ACCESSORY PHASES IN AUBRITES: SPECTRAL PROPERTIES AND IMPLICATIONS FOR ASTEROID 44 NYSA

EDWARD A. CLOUTIS

ER Georesearch Ltd., 4 Huntstrom Road N.E., Calgary, Alberta, Canada

and

MICHAEL J. GAFFEY

Department of Earth and Environmental Sciences, Rensselaer Polytechnic Institute, Troy, New York, U.S.A.

Abstract. The reflectance spectra of meteoritic metal, meteoritic troilite and the CR carbonaceous chondrite EET87770 have been measured in order to investigate the causes of the spectral differences between the surface of the E-class asteroid 44 Nysa and the opaque free fraction of the Happy Canyon aubrite meteorite. The data indicate that the spectral differences require the presence on Nysa's surface of a small amount of a spectrally red sloped material, of which metal and troilite are the most reasonable candidates, and a material possessing absorption bands near $0.9 \mu m$ and $1.8 \mu m$. A material similar to the carbonaceous chondrite inclusions found in some aubrites can provide a match to the $0.9 \mu m$ feature and perhaps the $1.8 \mu m$ feature. The required abundances of these components depends on whether they are areally distributed or intimately mixed with an enstatite rich material. Based on the petrologic associations seen in aubrites and a series of simulated mineral mixtures, an intimate mixture of 69–92% enstatite and 1–11% metal + troilite and an areal component of 7–20% carbonaceous chondrite type material can provide a reasonable match to the $0.3–2.6 \mu m$ spectrum of Nysa.

1. Introduction

Observational data, including visible and near-infrared spectroscopy (Chapman and Gaffey, 1979; Bell *et al.*, 1988; Gaffey *et al.*, 1989), infrared photometry (Veeder *et al.*, 1978) and photopolarimetry (Zellner, 1975; Zellner *et al.*, 1977) for asteroid 44 Nysa suggest that this object, a member of the E asteroid class, may be mineralogically similar to aubrite meteorites. The most compelling evidence for this association involves the high geometric and absolute albedo (~38% and ~49%, respectively; Zellner, 1975; Gaffey *et al.*, 1989). These values strongly suggest that the dominant surface component is a transition metal free silicate such as forsterite, plagioclase feldspar, enstatite or diopside.

Enstatite is considered the most viable of these on the basis of the meteoritical evidence: of the possible candidate materials, only enstatite rich meteorites are known. Two enstatite rich meteorite groups have been identified, enstatite (E) chondrites and aubrites (enstatite rich achondrites). For the purposes of spectral identification, they differ primarily in the amounts of opaque components (metal and troilite) they contain (Keil, 1968; Watters and Prinz, 1979). Much of the
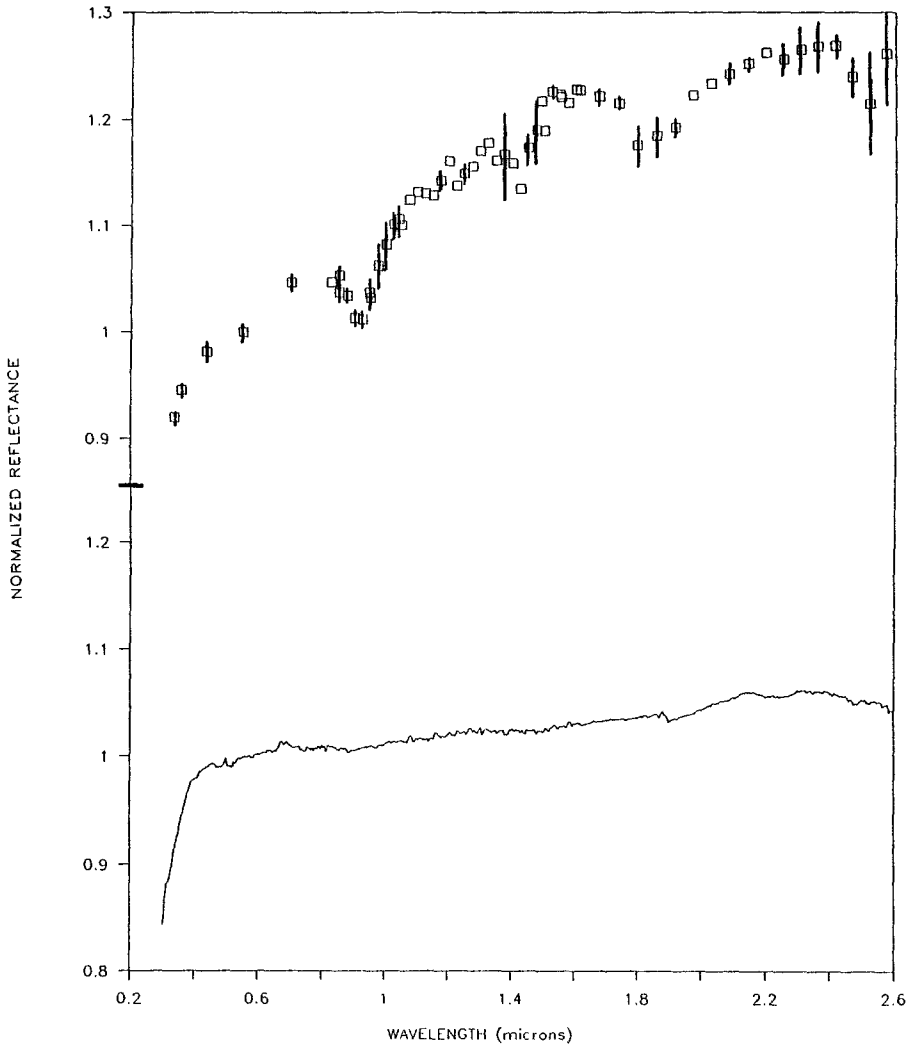
Fig. 1.   Normalized reflectance spectra (1 at 0.56 μm) of 44 Nysa (upper) (Zellner *et al.*, 1985; Gaffey *et al.*, 1989) and the opaque free fraction of the Happy Canyon aubrite (lower). Vertical scale is the same for both spectra.

evidence linking 44 Nysa to aubrite meteorites was the subject of an earlier study (Cloutis *et al.*, 1990b). A spectral comparison of the opaque free fraction of the Happy Canyon (HC) aubrite to Nysa indicated that while absolute reflectance values in the visible region are similar, Nysa exhibited a redder slope and a more strongly featured spectrum than HC (Figure 1).

   If Nysa is related to the aubrites the spectral differences may be due to the opaque minerals present in aubrites, which were removed prior to the spectral

TABLE I

Chemical analyses of some of the samples used in this study

Wt. %	PYX003	PYX205	Wt. %	TRO201	PRH101
SiO_2	50.33	60.40	Fe	61.50	58.53
Al_2O_3	5.46	0.00	Ni	0.03	0.70
FeO	17.30	0.07	S	37.71	40.36
Fe_2O_3	1.43	N.D.	V	0.00	0.00
MgO	23.58	40.78	Co	0.02	0.07
CaO	1.59	0.34	P	0.00	0.00
Na_2O	0.05	N.D.	Cr	0.32	0.08
TiO_2	0.41	0.00	Mg	0.00	0.04
Cr_2O_3	0.11	0.00	Mn	0.00	0.00
V_2O_5	0.02	0.03	Cu	0.00	0.00
CoO	0.04	0.00	Al	0.02	0.05
NiO	0.01	0.12	Pb	0.00	0.00
MnO	0.29	0.04	Zn	0.08	0.18
ZnO	N.D.	0.00	Ti	0.00	0.00
Total	100.62	101.78		99.68	100.01
Atomic ratios					
Mg	68.5	99.3	Fe	11.6	10.9
Fe^{2+}	28.2	0.1	S	12.4	13.1
Ca	3.3	0.6			

PYX003, orthopyroxene; PYX205, enstatite in Happy Canyon aubrite; TR0201, troilite from Canyon Diablo iron meteorite; PRH101, terrestrial pyrrhotite.
N.D. – Not Determined.

measurements of Happy Canyon, or surface processes operating on asteroids which may not be preserved in recovered meteorites (Britt and Pieters, 1987).

2. Experimental Procedure

A variety of samples were spectrally characterized including a terrestrial low calcium pyroxene from Mantyharja, Finland (PYX003), the opaque free fraction of the Happy Canyon aubrite (HC) whose pyroxene analysis is presented as PYX205, meteoritic metal ground from the Odessa, Texas coarse octahedrite (Buchwald, 1975), troilite from the Canyon Diablo coarse octahedrite (TRO201), a synthetic stoichiometric troilite (FeS, TRO202) obtained from Electronic Space Products International (purity 99.999%), terrestrial pyrrhotite (PRH101, locality unknown) and a sample of the Antarctic CR carbonaceous chondrite EET87770,19 from the NASA Planetary Materials Branch Meteorite Working Group.

The compositions of the various samples used in this study have been determined by electron microprobe analysis at the University of Calgary SEMQ facility and are averages of 4–8 point analyses and area scans. The data have been reduced using Bence–Albee α and β correction factors and are presented in Table I.

Ferrous iron values have been obtained by wet chemical methods and ferric iron as the difference between total and ferrous iron.

The powdered mineral samples used for the spectral measurements were prepared by crushing the samples in an alumina mortar and pestle. Any impurities were removed through a combination of magnetic separation and hand picking. The cleaned samples were repeatedly wet sieved with acetone to obtain well sorted size ranges. The reflectance spectra have been acquired at the NASA Reflectance Experiment Laboratory (RELAB) facility in the Department of Geological Sciences at Brown University (Pieters, 1983). The bidirectional reflectance spectra (0.3–2.6 μm) were measured at 5 nm resolution relative to halon, a near perfect diffuse reflector in the 0.3–2.6 μm region (Weidner and Hsia, 1981) and corrected for minor ($\sim$2%) irregularities in halon's absolute reflectance in the 2 μm region, as well as for dark current offsets. The PYX003 and EET87770 spectra were measured at $i = 30°$ and $e = 0°$, all others were measured at $i = 0°$ and $e = 15°$. The sample spectra were measured for <45 μm sized fractions except PYX205 and one of the metal samples where the 45–90 μm sized fractions were used. Band depths (D_b) have been measured using Equation (32) of Clark and Roush (1984).

3. The Spectrum of Nysa

The Eight Color Asteroid Survey (ECAS; Zellner *et al.*, 1985) and 52 color asteroid survey data for Nysa (Bell *et al.*, 1988; Gaffey *et al.*, 1989) are shown in Figure 1 along with the HC spectrum. Both spectra are reasonably well matched at wavelengths below $\sim$0.7 μm. At longer wavelengths the Nysa spectrum is more red sloped (reflectance generally increasing toward longer wavelengths) than HC or the other available aubrite spectra (Gaffey, 1974, 1976). Spectral slope has been quantified using the ratio of the reflectance at 2.5 μm to that at 0.8 μm (Table II). The Nysa spectrum exhibits a number of apparent absorption features near 0.9 μm, 1.4 μm, 1.8–1.9 μm and 2.5 μm. The 1.4 μm and 1.9 μm features may be due to telluric water which was incompletely removed during data reduction and will not be considered further here. The 0.9 μm, 1.8 μm and 2.5 μm bands are relatively shallow with band depths on the order of 3–7% (Table II). The wavelength positions of the 0.9 μm and 1.8 μm bands suggests the presence of a spectrally significant amount of a low iron, low calcium content pyroxene (Cloutis and Gaffey, 1991).

4. The Spectra of Aubrites and Enstatite Chondrites

Since an enstatite rich lithology is indicated for the surface of Nysa (Cloutis *et al.*, 1990b), the available reflectance spectra for enstatite rich meteorites (E-chondrites and aubrites) have been compared to the spectrum of Nysa (Gaffey, 1974; Salisbury *et al.*, 1975; Gaffey, 1976; Miyamoto, 1987). A number of spectral parameters for Nysa which are useful for comparing to the meteorite spectra are listed in

TABLE II

Selected spectral parameters of asteroid 44 Nysa, aubrites, E-chondrites, synthetic forsterite and meteoritic minerals

	Grain size (μm)	Reflectance ratio (2.5 μm/0.8 μm)	Band depth at 0.9 μm (%)	Band depth at 1.8 μm (%)	Absolute reflectance at 0.56 μm (%)	Source of data
44 Nysa	–	1.16	~3–7	4–5	~49	1
Aubrites						
Happy Canyon[a]	45–90	1.04	1	<1	44	2
Cumberland Falls	N.A.	0.87	~2	<1	23	3
Norton County[b]	N.A.	1.13	≤2	<1	42	3
Bishopville[b]	N.A.	0.92	~2	<1	48	3
E-chondrites (petrologic grade)						
Y-691 (E3)	<46	1.30	<2	<2	10	4
Y-691 (E3)	Plate	1.15	<2	<2	9	4
Abee (E4)	N.A.	1.46	~3	<1	6	3
Abee (E4)	<74	~1.5	<1	<1	9	5
Indarch[b] (E4)	N.A.	1.29	~5	<1	5	3
Indarch (E4)	<74	~1.5	<1	<1	9	5
St. Mark's[b] (E5)	N.A.	1.17	~3	<1	9	3
Hvittis[c] (E6)	N.A.	1.13	~3	<1	18	3
Hvittis (E6)	<74	~1.2	<2	<1	16	5
Khairpur (E6)	N.A.	1.16	~2	<1	12	3
Pillistfer (E6)	N.A.	1.17	~2	<1	16	3
Synthetic minerals, CR chondrite, meteoritic minerals						
Fosterite, synthetic	<37	1.29	<1	<1	72	6
EET87770, CR chondrite	<45	1.17	4	1	10	2
Troilite, synthetic	<45	1.06	17	<1	5	2
Troilite, meteoritic	<45	1.47	<1	<1	6	2
Troilite, meteoritic	N.A.	1.29	<1	<1	6	7
Meteoritic metal	<45	1.80	<1	<1	11	2
Meteoritic metal	45–90	1.99	<1	<1	10	2

[a] Opaque free fraction.
[b] Visible evidence of alteration.
[c] Spectral evidence of alteration.
N.A. – Not Available.
Sources of data: [1] Gaffey *et al.* (1989); [2] This study; [3] Gaffey (1974, 1976); [4] Miyamoto (1987); [5] Salisbury *et al.* (1975); [6] Adams (1975); [7] Britt and Pieters (1990).

Table II, including absolute reflectance, overall slope (2.5 μm/0.8 μm reflectance ratio) and 0.9 and 1.8 μm band depths. From this data it appears that aubrites generally provide a better match to Nysa in terms of absolute reflectance than do the E-chondrites. E-chondrites provide the best match in terms of spectral slope

while petrologic grade 4 and 5 E-chondrites provide the best match in terms of the 0.9 μm band depth. Thus both E-chondrites and aubrites possess spectral features comparable to Nysa.

Two points must be considered in evaluating the data. Adams and Filice (1967) have shown that decreasing grain size results in an increase in overall reflectance for silicates. Decreasing the average grain size of the E-chondrites by a factor of 2 would not be sufficient to increase their average reflectance to Nysa values (Adams and Filice, 1967; Miyamoto, 1987; Cloutis et al., 1986). A number of the aubrite and E-chondrite specimens which were spectrally characterized showed visible evidence of rust due to oxidation of the metal. The presence of this weathering product can and does affect spectral slopes, most noticeably in the visible spectral region (Gaffey, 1974; Salisbury and Hunt, 1974; Salisbury et al., 1975; Gooding, 1981). The opaque-and alteration-free aubrite spectra are not as red sloped as Nysa.

This suggests that neither the aubrites nor the E-chondrites are able to simultaneously reproduce the slope, absolute reflectance and absorption bands of the Nysa spectrum. The absolute reflectance differences between the E-chondrites and Nysa appear to be irreconcilable which suggests that the surface materials on Nysa are similar to the aubrites (enstatite-rich, opaque-poor). However, an additional component or components must be invoked to account for the 0.9 μm and 1.8 μm absorption features and the differences in overall slope.

5. Spectra of Possible Accessory Phases

Aubrites are not composed solely of enstatite although this material forms the bulk of the meteorites (75–98%). They also contain lesser amounts of plagioclase feldspar (1–16%), diopside (0.2–8.1%), olivine (0.3–10%), metallic nickel-iron (<0.1–3.7%) and troilite (<0.1–7.1%) (Reid and Cohen, 1967; Olsen et al., 1977; Watters and Prinz, 1979; Watters et al., 1980; Keil et al., 1989). They also contain trace amounts of other minerals such as oldhamite, caswellsilverite, daubreelite, alabandite and schreibersite (Keil and Fredriksson, 1963; Watters and Prinz, 1979; Okada and Keil, 1982). Some aubrites also contain chondritic inclusions which are readily apparent due to their dark color (Binns, 1969; Neal and Lipschutz, 1981; Verkouteren and Lipschutz, 1983; Lipschutz et al., 1988; Weisberg et al., 1988; Grady et al., 1991).

The Happy Canyon aubrite contains enstatite, plagioclase and diopside and minor amounts of metal and troilite which have survived extensive terrestrial weathering (Olsen et al., 1977). The opaque free fraction of Happy Canyon that has been spectrally characterized (Figure 1) contains contributions from enstatite, plagioclase and diopside. Since the HC spectrum does not match the red slope and absorption bands of Nysa but can account for the high absolute reflectance (Cloutis et al., 1990b), other materials must be invoked to explain these differences. In order for possible accessory materials in aubrites to be considered viable

for explaining the spectral differences between HC and Nysa they must exhibit desirable spectral features, should be present in aubrites, and the required abundances should ideally be in agreement with the data for aubrites.

5.1. OLIVINE

The olivine in aubrites is essentially pure forsterite (Fo99.79–99.99; Watters and Prinz, 1979). The reflectance spectrum of a <37 μm sized synthetic iron free forsterite (Adams, 1975) exhibits high overall reflectance (>70%) across the 0.5–2.5 μm range and a red slope (2.5/0.8 μm reflectance ratio of 1.29) and no absorption bands. Forsterite abundances of up to 10% are found in aubrites (Watters and Prinz, 1979). However the Bishopville aubrite which contains 6.7% forsterite (Watters and Prinz, 1979) does not exhibit a red slope (Gaffey, 1974, 1976; Table II). This suggests that forsterite cannot reasonably be invoked to account for the slope difference between HC and Nysa or the 0.9 μm and 1.8 μm absorption bands of Nysa.

5.2. PLAGIOCLASE FELDSPAR

Happy Canyon contains 5–10% (An26) plagioclase feldspar (Olsen *et al.*, 1977). This type of plagioclase exhibits high overall reflectance and an absorption band near 1.17 μm (Adams, 1975; Adams and Goullaud, 1978). No evidence of a plagioclase absorption band is seen in the HC spectrum at this wavelength (Figure 1) and the Nysa data are too noisy to identify a band at this wavelength. The 2.5 μm/0.8 μm reflectance ratio of plagioclase of this composition is ~1 and it shows no absorption bands near 0.9 μm and 1.8 μm. Thus plagioclase feldspar, even if present at the tens of percent level on the surface of Nysa cannot account for the slope difference between HC and Nysa or the 0.9 μm and 1.8 μm absorption bands.

5.3. PYROXENE

The wavelength positions of the absorption features near 0.9 μm and 1.8 μm in Nysa's spectrum coincide with those expected for a low iron, low calcium content pyroxene (Adams, 1974; Cloutis and Gaffey, 1991). The HC and available aubrite spectra indicate that the iron content of the enstatite in Happy Canyon and aubrites (Fs0.01–0.4; Olsen *et al.*, 1977; Watters and Prinz, 1979) is apparently too low to result in appreciable absorption bands. Enstatite more iron rich than Fs0.4 has not been found in aubrites (Reid and Cohen, 1967; Watters and Prinz, 1979).

However, enstatite as iron poor as Fs3 exhibits absorption bands as deep as 30% in <37 μm sized sample spectra (Adams, 1968) and the presence of only a few percent of this material intimately mixed with aubrite type enstatite would result in pyroxene absorption bands near 0.9 μm and 1.8 μm with depths similar to Nysa. The reflectance spectrum of an iron and aluminum bearing orthopyroxene
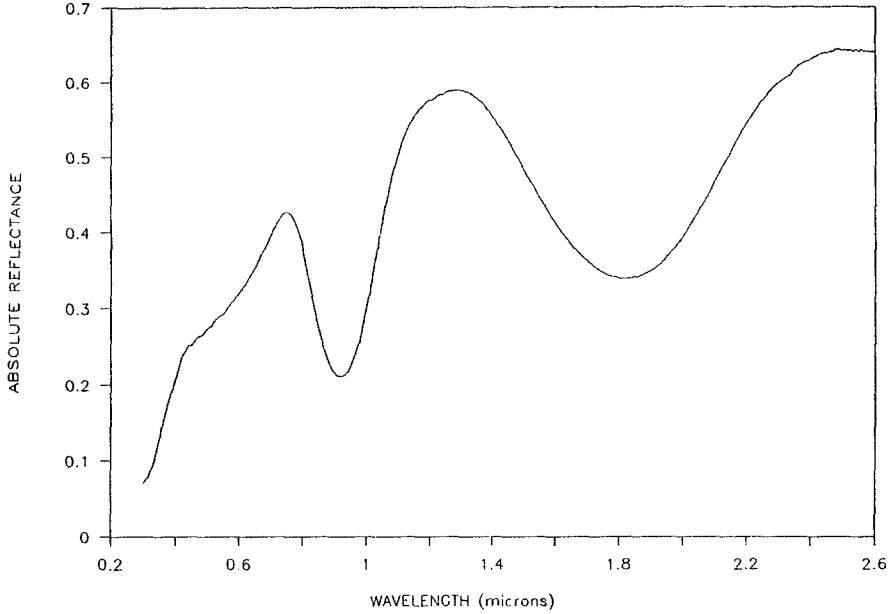
Fig. 2. Absolute reflectance spectrum of the iron- and aluminum-bearing pyroxene PYX003.

(PYX003, Table I) is shown in Figure 2. This pyroxene was chosen for this study because of the unavailability of a suitably low iron enstatite and because the presence of aluminum shifts the major ferrous iron absorption bands to shorter wavelengths (Cloutis *et al.*, 1990c), in this case to near 0.9 μm and 1.8 μm.

5.4. IRON SULPHIDES

Titanium bearing troilite (FeS) abundances range from <0.1% to 7.1% in aubrites (Watters and Prinz, 1979; Watters *et al.*, 1980; Keil *et al.*, 1989). The titanium content of these troilites (up to 5.7%) exceeds that of E-chondrite troilite. In order to ascertain whether troilite or a related iron sulphide could account for some of the spectral properties of Nysa, the reflectance spectra of meteoritic troilite (TRO201, from the Canyon Diablo iron meteorite), synthetic troilite (TRO202, pure FeS) and pyrrhotite (PRH101, $Fe_{1-x}S$) were measured. Their reflectance spectra are presented in Figure 3 and the compositions of TRO201 and PRH101 are given in Table I.

    X-ray diffraction analysis of the samples indicates that the pyrrhotite and meteoritic troilite are essentially pure. Their spectra are generally similar, both show red slopes and no resolvable absorption bands. The meteoritic troilite spectrum exhibits an overall red slope (2.5 μm/0.8 μm ratio of 1.47) but no absorption bands near 0.9 μm and 1.8 μm. Troilite from another iron meteorite, Mundrabilla, is spectrally similar to the Canyon Diablo troilite – a red slope and no resolvable
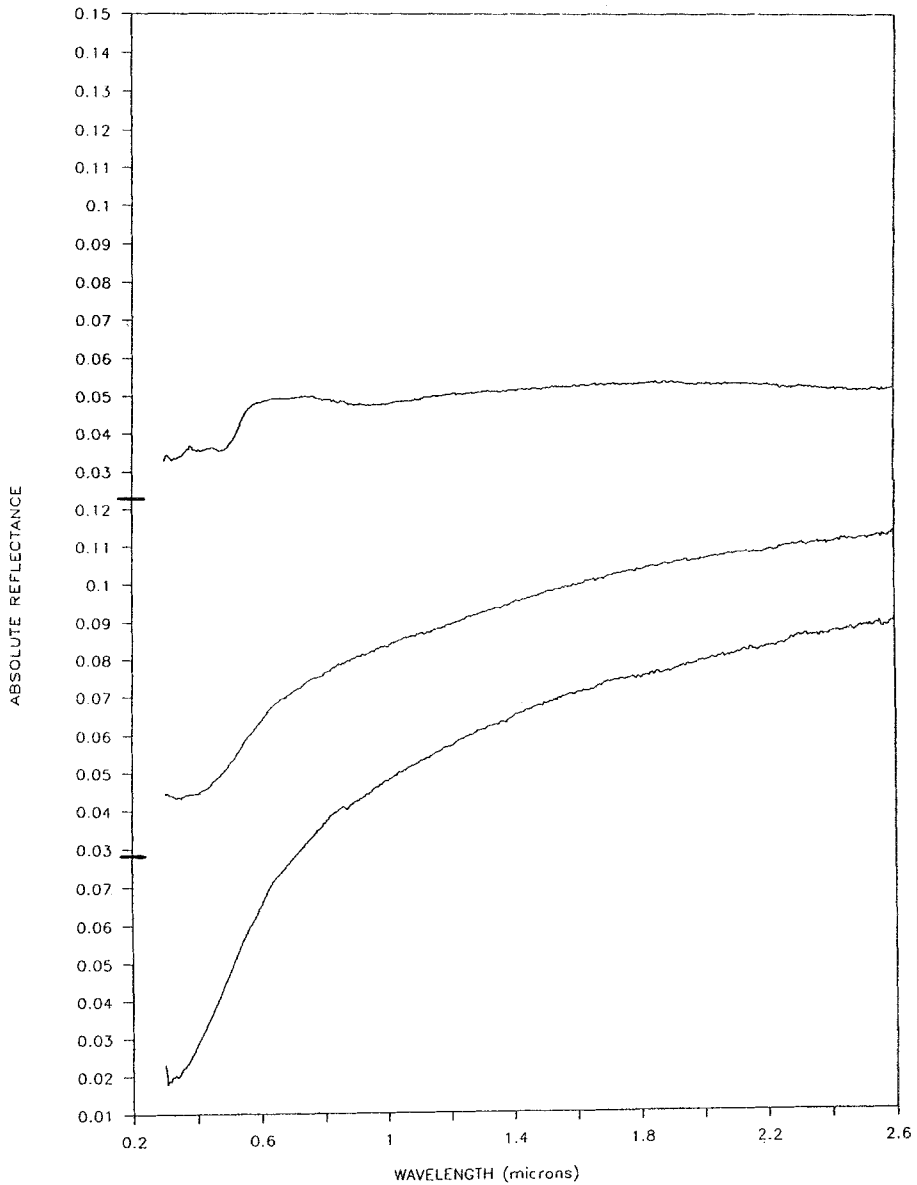
Fig. 3.   Absolute reflectance spectra of synthetic troilite (TR0202, upper), meteoritic troilite (TR0201, middle) and pyrrhotite (PRH101, lower).

absorption bands (Britt and Pieters, 1990). The spectrum of the synthetic troilite does not exhibit a red slope in the 0.8–2.5 μm range but shows an absorption band near 0.95 μm. The cause of the spectral differences between the two troilite samples is not known but may be related to the differences in their respective formation conditions.

The amount of intimately mixed troilite required to reconcile the slope differences between Nysa and HC is on the order of 10–20%, outside the range of the aubrites. This amount of troilite, intimately mixed with enstatite would lower overall reflectance to well below that of Nysa and could not, in any case, account for the 0.9 μm and 1.8 μm absorption feature in Nysa's spectrum.

5.5. METEORITIC METAL

Aubrites are more metal poor than E-chondrites but can contain up to 3.7 wt% metal (Watters and Prinz, 1979). The reflectance spectra of <45 μm and 45–90 μm sized meteoritic metal are shown in Figure 4. As expected, the metal spectra are red sloped (Table II) and display no obvious absorption features in the 0.3–2.6 μm region. Metal can be invoked to account for the red spectral slope of Nysa if it is present in amounts exceeding those found in aubrites (see below). To date, no viable mechanism has been found for preferentially enriching metal abundances on asteroid surfaces (Gaffey, 1986). The metal also cannot account for the 0.9 μm and 1.8 μm absorption bands of Nysa.

5.6. CHONDRITIC INCLUSIONS

A number of enstatite rich meteorites, both E-chondrites such as Abee and aubrites such as Cumberland Falls, Shallowater and ALH78113, contain xenolithic inclusions of a material distinctly darker than the host material (Binns, 1969; Neal and Lipschutz, 1981; Score et al., 1982; Rubin and Keil, 1983; Verkouteren and Lipschutz, 1983; Sears et al., 1983; Lipschutz et al., 1988; Keil et al., 1989). The presence of this material in more than one aubrite suggests that it may also conceivably be present on the surface of Nysa. Analyses of these inclusions indicate mineralogical affinities with various meteorite groups such as the F-chondrites. These inclusions are composed predominantly of low iron olivine, orthopyroxene and opaque phases (Graham et al., 1977; Neal and Lipschutz, 1981; Verkouteren and Lipschutz, 1983).

The amount of this material required for spectral analysis and its relative scarcity negated the possibility of measuring its spectral properties; consequently a sample of the Antarctic CR carbonaceous chondrite meteorite EET87770 was spectrally characterized. The mineralogy of the CR chondrites (Mason and Wiik, 1962; Meteorite Working Group, 1989; Weisberg et al., 1989a, 1989b, 1990; Weisberg and Prinz, 1991) is generally similar to the chondritic inclusions in terms of optically significant components – low iron pyroxene and olivine and abundant opaque phases. The reflectance spectrum of EET87770 (Figure 5) exhibits a number of desirable spectral features: the 0.8–2.5 μm slope is approximately as red as Nysa (Table II) and it exhibits an absorption band near 0.9 μm with a band depth approximately equal to Nysa. There is a slight indication of an absorption feature in the 1.8–1.9 μm region but this may be the result of terrestrial weathering (Meteorite Working Group, 1989). The pyroxene:olivine ratio of EET87770 is unknown but an increase in this ratio would result in deeper pyroxene absorption
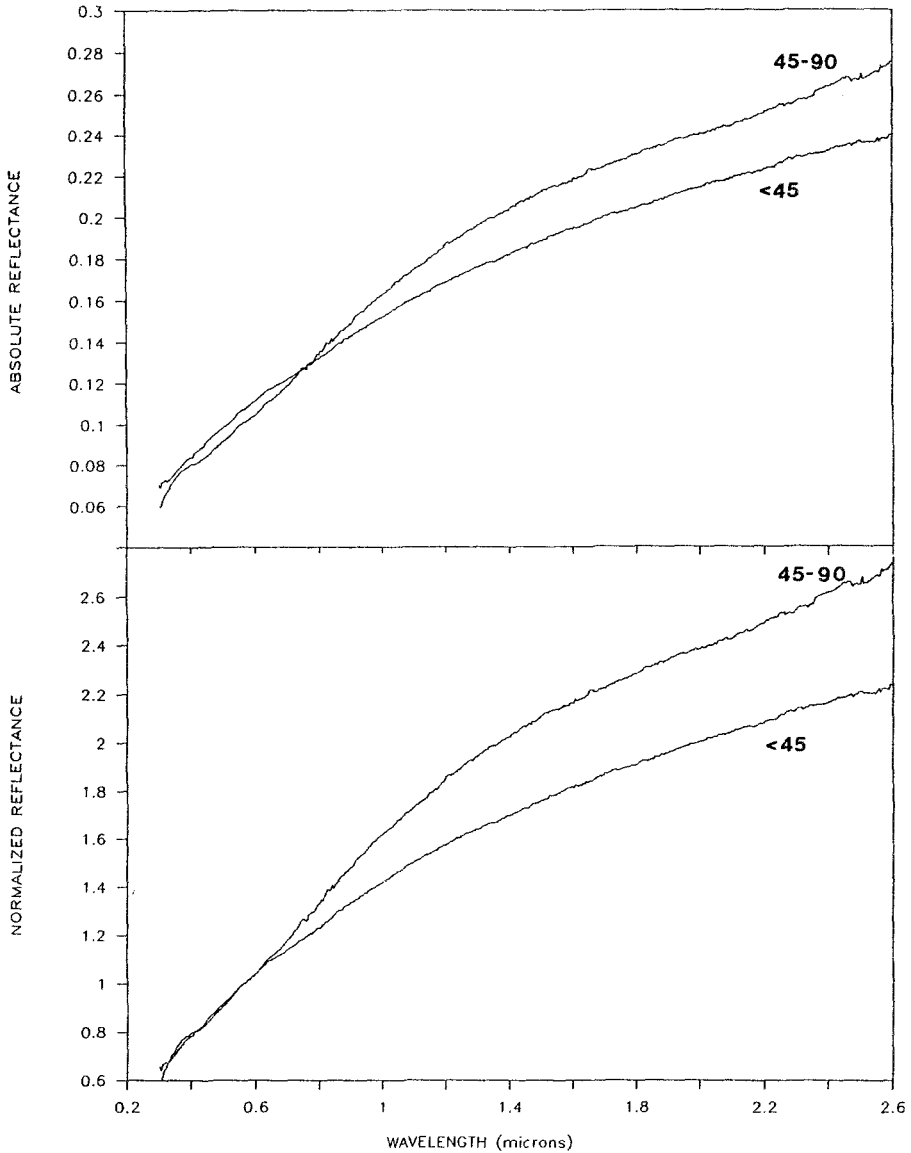
Fig. 4. Absolute (upper) and normalized (1 at 0.56 μm, lower) reflectance spectra of <45 μm and
45–90 μm size metal from the Odessa iron meteorite.

bands near 0.9 μm and 1.8 μm. These factors suggest that the chondritic inclusions
found in aubrites may possess a number of spectral features which are compatible
with those seen in the spectrum of Nysa.

Reflectance spectra of other carbonaceous chondrites (Johnson and Fanale 1973;
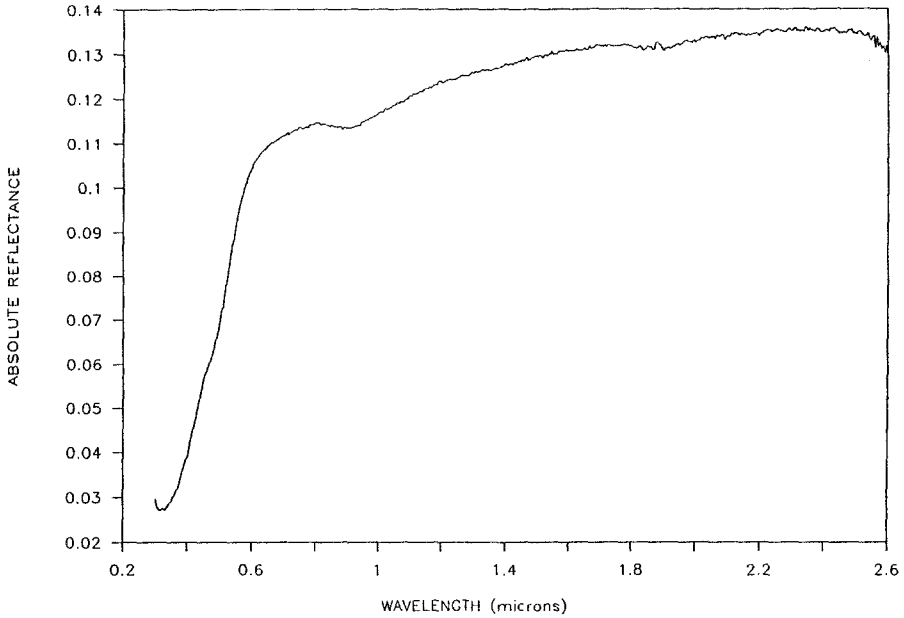Gaffey, 1974, 1976) particularly C3 chondrites such as Warrenton and Lance

Fig. 5.   Absolute reflectance spectrum of a <45 μm size sample of the CR carbonaceous chondrite EET87770.

exhibit resolvable pyroxene absorption bands. Thus while EET87770 does not display all the requisite spectral features to account for those seen in the spectrum of Nysa, small changes in its mineralogy could conceivably resolve many of the differences.

6. Spectral Effects of Shock and Space Weathering

The exposure of Nysa's surface to the space environment may lead to changes in its spectral properties. The nature of any spectrum altering effects due to this exposure are not fully understood. Impacts on the surface of an asteroid can disrupt the crystalline structure of a mineral resulting in spectral changes. For silicates these changes generally involve an increase in spectral slope followed by a decrease at higher shock pressures and progressive decreases in both band depths and overall reflectance (Adams et al., 1979; Pieters, 1984; King, 1986; Britt and Pieters, 1990). Consequently impact shock could plausibly acount for some or all of the positive slope difference between the HC and Nysa spectra but not for the 0.9 μm and 1.8 μm absorption bands.

   Studies of presumed asteroid regolith samples (solar gas rich samples and fragmental breccias) indicate that exposure to the space environment leads to a reduction in both mineral absorption band depths and overall reflectance (Britt and Pieters, 1987; Bell and Keil, 1988; Britt and Pieters, 1990). This exposure may

also lead to an increasingly red slope and a concomitant decrease in overall reflectance while band depths do not show any increase. The high albedos of Nysa (~49%) and Happy Canyon (44%) suggest that space weathering and impacts and their associated decreases in albedo have not had a dramatic effect on the spectrum of Nysa.

7. Spectral Modelling of Nysa's Spectrum

Based on the evidence that the surface of Nysa is dominated by iron-poor silicates similar to those found in aubrites, the major spectral differences between the opaque free fraction of the Happy Canyon aubrite and Nysa are the differences in overall slope and the various absorption bands seen in Nysa's spectrum. The high albedo and photopolarimetric properties of Nysa suggests that a significant fraction of its surface is composed of fine grained (<45 μm size) enstatite (Zellner, 1975; Zellner et al., 1977; Cloutis et al., 1990b).

A number of plausible accessory phases and mechanisms have been identified above which could account for some or all of the spectral differences, including troilite, metal, chondritic inclusions and space weathering. Troilite and metal abundances in aubrites are generally too low to cause a significant reddening of the spectral slope (Gaffey, 1974, 1976). The chondritic inclusions identified in some aubrites may be as red sloped as Nysa but have a much lower albedo which restricts their possible abundance.

Of the plausible accessory phases and mechanisms identified, chondritic inclusions may be able to account for the 0.9 μm and 1.8 μm absorption features. A pyroxene enriched CR chondrite type material (mineralogically similar to the inclusions) would exhibit absorption bands at these wavelengths and is probably red sloped (Figure 5). The red slope could also be accounted for by either meteoritic troilite and/or metal at abundances greater than those found in almost all aubrites.

The general spectral properties of the various materials considered suggests that the spectrum of Nysa could be accounted for by a fine-grained enstatite rich material containing a few percent spectrally red sloped materials such as troilite and/or metal, probably intimately mixed with the enstatite, and a few percent to a few tens of percent of a chondritic material similar to the inclusions found in some aubrites. The abundances of opaque components cannot exceed a few percent (if intimately mixed with enstatite) or a few tens of percent (if areally distributed) if the high albedo of Nysa is to be accounted for (Cloutis et al., 1990b). An extensive series of additive spectral mixtures were generated in an attempt to reproduce the Nysa spectrum based on these restrictions and to determine approximate upper and lower limits for the various phases. Areal mixtures were used to generate the models because the chondritic inclusions in aubrites are generally identified as discrete enclaves (Binns, 1969; Neal and Lipschutz, 1981; Score et al., 1982;

Verkouteren and Lipschutz, 1983; Lipschutz *et al.*, 1988) and an aubrite parent body may also possess discrete chondrite inclusion rich areas (Keil *et al.*, 1989).

In order to more closely simulate the possible spectral properties of the chondritic inclusions a small amount of the pyroxene (PYX003) spectrum was used in addition to the EET87770 spectrum in the models. Since the metal and troilite are both red sloped and spectrally featureless, only metal was areally added to the model spectra for ease of computation. Areal mixtures of opaques underestimate the spectrum altering effects of intimately mixed opaques, consequently the abundances of opaques in these mixtures represent the maximum possible limits.

Additive mixtures were generated initially at 10 wt% increments of Happy Canyon and 5 wt% increments of EET87770, metal and orthopyroxene in order to quickly identify the most reasonable spectral matches. The closest matches to the Nysa spectrum were identified using least squares minimization and similarity in overall reflectance. Once the broad limits on the most reasonable mixtures had been established, additional mixtures were generated using 5 wt% increments of Happy Canyon, 2 wt% increments of EET87770 and metal and 1 wt% increments of orthopyroxene. Least squares minimization and similarities in overall reflectance were again used to identify the best match. Orthopyroxene abundance was additionally constrained by requiring that the pyroxene absorption band depths near 1 μm and 2 μm not exceed the values for Nysa (~5%).

The spectrum of the closest match to the Nysa spectrum, an additive mixture of 60% Happy Canyon (Figure 1), 16% EET87770 (Figure 5), 20% 45–90 μm size metal (Figure 4) and 4% orthopyroxene (PYX003, Figure 2) is shown in Figure 6 along with the Nysa spectrum. This mixture generally reproduced the Nysa spectrum at shorter wavelengths and the wavelength position and depth of the 0.9 μm absorption feature. Based on the spectral data for metal silicate mixtures and metal-opaque mixtures (Cloutis *et al.*, 1990a,c) this spectrum is similar to that expected for an intimate mixture of 77% Happy Canyon and 8% meteoritic metal + troilite and an additive 15% component of EET87770 and PYX003.

These values lie within reasonable mineralogical constraints. The presumed metal + troilite abundances (8%) can vary by up to ±3% without significantly affecting the fit to Nysa. The lower limit can be even reduced even further if the abundance of (red sloped) carbonaceous inclusions is increased. This metal + troilite abundance is within the range of the Shallowater aubrite (Watters and Prinz, 1979) which appears to be a unique aubrite and may be genetically distinct from the other members of the group (Keil *et al.*, 1989). The effects of space weathering have not been considered but the spectrum reddening effects of weathering coupled with some degree of intimate mixing of the carbonaceous inclusions may allow metal + troilite abundances to range as low as 1%. The possible abundance range of carbonaceous inclusions is somewhat uncertain because their spectra have not been directly measured. Their spectral properties are inferred from EET87770 (Figure 5) and other carbonaceous chondrites (Johnson and Fanale, 1973; Gaffey,
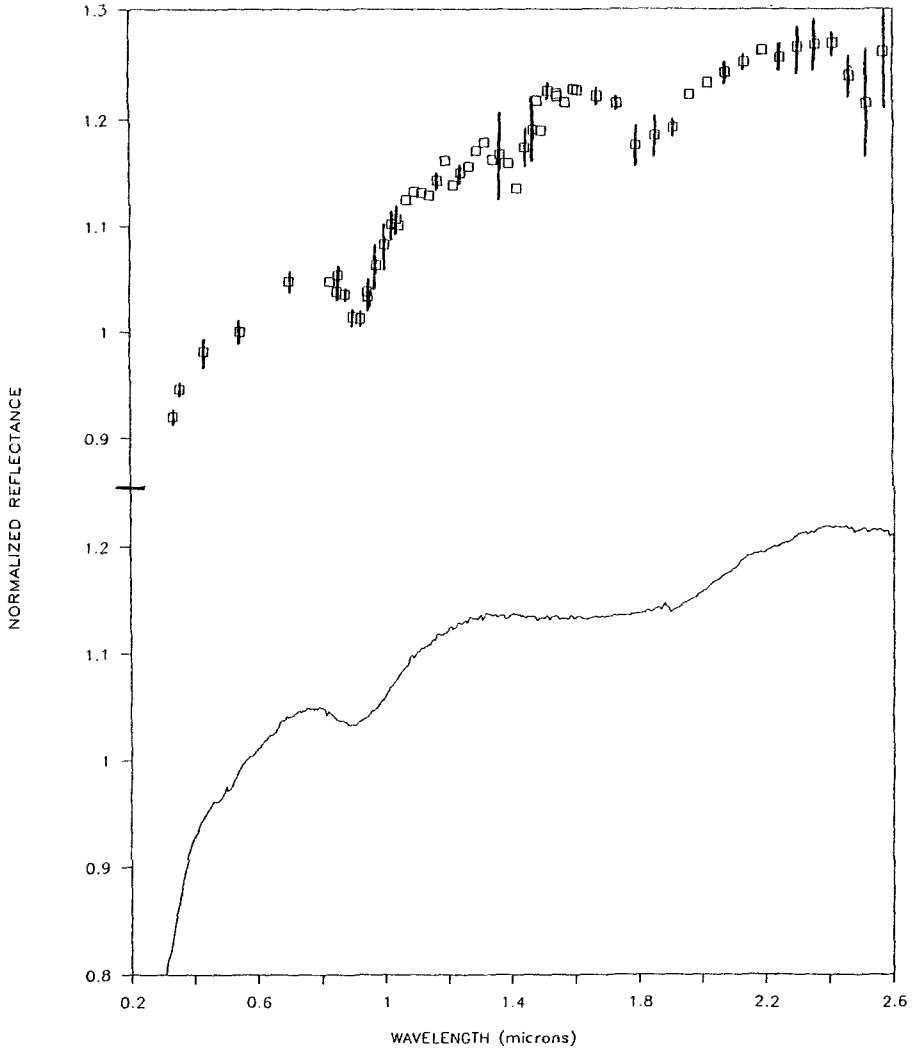
Fig. 6.   Normalized reflectance spectrum (1 at 0.56 μm) of asteroid 44 Nysa (upper) and an additive mixture of various components (lower). See text for details. Vertical scale is the same for both spectra.

1974, 1976). Given the low absolute reflectance of EET87770 and other carbonaceous chondrites, the abundance of carbonaceous chondrite inclusions in an areal mixture probably cannot exceed ~20% (<5% if intimately mixed) without irretrievably lowering the albedo of the mixture to excessively low values. Similarly the areal chondritic inclusion abundance must exceed ~7% to account for the 0.9 μm and 1.8 μm absorption bands. The fact that chondritic inclusions have been found in more than one aubrite suggests that the incorporation of a chondritic inclusion type material in the models is justified.

8. Conclusions

The reflectance spectrum of Nysa displays a number of significant differences from that of the opaque free fraction of the Happy Canyon aubrite. The differences are due to the presence of a component or components with a slight red slope and absorption bands near 0.9 μm and 1.8 μm. Meteoritic metal, troilite and carbonaceous chondrite type inclusions are all plausible candidates; metal and/or troilite for the red slope and carbonaceous chondrite inclusions for the 0.9 μm and 1.8 μm absorption bands. This and previous spectral studies of mafic silicate-metal and mafic silicate-opaque assemblages suggest that an assemblage composed of an intimate mixture of 1–11% metal + troilite and 69–92% enstatite with a 7–20% areal component of carbonaceous chondrite material can plausibly account for the red slope and 0.9 μm and 1.8 μm absorption bands of Nysa.

Acknowledgments

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