcsec) | $T_{exp}$ (s) | $n_{exp}$ | airmass | Solar Analog (airmass) |
|-----------|--------------|-------|---------------|--------------|-----------|---------|------------------------|
| 01 May 06 | 01:14        | #1    | 5.0           | 1800         | 3×600s    | 1.27    | SA102-1081 (1.20)      |
| 20 May 06 | 23:26        | #1    | 5.0           | 1200         | 2×600s    | 1.34    | SA102-1081 (1.16)      |
| 21 May 06 | 23:41        | #1    | 5.0           | 1200         | 2×600s    | 1.40    | SA102-1081 (1.17)      |
| Date      | UT$_{start}$ | Band ($\mu$m) | Slit (arcsec) | $T_{exp}$ (s) | $n_{exp}$ | airmass | Solar Analog (airmass) |
|-----------|--------------|-------------|---------------|--------------|-----------|---------|------------------------|
| 25 May 06 | 00:05        | 1.10÷1.30  | 2.0           | 7200         | 3×2400s   | 1.15    | SA102-1081 (1.23)      |
| 25 May 06 | 01:51        | 1.84÷2.56  | 2.0           | 2520         | 1×2520s   | 1.14    | SA102-1081 (1.21)      |
Figure captions

FIGURE 1: Single night lightcurves of (144898) 2004 VD17 corrected for light-time. For V filter: (a) 1st May, (b) 21st May, (c) 22nd May; for R filter: (d) 1st May, (e) 21st May, (f) 22nd May.

FIGURE 2: Visible spectra of (144898) 2004 VD17 normalized at 0.55 μm. The three spectra are shifted by 0.5 for clarity.

FIGURE 3: Near-infrared spectra of (144898) 2004 VD17: (up) J filter, normalized at 1.25 μm; (down) Ks filter, normalized at 2.16 μm.

FIGURE 4: Polarization degree in the V band versus phase angle of (144898) 2004 VD17 and Near Earth and Main Belt E-type asteroids from Kiselev et al. (2002) and Fornasier et al. (2006a).

FIGURE 5: (144898) 2004 VD17 visible and near-infrared combined spectrum, normalized at 0.55 μm. The continuous line represents the spectrum of the Mayo Belwa aubrite meteorite.

FIGURE 6: (144898) 2004 VD17 composed lightcurves in V filter, folded with a period of 1.99 hours: (up) 1st May night: Δm = 0 corresponds to a mean magnitude of 19.32; the coverage of the spectra obtained on 1st May (1), 21st May (2) and 22nd May (3) is shown on the top; (down) 21st May (black dots) and 22nd May (white squares): Δm = 0 corresponds to a mean magnitude of 19.68. The lightcurve zero point is at 0UT of 12th May.

FIGURE 7: (144898) 2004 VD17 composed lightcurves in R filter, folded with a period of 1.99 hours: (up) 1st May night: Δm = 0 corresponds to a mean magnitude of 18.93; (down) 21st May (black dots) and 22nd May (white squares): Δm = 0 corresponds to a mean magnitude of 19.29. The
lightcurve zero point is at 0UT of 13th May.
Figures

Figure 1: De Luise et al. – Physical Investigation of PHA 2004VD17
Figure 2: De Luise et al. – Physical Investigation of PHA 2004VD17
Figure 3: De Luise et al. – Physical Investigation of PHA 2004VD17
Figure 4: De Luise et al. – Physical Investigation of PHA 2004VD17

Figure 5: De Luise et al. – Physical Investigation of PHA 2004VD17
Figure 6: De Luise et al. – Physical Investigation of PHA 2004VD17
Figure 7: De Luise et al. – Physical Investigation of PHA 2004VD17