

VISIBLE SPECTROSCOPY OF DARK, PRIMITIVE ASTEROIDS¹

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ABSTRACT

In the last years we have started a spectroscopic survey in the visible of dark primitive asteroids. These objects, considered the remnants of primordial processes of our solar system, belong essentially to the taxonomical classes C, P, and D. They are thought to contain water ice in their interiors and mineral assemblages derived from aqueous alteration processes of surface materials. In this paper we present the observations of 18 low-albedo asteroids. Only one asteroid, 238 Hypatia, has shown a feature centered around $0.6\ \mu\text{m}$, probably due to charge transfer transition $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$ in iron oxides (aqueous alteration products). The results obtained are discussed. The behavior of the reflectance of the objects with the heliocentric distance, with the albedo, and with the reflectivity of the known cometary nuclei will also be analyzed. © 1995 American Astronomical Society.

1. INTRODUCTION

Asteroids and comets have a close relationship with the planetesimals which formed in the solar nebula before 4.5 Gyr ago. These objects are considered the remnants of the primordial processes which characterized the evolution of the Solar System, immediately after the collapse of the protoplanetary nebula and before the formation of the planets. Since then, comets seem to have been submitted to a very low level of compositional evolution.

Many asteroids, especially those in the inner part of the main belt and the majority of the Near Earth Asteroids, belong to the S taxonomical class, whose bright albedos and spectral characteristics suggest that they have been fully heated and differentiated: their thermal evolution has been significant. On the other hand, the outer asteroids, smaller and with low albedo, have probably not undergone much thermal and geological evolution.

Therefore, many small bodies may have preserved materials which witnessed the condensation and the early phases of the formation of the Solar System. Detailed mineralogical characterizations of asteroids allow study of their evolutionary history and the history of our planetary system. The composition distribution of the asteroids is generally dependent on the heliocentric distance. In fact, beyond about 2.6 AU the asteroid belt is dominated by very low albedo objects belonging to the dark C, P, and D taxonomical classes, according to all current classifications (Tholen 1984; Barucci *et al.*

1987; Tedesco *et al.* 1989). The D asteroids are recognized to be the most primitive known asteroid types (Barucci *et al.* 1987; Bell *et al.* 1989). It is believed that the C asteroids are darkened by organic material and that the Ds, formed at lower temperature in the solar nebula, are even richer in organic material even if other darkening materials like magnetite and iron sulfide (both of which have been seen in meteorite samples) might be present on these objects. This is apparently due to the condensation of low-temperature, carbonaceous, dark, opaque minerals in the original solar nebula.

Grady & Veverka (1980) suggest that, on the average, the further we go from the Sun, the redder these objects become, owing to an increasing amount of hydrocarbons present on the asteroidal surface material. Vilas & Smith (1985) suggested that the increased reddening might be due to increasing simplicity in the hydrocarbons present with the heliocentric distance, owing to an increasing amount of H in the molecules.

It is now accepted (Vilas 1994) that a particular zone of the outer mainbelt is characterized by objects which have been aqueously altered, that is the low temperature ($<320\ \text{K}$) chemical alteration of materials by liquid water which acts as a solvent and produces materials like phyllosilicates, sulfates, oxides, carbonates, and hydroxides. Asteroids which have shown the presence of aqueous altered materials (hydrated silicates) seem to dominate the region between 2.6 and 3.5 AU and are essentially C asteroids. This might indicate the presence of water ice in the original asteroids that has been heated during the primordial phases of our Sun (T Tauri).

The proof of the presence of aqueous alteration products

¹Based on observations carried out at the European Southern Observatory (ESO), La Silla, Chile and at the Asiago Observatory, Italy.

TABLE 1. Observational characteristics.

Asteroid	Date	Observ.	Telesc.	r [AU]	Δ [AU]	Phase Angle[°]	m_v	Solar Analog
185 Eunike	15/08/93	Asiago	1.82m	2.578	1.626	9.69	11.4	HD 181655
313 Chaldea	"	"	"	2.794	1.897	11.68	13.2	HD 191854
654 Zelinda	17/08/93	"	"	2.808	1.836	7.08	12.6	"
142 Polana	"	"	"	2.532	1.591	-10.74	14.0	"
444 Gypsis	"	"	"	2.326	1.944	-25.47	12.2	"
336 Lacadiera	14/09/93	"	"	2.118	1.343	21.89	13.1	16 Cyg B
238 Hypatia	"	"	"	2.751	1.811	9.23	12.3	"
175 Andromache	"	"	"	2.568	1.799	-17.38	12.5	"
624 Hektor	25/09/93	ESO	1.50m	5.256	5.065	10.95	15.3	Hyades64
1167 Dubiago	"	"	"	3.190	2.442	13.74	15.1	"
76 Freia	"	"	"	3.596	2.665	6.90	13.4	"
606 Brangane	26/09/93	"	"	2.226	1.707	26.04	14.1	"
475 Oclo	"	"	"	1.603	0.725	25.94	13.4	"
31 Euphrosine	"	"	"	3.621	3.109	14.77	14.8	"
308 Polyxo	"	"	"	2.713	1.713	-3.53	11.7	"
153 Hilda	"	"	"	4.067	3.106	-4.56	13.4	"
70 Panopaea	"	"	"	2.389	1.432	-9.22	12.5	"
146 Lucina	23/12/93	Asiago	1.82m	2.893	2.192	11.23	13.1	16 Cyg B

on C asteroids is also largely a result of observations around $3\ \mu\text{m}$ by Lebofsky (1980) and by Jones *et al.* (1990), showing the strong water of hydration absorption feature centered around that wavelength.

The D asteroids, instead, have probably never experienced hydration processes, owing to the major distance from the Sun, and probably still contain water ice in their interiors.

Moreover, laboratory analysis suggest that the sources of the dark matter may be complex organic materials together with aqueous alteration products of igneous minerals, and also sulfides and magnetite may be possible sources of the opaques. Analysis of visible and infrared spectra is the only way at present to study the surface composition and the mineralogical and petrological characteristics of asteroids. In this

TABLE 2. Colors S' of the observed asteroids. The spectral ranges of the spectra obtained are also reported. The taxonomical classes reported are based on Barucci *et al.* (1987) and Tholen (1984) classifications.

Asteroid	Start Å	End Å	Slope S' %/10 ³ Å	$\sigma_{S'}$ %/10 ³ Å	Tholen Classification	Barucci Classification
185 Eunike	5020	9280	0.7	0.2	C	C
313 Chaldea	5020	9050	3.9	0.3	C	C
654 Zelinda	5020	9280	3.1	0.2	C	C
142 Polana	5020	9280	2.0	0.3	F	C
444 Gypsis	5020	9280	5.1	0.2	C	C
336 Lacadiera	5178	8950	8.1	0.9	D	D
238 Hypatia	5200	8950	2.9	0.8	C	C
175 Andromache	5150	9060	6.9	0.2	C	D
624 Hektor	5000	9285	16.1	0.3	D	D
1167 Dubiago	5000	9280	12.7	0.5	D	D
76 Freia	5000	9300	7.7	0.2	P	C
606 Brangane	5000	9025	16.7	0.5	T	D3
475 Oclo	5000	8960	12.7	0.3	P	C
31 Euphrosine	5000	8950	13.8	0.3	C	C
308 Polyxo	5000	8950	13.9	0.3	T	D3
153 Hilda	5000	8950	12.4	0.4	P	C
70 Panopaea	5000	8950	12.6	0.3	C	C
146 Lucina	5408	9785	9.9	0.2	C	C

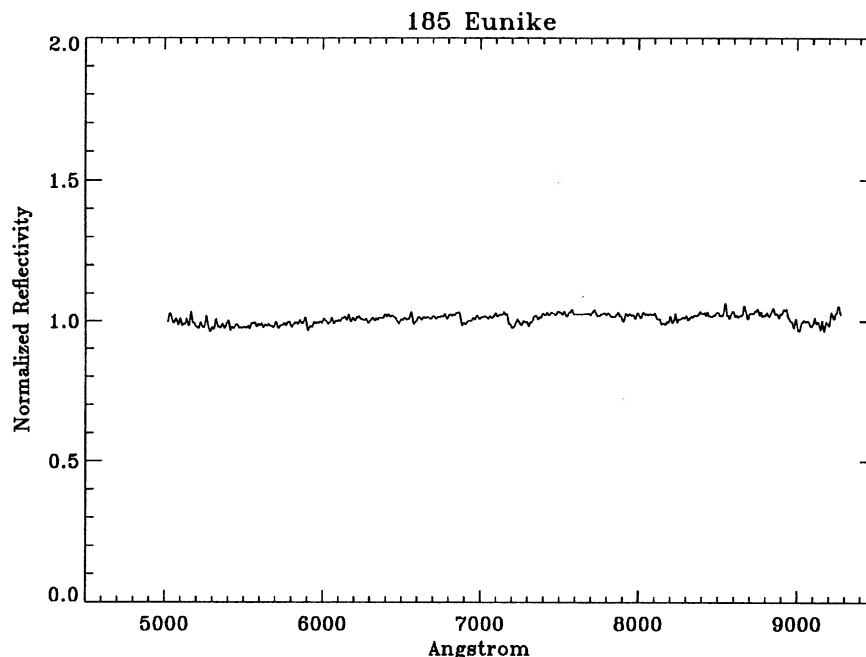


FIG. 1. Reflectivity spectrum of 185 Eunike normalized at 1 around 7000 Å.

context we started in 1993 a spectroscopic survey of asteroids: Near Earth objects in the visible region (Lazzarin *et al.* 1995), dark asteroids in the near infrared region (Barucci *et al.* 1994), and in the visible in the present work. The aim of this work is to investigate low albedo, primitive objects of the main belt, in particular to search for the presence of features in the reflectance spectra due to aqueous alteration products or to organic materials. In the present paper we will discuss the obtained results. The behavior of the reflectance

of the objects with the heliocentric distance, with the albedo, and with the reflectivity of the known cometary nuclei will also be analyzed.

2. OBSERVATIONS AND DATA REDUCTION

The data presented, 18 low-resolution spectra, have been obtained during different observing runs in the course of 1993 (Table 1).

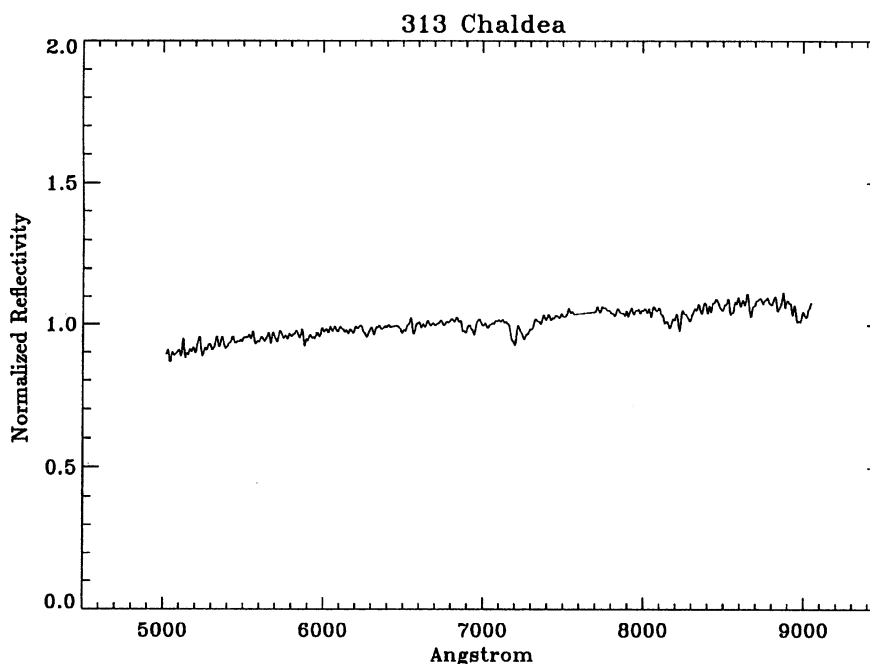


FIG. 2. Reflectivity spectrum of 313 Chaldea normalized at 1 around 7000 Å.

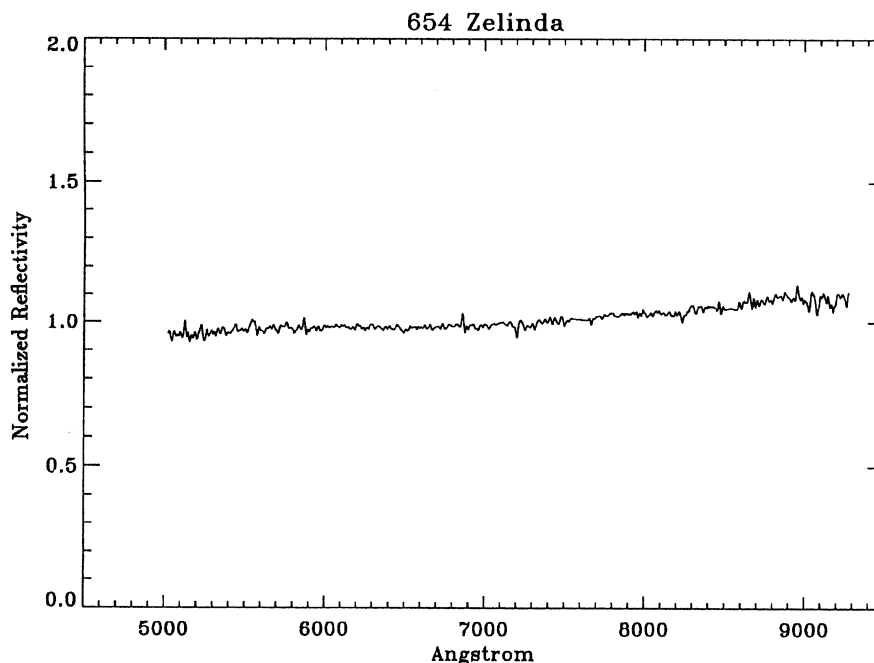


FIG. 3. Reflectivity spectrum of 654 Zelinda normalized at 1 around 7000 Å.

The observations were performed at the European Southern Observatory of 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) as 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 pixels, yielding a dispersion of 5

Å/pixel in the wavelength direction. The spectral range covered is about $0.5 < \lambda < 1 \mu\text{m}$ 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

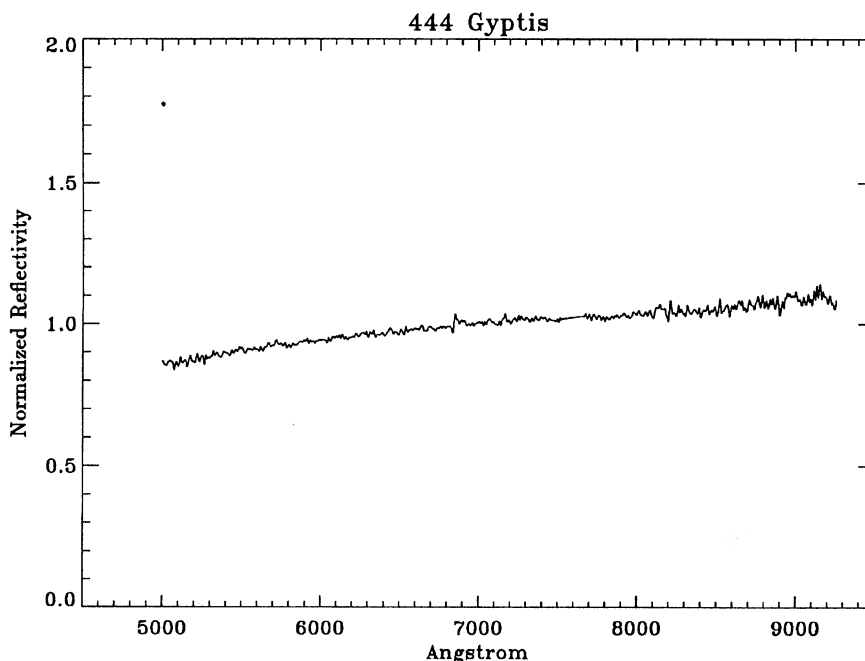


FIG. 4. Reflectivity spectrum of 444 Gypsis normalized at 1 around 7000 Å.

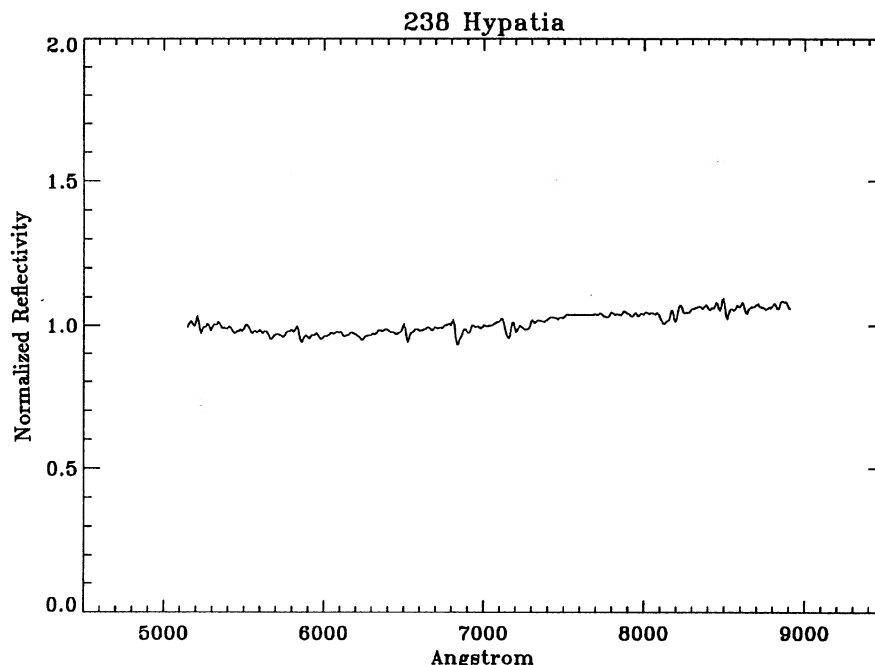


FIG. 5. Reflectivity spectrum of 238 Hypatia normalized at 1 around 7000 Å.

about 7.8 Å/pixel in the wavelength direction. The spectral coverage is about $0.5 < \lambda < 1 \mu\text{m}$ with an instrumental FWHM of 15.6 Å.

The spectral range is not the same for all the spectra (Table 2).

In both cases the slit was chosen relatively wide (2 arcsec for La Silla and 3 arcsec for Asiago), owing to the seeing

conditions during the observations and to reduce effects due to the differential refraction and the possibility of losing signal due to guiding errors of the telescope.

The reduction of the spectra has been performed using standard procedures (Luu & Jewitt 1989) of data reduction using the software MIDAS and IDL. In order to calibrate the observational data, bias, flatfield, calibration lamp, spectro-

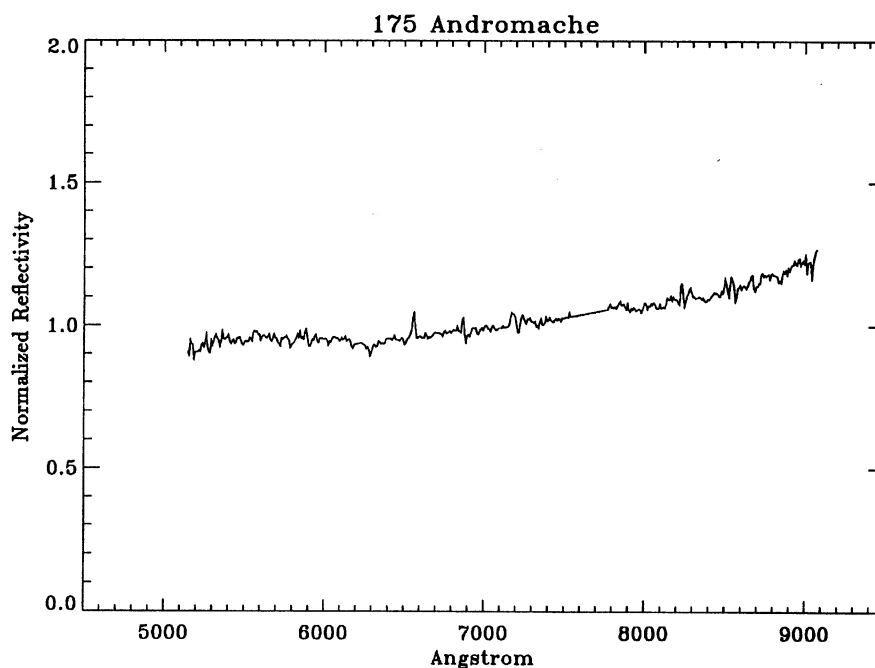


FIG. 6. Reflectivity spectrum of 175 Andromache normalized at 1 around 7000 Å.

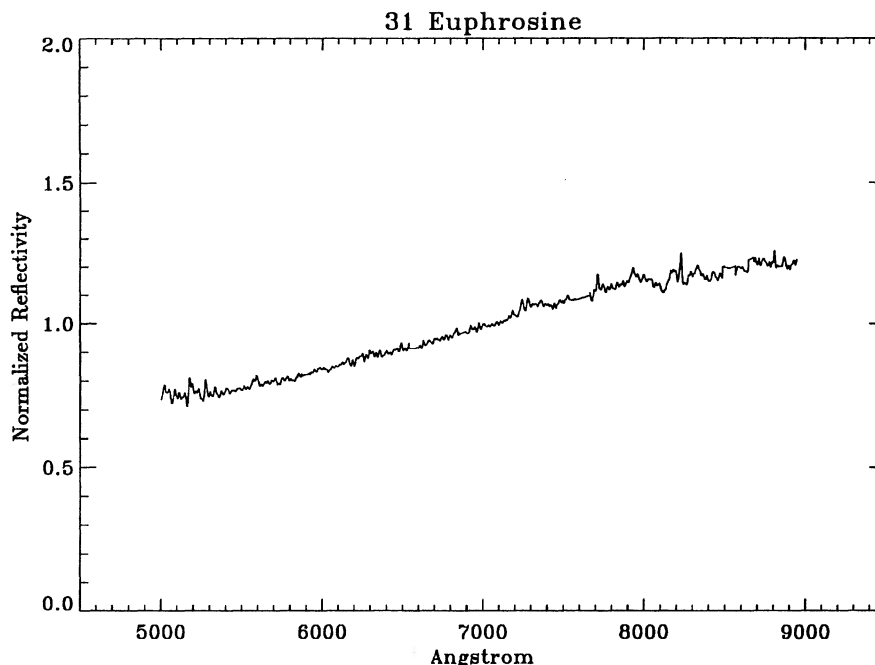


FIG. 7. Reflectivity spectrum of 31 Euphrosine normalized at 1 around 7000 Å.

photometric standard stars, and solar analogs (Hardorp, 1978) spectra were secured at different intervals throughout the observational period.

3. RESULTS

The reflectance spectra of the asteroids are reported in Figs. 1–18. We have observed nine objects of C class, one F, five D, and three P. 624 Hektor is a Trojan, 76 Freia and 1167

Dubiago are Cybele asteroids (asteroids located in the region bounded by the 2:1 and 5:3 resonances with Jupiter's orbit, beyond the main asteroid belt), and 153 Hilda is located in the Hilda group in the 3:2 resonance with Jupiter's orbit.

The other asteroids belong to the outer main belt, in particular the Cs to the *alteration zone* (Vilas 1994). The spectra are normalized at 1 around 0.7 μm . Some of them show spurious features, probably due to the division by the solar analog spectrum, which is an imperfect elimination of the

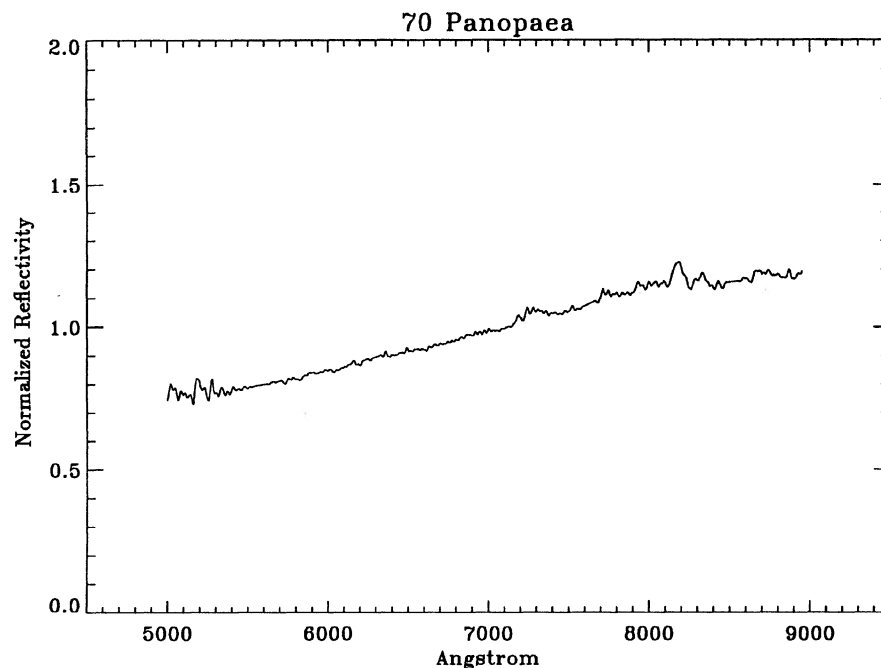


FIG. 8. Reflectivity spectrum of 70 Panopaea normalized at 1 around 7000 Å.

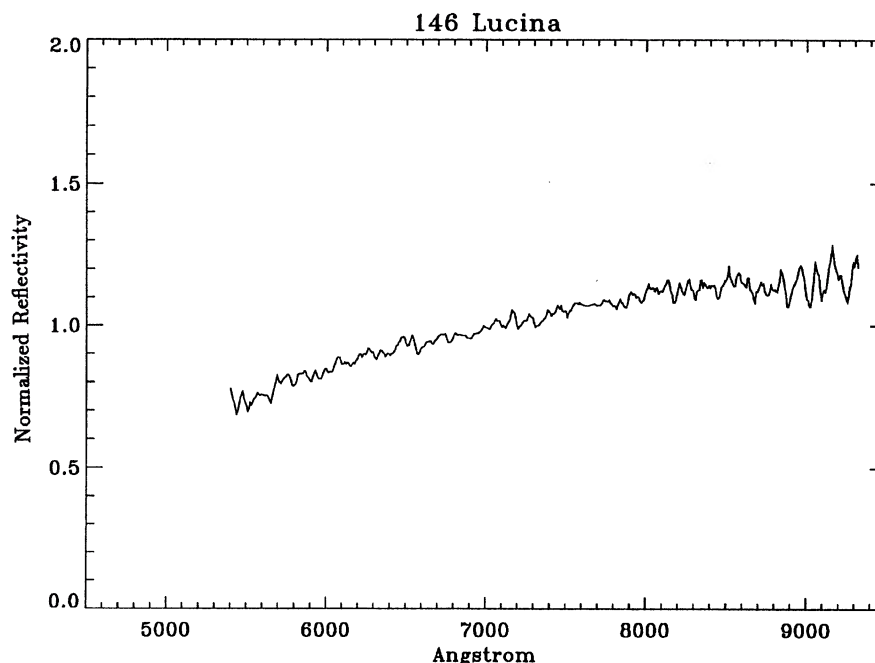


FIG. 9. Reflectivity spectrum of 146 Lucina normalized at 1 around 7000 Å.

solar features, or due to an imperfect cancellation of the atmospheric O₂ bands at 7612 and 6880 Å. The strong atmospheric water absorptions which start near 0.9 μm, coupled with a drop in the CCD response at those λ, have influenced the behavior of the spectra in this region and especially the identification of spectral features that might be present between 0.8 and 0.9 μm.

The reflectance spectra have neutral slope (*color*) or redder than the solar one, typical of these low albedo objects.

The *color* has been determined computing the reflectivity gradient of the spectra (Jewitt & Luu 1989):

$$S'(\lambda_1, \lambda_2) = \frac{\Delta S}{\Delta \lambda}, \quad (1)$$

which gives the reflectivity variation as function of wavelength in the spectral range considered. In this case, the spectral range in which we have determined S' is $0.60 < \lambda < 0.85$

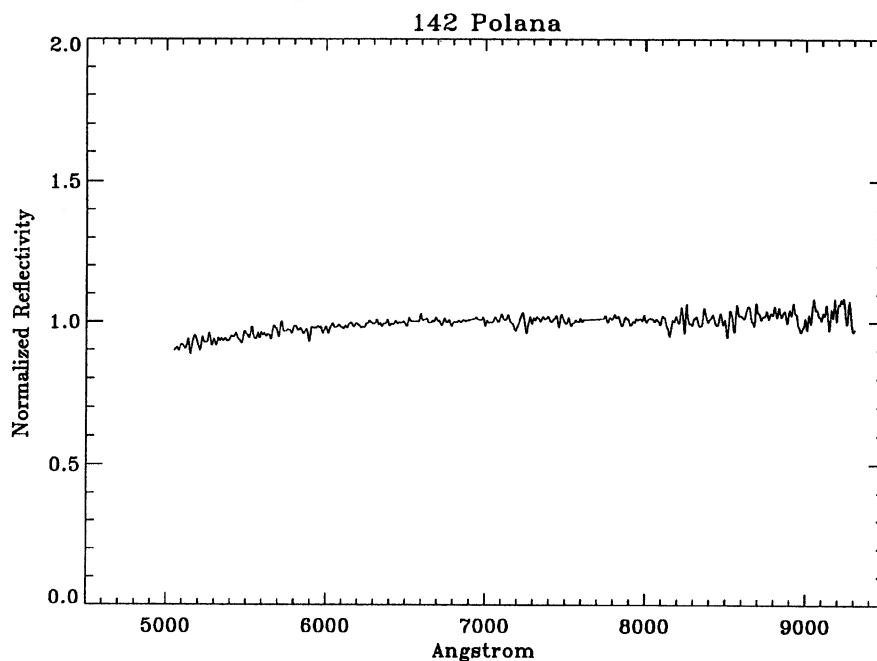


FIG. 10. Reflectivity spectrum of 142 Polana normalized at 1 around 7000 Å.

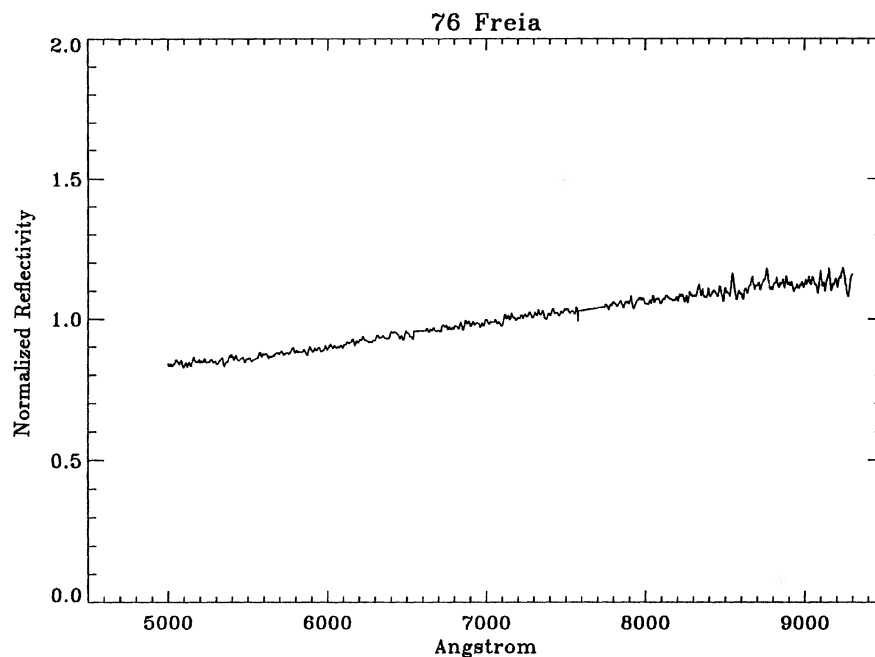


FIG. 11. Reflectivity spectrum of 76 Freia normalized at 1 around 7000 Å.

μm and the values for the 18 spectra, expressed in $\%/10^3 \text{ \AA}$, are reported in Table 2.

4. DATA ANALYSIS

Spectra of asteroids with spectral resolution similar to ours, but often in different spectral ranges, have been obtained by Vilas & Smith (1985), Vilas & McFadden (1992), Vilas *et al.* (1993), Jewitt & Luu (1990), and Fitzsimmons

et al. (1994). Fitzsimmons *et al.* (1994) have determined the reflectivity gradients for several D-type objects and among them 1167 Dubiago, 606 Brangane, and 308 Polyxo, present also in this work. The values obtained by Fitzsimmons *et al.* (1994) are, respectively, $S' = 9.4, 14.4, 9.6, 8.9\%/10^3 \text{ \AA}$, different from ours (Table 2). Anyway, the spectral range in which Fitzsimmons *et al.* (1994) determined S' is $0.4 < \lambda < 0.74 \mu\text{m}$ and, as the spectra are not a perfect linear functions of λ , the spectral range in which the linear interpolation

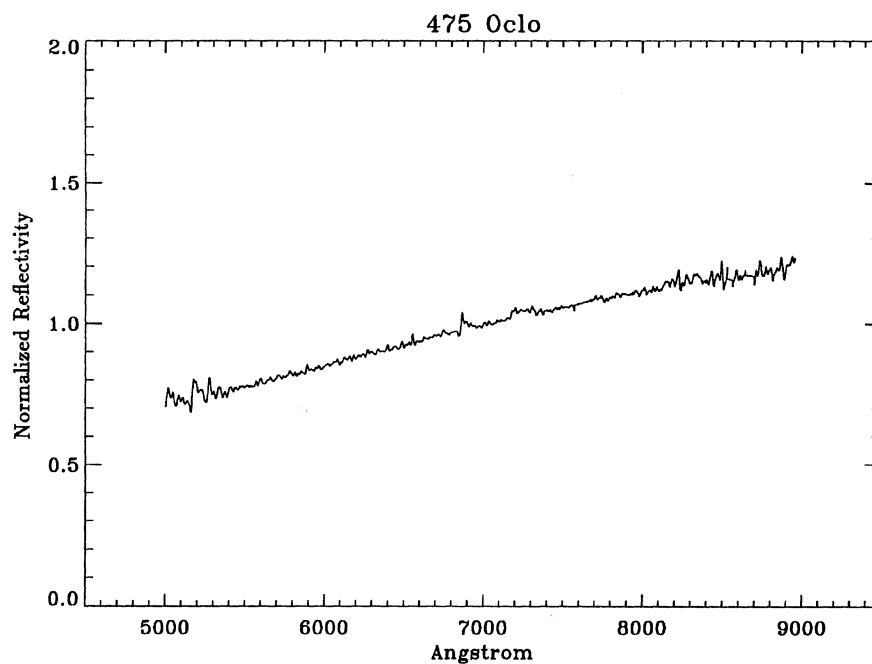


FIG. 12. Reflectivity spectrum of 475 Oclo normalized at 1 around 7000 Å.

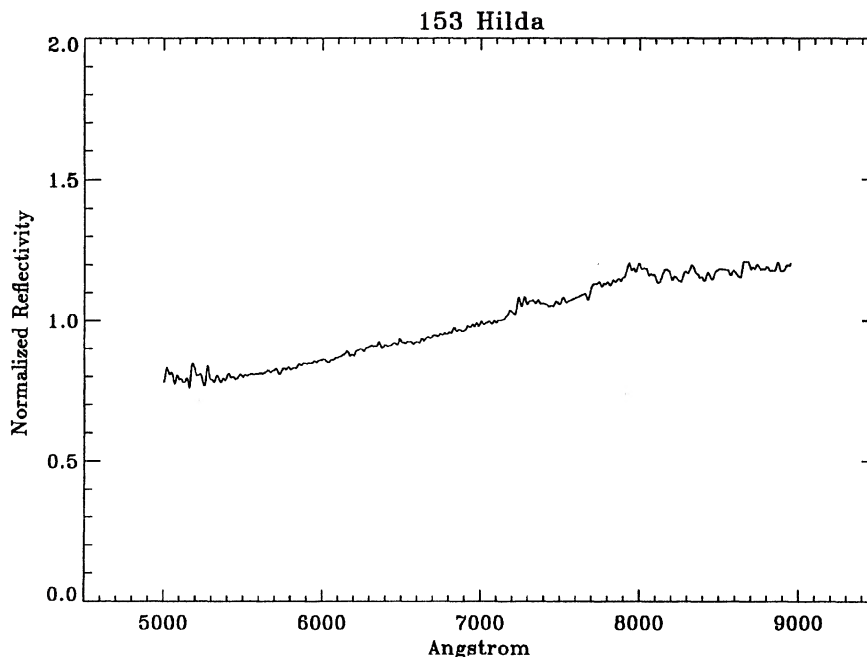


FIG. 13. Reflectivity spectrum of 153 Hilda normalized at 1 around 7000 Å.

is computed might be significant. We have a similar difference for the reflectivity of 624 Hektor determined by Jewitt & Luu (1990) ($S' = 8.8\%/10^3 \text{ Å}$), that can be explained in the same way.

A very qualitative comparison can be made with the spectra obtained by Vilas *et al.* (1993), for which S' has not been determined. For example, 31 Euphrosine and 606 Brangane are flatter than our spectra, 153 Hilda is more noisy, 624 Hektor is redder, 76 Freia is very similar to ours. These differences are not very easily interpreted. Simple explanations

could be that the asteroids have been observed at different phase angles or they have shown different surface regions with different reflectance properties and so different compositional areas when observed by the different observers.

Below we report the analysis of the spectra obtained in this work.

4.1 C Asteroids

The C asteroids observed belong to the *alteration zone* identified by Vilas (1994), except 313 Chaldaea ($a=2.4 \text{ AU}$)

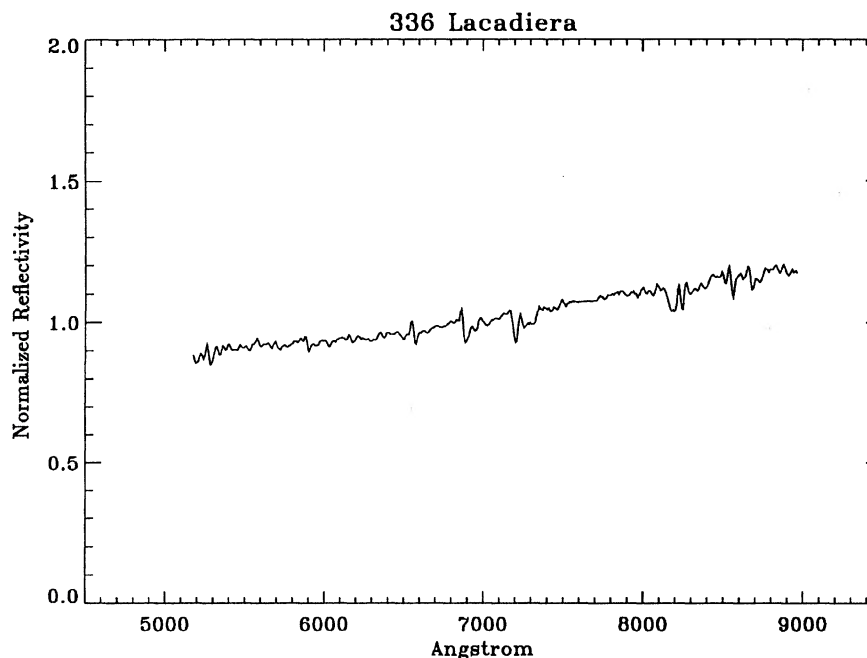


FIG. 14. Reflectivity spectrum of 336 Lacadiera normalized at 1 around 7000 Å.

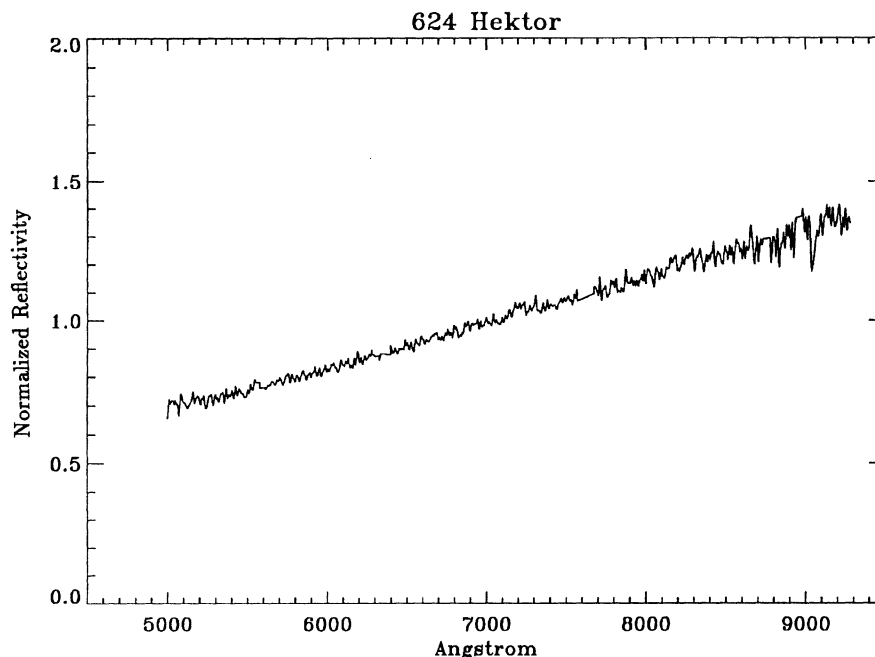


FIG. 15. Reflectivity spectrum of 624 Hektor normalized at 1 around 7000 Å.

and 654 Zelinda ($a=2.3$ AU). Among these objects, only 238 Hypatia shows an absorption feature centered around $0.6\ \mu\text{m}$ with a depth with respect to the continuum of about 6%. It is probably due to aqueous altered materials ($\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$ in iron oxides) (Vilas *et al.* 1994).

The *color* of the C objects is not neutral for all objects, with variations between $S'=0.7\%/10^3\ \text{\AA}$ (185 Eunike) and $S'=13.8\%/10^3\ \text{\AA}$ (31 Euphrosine).

The difference in reflectivity among the observed C aster-

oids (Table 2) might be due to a different surface composition.

Differences in surface composition have been suggested for the low-albedo asteroids, especially the C class, by Vilas *et al.* (1994) and by Britt *et al.* (1994).

We have carried out a statistical analysis to determine a possible correlation between S' and the semimajor axis a and S' and the albedo p_v . The values of a and p_v are reported in Table 3. Linear interpolation is not compatible with the er-

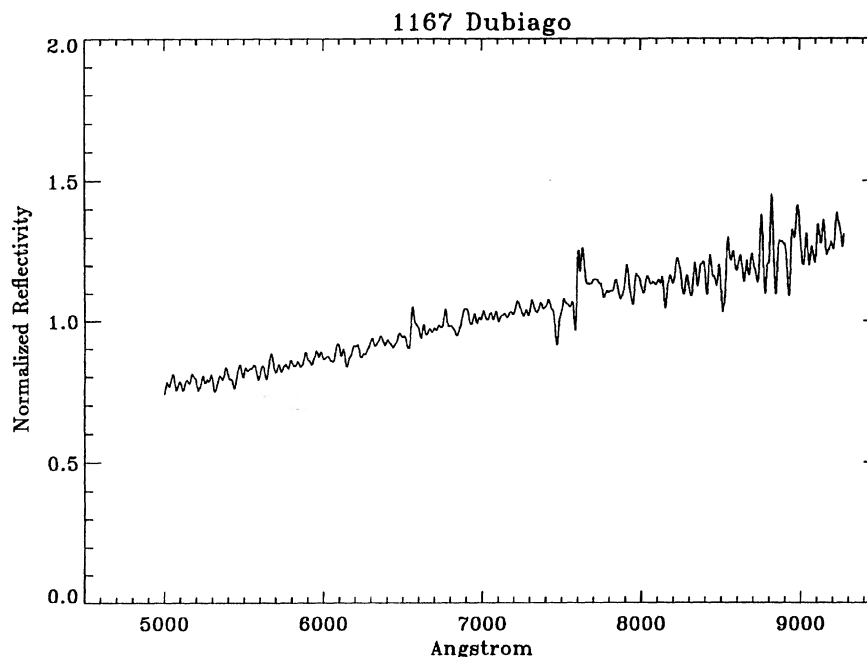


FIG. 16. Reflectivity spectrum of 1167 Dubiago normalized at 1 around 7000 Å.

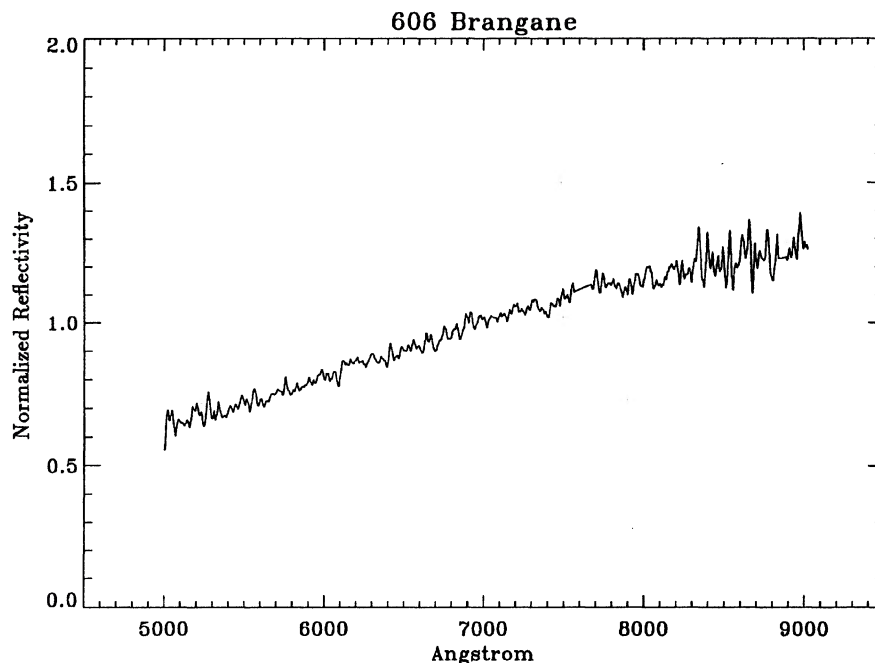


FIG. 17. Reflectivity spectrum of 606 Brangane normalized at 1 around 7000 Å.

rors in any of the two cases with a confidence level of 95%. So, no linear correlation has been found between S' and the two parameters. The average value of S' is $6.5 \pm 0.1\%/10^3 \text{ Å}$.

4.2 F Asteroids

142 Polana, the F type asteroid observed, shows a spectral slope similar to that of Cs ($S' = 2.0 \pm 0.3\%/10^3 \text{ Å}$). The ob-

tained spectrum disagrees with the behavior of the one obtained by Vilas *et al.* (1993) that shows a negative slope.

4.3 P Asteroids

76 Freia, 153 Hilda, and 475 Oclo, classified as C in Barucci *et al.* (1987) taxonomy, are considered P type by Tholen. For this reason we analyzed them separately. They

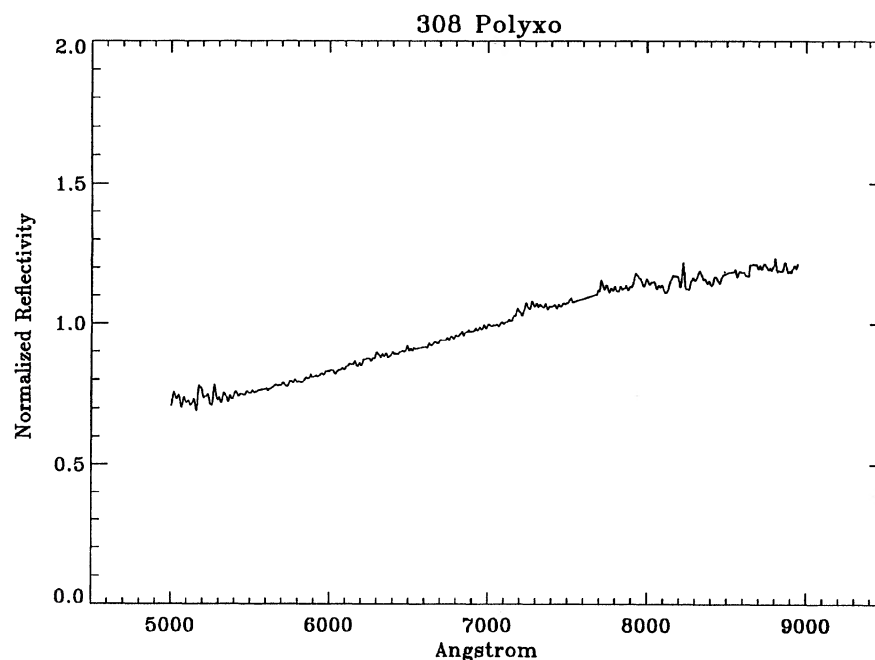


FIG. 18. Reflectivity spectrum of 308 Polyxo normalized at 1 around 7000 Å.

TABLE 3. Physical characteristics of the observed asteroids: IRAS albedo p_v (Tedesco *et al.* 1992), diameter (Tedesco *et al.* 1992), semimajor axis, and taxonomical class. Albedo and diameter of 475 Oclo derive from Tedesco (1989).

Asteroid	p_v	Diameter [Km]	a [AU]	Class
185 Eunike	0.064 ± 0.002	157.5 ± 2.6	2.739	C
313 Chaldea	0.052 ± 0.002	96.3 ± 1.7	2.376	C
654 Zelinda	0.042 ± 0.003	3.9 ± 0.9	2.297	C
142 Polana	0.045 ± 0.003	55.3 ± 1.6	2.419	F-C
444 Gyptis	0.051 ± 0.010	159.6 ± 13.1	2.771	C
336 Lacadiera	0.046 ± 0.003	69.3 ± 2.4	2.252	D
238 Hypatia	0.043 ± 0.002	148.5 ± 3.6	2.907	C
175 Andromache	0.082 ± 0.005	100.9 ± 2.9	3.212	C
624 Hektor			5.201	D
1167 Dubiago	0.051 ± 0.010	63.1 ± 5.6	3.413	D
76 Freia	0.036 ± 0.002	183.7 ± 4.0	3.390	P-C
606 Brangane	0.097 ± 0.013	35.5 ± 2.2	2.587	T-D3
475 Oclo	0.033 ± 0.005	31.0 ± 2.0	2.596	P-C
31 Euphrosine	0.054 ± 0.005	255.9 ± 11.5	3.156	C
308 Polyxo	0.048 ± 0.003	140.7 ± 3.8	2.750	T-D3
153 Hilda	0.062 ± 0.002	170.6 ± 3.3	3.696	P-C
70 Panopaea	0.067 ± 0.003	122.2 ± 2.3	2.616	C
146 Lucina	0.053 ± 0.002	132.2 ± 2.4	2.719	C

show a $\langle S' \rangle = 10.9 \pm 0.2\% / 10^3 \text{ \AA}$, intermediate value between C and D. 76 Freia and 153 Hilda has already been observed by Vilas & McFadden (1992) and Vilas *et al.* (1993), and they confirm our results.

4.4 D Asteroids

The D asteroids till now observed belong to the main belt, except the trojan 624 Hektor and the Cybele asteroid 1167 Dubiago.

Spectra of Hektor, Dubiago, Brangane with similar resolution and spectral range to ours have been obtained by Vilas & McFadden (1992), Vilas *et al.* (1993), and Jewitt & Luu (1990) and they confirm the behavior of the spectra of the three objects obtained in this work.

The *color* of the D asteroids obtained is redder than the solar one, a typical behavior of the D objects, with an average value $\langle S' \rangle = 13.5 \pm 0.2\% / 10^3 \text{ \AA}$. We have not determined any dependence of the *color* on the heliocentric distance as otherwise determined by Lagerkvist *et al.* (1993), but the number of our objects is at present not statistically very significant to confirm this result. We have determined no dependence of S' on the albedo.

4.5 Comparison Among the Observed Objects

We tried to determine a possible relation among low albedo objects of different taxonomical classes or if these classes are well separated.

With the same method used for C asteroids, we have looked for a linear correlation among the points in the planes (S', a) , and (S', p_v) , using a least square fit and considering the errors on both variables (Fasano & Vio 1988). In this computation we have not included 624 Hektor as its albedo

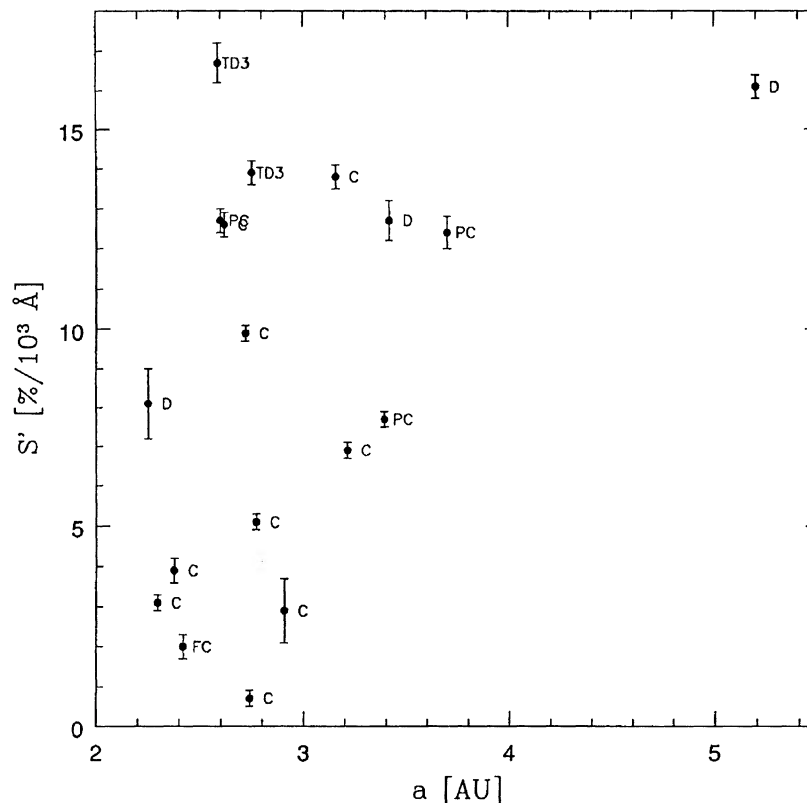
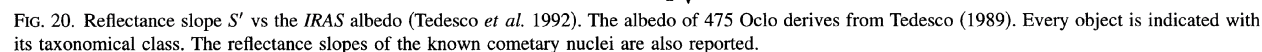


FIG. 19. Reflectance slope S' vs the semimajor axis. Every object is indicated with its taxonomical class.



4.6 Comparison with Cometary Nuclei

We compare also the surface composition of dark asteroids with that of the known cometary nuclei as previously done by Jewitt & Luu (1990) and Fitzsimmons *et al.* (1994). The cometary nuclei are at present a very few number and the quality of the data is very poor, as it is a very difficult



task to obtain spectra of cometary nuclei without coma. For this reason, any kind of comparison must be considered a preliminary one.

We compared the two classes of objects using their *color* because at present no characteristic features on the spectra of cometary nuclei are known. The spectra of the available cometary nuclei are usually featureless with positive slopes. At present, the colors of the known cometary nuclei are: Halley, $S' = 6 \pm 3\%/10^3 \text{ \AA}$ (Thomas & Keller 1989); Tempel 2, $S' = 20 \pm 3\%/10^3 \text{ \AA}$ (Jewitt & Luu 1989); Neujmin 1, $S' = 12 \pm 1\%/10^3 \text{ \AA}$ (Jewitt & Meech 1988); Encke, $S' = 11 \pm 1\%/10^3 \text{ \AA}$ (Luu 1993); Arend-Rigaux, $S' = 9.3 \pm 0.6\%/10^3 \text{ \AA}$ (Millis *et al.* 1988); 2060 Chiron, $S' = -0.5 \pm 0.2\%/10^3 \text{ \AA}$ (Fitzsimmons *et al.* 1994). Chiron is the only nucleus known which shows a spectrum with a negative slope. In Fig. 21 we report the color diagram for the two types of objects. In spite of the small number of available objects, the comparison shows a good overlapping, suggesting a possible common origin of the two groups of objects.

For the comparison we used also the albedos (p_v) of these objects [Halley: 0.04 ± 0.01 (Sagdeev *et al.* 1986); Tempel 2: 0.023 ± 0.007 (A'Hearn *et al.* 1988); Neujmin 1: 0.022 ± 0.010 (Campins *et al.* 1989); Arend-Rigaux: 0.028 ± 0.05 (Millis *et al.* 1988); 2060 Chiron: ≥ 0.04 (Jewitt & Luu 1992)], as shown in Fig. 20.

The comets Neujmin1, Arend-Rigaux, and Halley show clearly albedo and colors similar to those of the dark asteroids. It is evident that more data of good quality are needed for these comparisons, especially of cometary nuclei.

5. CONCLUSION

From the observations till now performed, the importance of the investigation on the primitive objects surface composition is evident as its knowledge helps to study and define the evolution of the primordial solar nebula and its thermal distribution.

To date, there is no clear evidence for absorption features

in the visible spectra of either D-class asteroids or cometary nuclei.

It is believed that these more distant asteroids could contain ice in their interiors. Probably, the original composition of the outer main-belt objects was an assemblage of anhydrous silicates, water ice, and interstellar organic material (like kerogen). A similar composition is probably present also on C asteroids which are nearer to the Sun than the Ds, but probably they have been more thermally processed and this caused ice fusion and aqueous alteration processes on their surface. Among the sample of nine C objects observed, only one of them has shown a feature probably due to the presence of aqueous processed materials.

The fact that not all C asteroids observed show features of aqueous alteration products has been explained for example by Lebofsky (1980) as due to the heating of the objects caused by the impacts, the dehydration of the clay minerals in the vacuum, and the sublimation of water ice eventually present on the surface. Moreover, the primordial heating might not have affected all the objects in the same manner.

There are other reasons why C-class asteroids may not show absorption features, ranging from Britt's idea (Britt *et al.* 1994) that many Cs are shock darkened of different composition, to Vilas' suggestions (Vilas *et al.* 1994) that variations exist among classes and possibly across the surfaces of the same asteroid.

The results obtained from the comparison of S' of cometary nuclei and dark asteroids indicate that, at least for surface composition, the distinction between comets and asteroids is not so sharp any more, especially as far as dark asteroids are concerned.

We suggest that more data of dark asteroids are needed, in particular of D objects, to investigate the hydration state of their surfaces. We need also more observations of cometary nuclei, even if they are very faint when they are without a visible coma, to investigate the possible common origin of comets and dark asteroids.

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