

# Spectral Reflectance Properties of Carbon-Bearing Materials

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Received September 24, 1993; revised December 23, 1993

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The 0.3-2.6  $\mu\text{m}$  spectral reflectance properties of carbon polymorphs (graphite, carbon black, diamond), carbides (silicon carbide, cementite), and macromolecular organic-bearing materials (coal, coal tar extract, oil sand, oil shale) are found to vary from sample to sample and among groups. The carbon polymorphs are readily distinguishable on the basis of their visible-near infrared spectral slopes and shapes. The spectra of macromolecular organic-bearing materials show increases in reflectance toward longer wavelengths, exceeding the reflectance rise of more carbon-rich materials. Reflectance spectra of carbonaceous materials are affected by the crystal structure, composition, and degree of order/disorder of the samples. The characteristic spectral properties can potentially be exploited to identify individual carbonaceous grains in meteorites (as separates or *in situ*) or to conduct remote sensing geothermometry and identification of carbonaceous phases on asteroids. © 1994 Academic Press, Inc.

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## INTRODUCTION

The carbon-bearing phases present in many classes of meteorites have received an inordinate amount of attention given their generally low abundances (<~5 wt%). The application of visible and near infrared spectroscopy to analysis of these phases has generally lagged behind the application of other analytical techniques. Spectroscopy possesses a number of advantages over other more commonly employed analytical techniques. It is capable of providing structural and compositional information concerning amorphous or poorly crystalline phases which are not amenable to X ray diffraction analysis (e.g., Singer 1985) or phases containing low atomic weight elements which are not amenable to electron microprobe analysis (Pella 1986).

Meteoritic carbon-bearing phases are of interest because (1) they are potentially useful cosmochemometers which can provide information concerning preaccretionary nebular conditions and postaccretionary metamorphism (Mueller 1953, Kerridge 1985, Rietmeijer and Mackinnon 1985a,b, Wright *et al.* 1990), (2) they can contain isotopically "anomalous" element abundances which may reflect presolar nebular conditions (Bernatowicz *et al.* 1987, Zinner *et al.* 1987, Anders 1988, Blake *et al.* 1988, Zinner 1988, Amari *et al.* 1990), (3) they are the main carriers of primordial noble gases (Weber *et al.* 1971, 1976, Fukunaga *et al.* 1987, Matsuda *et al.* 1991) and (4) they can strongly affect the spectral signatures of more abundant minerals with which they are intimately associated in carbonaceous chondrites and ureilites (Johnson and Fanale 1973, Salisbury *et al.* 1975, Gaffey 1976, Gaffey and McCord 1979, Larson *et al.* 1979, Wagner *et al.* 1987, Moroz and Pieters 1991).

The term carbonaceous chondrites is used throughout the text to refer to meteorites which are generally regarded as chondrites regardless of whether they contain chondrules. This convention, although not completely accurate, is widely used (e.g., Wasson 1974, Kerridge and Matthews 1988).

Interplanetary dust particles (IDPs) have been studied by a number of techniques including infrared spectroscopy (Fraundorf *et al.* 1983, Sandford and Walker 1985, Sandford 1986). A number of them contain carbon-bearing phases as a major component (e.g., Allamandola *et al.* 1987, Blanford *et al.* 1988) in sufficient abundance to impart an overall black color to the grains (Brownlee *et al.* 1980, Wopenka 1988). This carbonaceous material has yet to be fully characterized but seems to comprise a number

of distinct phases including amorphous carbon, poorly graphitized carbon, turbostratic carbon, polycyclic aromatic hydrocarbons (PAHs), "kerogen-like" compounds, iron carbides, lonsdaleite, and various other hydrocarbons (Knacke 1977, di Brozolo *et al.* 1985, McKay *et al.* 1985, Christofferson and Buseck 1986, Rietmeijer and Mackinnon 1987, Wopenka 1988, Gibson and Hartmetz 1991, Gibson 1992). The carbonaceous phases in IDPs are of interest because they contain a number of isotopic anomalies (McKeegan *et al.* 1985, Gibson 1992 and references therein) and may be useful cosmothermometers (Rietmeijer and Mackinnon 1985a,b, Nuth 1990). Improvements in our analysis of these materials are essential if recently discovered extensive terrestrial deposits of IDPs are to be fully exploited (Murrell *et al.* 1980, Mackinnon 1987, Maurette *et al.* 1987).

A number of asteroid classes, including the B, C, D, F, G, P, and T classes, are characterized by low albedos ( $\sim 10\%$ ) and relatively featureless reflectance spectra (Tholen 1984, Tholen and Bell 1987, Gaffey *et al.* 1989). These spectral characteristics and cosmochemical considerations have led a number of investigators to suggest that carbon-bearing phases are responsible for the low albedo and general lack of mineral absorption features in their reflectance spectra (e.g., Hartmann *et al.* 1982, Jones *et al.* 1990). However the *direct* identification of carbonaceous material on asteroids is both rare and generally tenuous (Cruikshank and Brown 1987, Piscitelli *et al.* 1988, Cruikshank *et al.* 1990). If carbon-bearing phases are present on asteroid surfaces, changes in the composition, abundance, and structure of these phases may account for the variety of slopes seen in asteroid spectra with changes in heliocentric distance (Gradie and Tedesco 1982, Hartmann *et al.* 1987, Cruikshank 1989, Jones *et al.* 1990, Mueller *et al.* 1992) and the slopes of cometary nuclei spectra (Hanner *et al.* 1985, Brooke and Knacke 1986, Weissman *et al.* 1989).

The 0.3–2.6  $\mu\text{m}$  reflectance spectra of a variety of carbon polymorphs, carbides, and macromolecular carbon-bearing materials have been examined in order to attempt to unravel the physical and chemical properties which affect the spectra. Improved understanding of the compositional-spectral relationships should permit improvements in characterizing carbonaceous phases in meteorites, IDPs and asteroids. This information can in turn be applied to constraining pre- and postaccretionary processes which have affected these objects.

#### EXPERIMENTAL PROCEDURE

Both natural and synthetic samples have been used and are grouped into carbon polymorphs, carbides, and macromolecular organic-bearing classes. The carbon polymorphs include natural graphite from Sri Lanka

(GRP101,  $<45\text{-}\mu\text{m}$  grain size), synthetic "amorphous" graphite (GRP102,  $<45\text{-}\mu\text{m}$  grain size), synthetic carbon black (LCA101,  $<0.021\text{-}\mu\text{m}$  grain size), and natural diamond (DIA101,  $<1\text{-}\mu\text{m}$  grain size). The carbides include synthetic silicon carbide (SiC) in two grain sizes from different sources (SIC101,  $<37\text{-}\mu\text{m}$  grain size; SIC102, 7- $\mu\text{m}$  grain size) and synthetic cementite ( $\text{Fe}_3\text{C}$ ) (CEM101,  $<45\text{-}\mu\text{m}$  grain size). The macromolecular organic-bearing phases were selected on the basis of their compositional complexity and abundance of aromatic organics and include bituminous coal from Frank, Alberta (COAL01,  $<37\text{-}\mu\text{m}$  grain size), coal tar extract ( $<37\text{-}\mu\text{m}$  grain size), oil sand from the vicinity of Fort McMurray, Alberta (TAR17, unsorted) and oil shale from the vicinity of Rifle, Colorado (OILS10,  $<45\text{-}\mu\text{m}$  grain size).

Most of the samples were obtained in powdered form. Those that were not were crushed in an alumina mortar and pestle. Impurities were removed through a combination of hand picking and magnetic separation. All samples were dry sieved in order to minimize inadvertent chemical and structural alterations of the materials. The samples were characterized by X ray diffraction (XRD) analysis to determine relative degrees of order/disorder on the basis of relative peak heights, widths, and low angle scattering (Biscoe and Warren 1942, French 1964, Griffin 1967, Oberlin *et al.* 1980), for identifying the presence of any undesirable accessory phases, and for identifying the crystalline mineral phases present in the coal, oil shale, and oil sand samples.

Bidirectional reflectance spectra have been measured at the Reflectance Experiment Laboratory (RELAB) spectrometer facility in the Department of Geological Sciences at Brown University (Pieters 1983). The data were acquired at  $i=0^\circ$ ,  $e=15^\circ$ , and 5-nm resolution relative to halon, which is a near-perfect diffuse reflector in the 0.3- to 2.6- $\mu\text{m}$  range (Weidner and Hsia 1981). The spectra have been corrected for minor irregularities in halon's absolute reflectance in the 2- $\mu\text{m}$  region, as well as for dark current offsets. The terms red slope and blue slope are used throughout the ensuing discussion. Red slope indicates that reflectance generally *increases* toward longer wavelengths while blue slope indicates that reflectance generally *decreases* toward longer wavelengths.

#### RESULTS

Analysis of carbon-bearing materials in meteorites has been hampered by difficulties in isolating them and the lack of satisfactory methods for characterizing them in the solid state (Kitajima and Masuda 1992). In addition, commonly employed separation/concentration processes may cause undesirable compositional changes in carbonaceous materials (Murae 1992). The spectrally characterized samples have been divided into the three groups

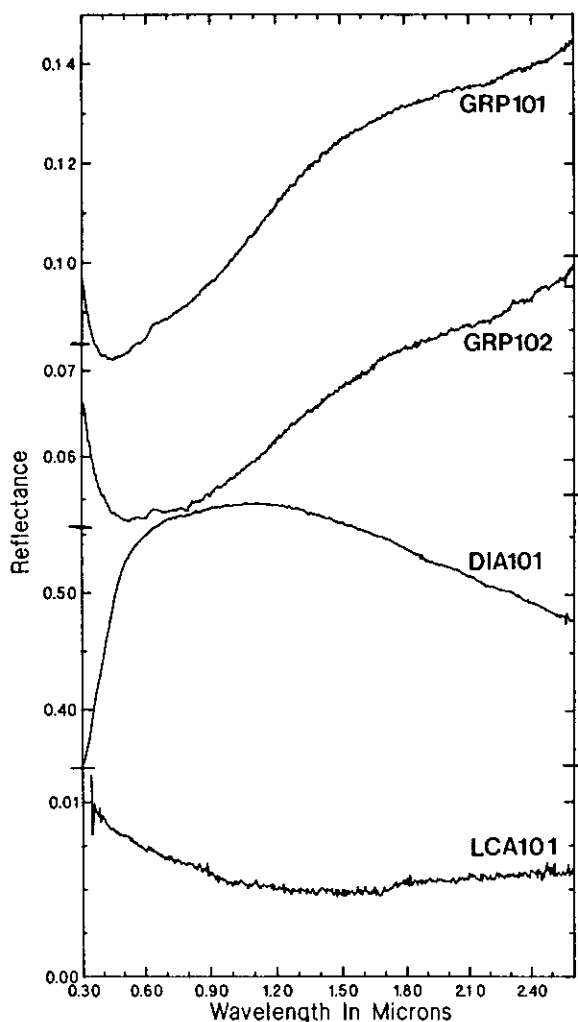


FIG. 1. Absolute reflectance spectra of powdered samples of carbon polymorphs: natural graphite (GRP101), synthetic "amorphous" graphite (GRP102), synthetic carbon black (LCA101), and natural diamond (DIA101). Vertical scale varies for each sample.

(carbon polymorphs, carbides, macromolecular organic-bearing phases) as outlined above.

### Carbon Polymorphs

Graphite is present in most classes of carbonaceous chondrites and in ureilites and exhibits varying degrees of order from poorly to well crystallized (Lipschutz 1964, Vdovykin 1970, Green *et al.* 1971, Smith and Buseck 1981, Fraundorf *et al.* 1982, Wopenka and Sandford 1984, Barber 1985, Amari *et al.* 1990, Zinner *et al.* 1990). XRD analysis of the graphite samples indicates that the natural graphite sample is more ordered than the synthetic "amorphous" sample which is in turn more ordered than the carbon black sample.

The two graphite reflectance spectra (Fig. 1) are gen-

erally similar in overall shape and both exhibit a reflectance minimum in the 0.4- to 0.5- $\mu\text{m}$  region and slope change near 1.5  $\mu\text{m}$ . All of these features are consistent with the results of transmission spectroscopy (Hennig 1965, Yasinsky and Ergun 1965, McCartney and Ergun 1967, Ergun 1968), photoacoustic spectroscopy (Lochmüller *et al.* 1981), and single crystal reflectance spectroscopy (Gilbert 1960, Ergun *et al.* 1967, McCartney and Ergun 1967, Foster and Howarth 1968). The crystal structure of graphite accounts for its spectral properties: a semimetal with extensively delocalized electrons (McMichael *et al.* 1954, Marchand 1987). The greater degree of order in the GRP101 sample is manifested as a narrower absorption band in the visible region and higher overall reflectance as compared to GRP102 (O'Reilly and Mosher 1983).

Carbon black is relevant to studies of carbonaceous phases in meteorites because a portion of the carbon in carbonaceous chondrites and to a lesser extent in ureilites is present in poorly crystalline and/or amorphous forms (Barber 1985, Wacker 1986, Wright *et al.* 1990, Kagi *et al.* 1991). XRD analysis of the carbon black sample indicates that it is largely amorphous with a broad, diffuse peak near 3.7 Å and extensive low angle scattering.

The reflectance spectrum of the carbon black sample (LCA101) is shown in Fig. 1. It exhibits low overall reflectance (<1.2%) and a shallow reflectance minimum in the 1.4- to 1.7- $\mu\text{m}$  region but is otherwise relatively featureless. Reflectance and photoacoustic spectra of other carbon black samples (Johnson and Fanale 1973, Gradie and Veverka 1980, Vidrine 1980, Lochmüller *et al.* 1981, Cruikshank 1987) are similar to the carbon black spectrum in Fig. 1: generally featureless with a slightly blue sloped spectrum. Any absorption bands would necessarily be broad due to the largely amorphous nature of the material (O'Reilly and Mosher 1983, Robertson and O'Reilly 1987).

Diamond is widespread in carbonaceous chondrites with abundances decreasing with increasing metamorphic grade (Ming and Anders 1988, Bernatowicz *et al.* 1989, Huss 1990). Some of this "diamond" may be partially amorphous or disordered and contain variable amounts of nitrogen, oxygen, and hydrogen (up to 40 atom%) (Blake *et al.* 1988, Bernatowicz *et al.* 1989). Diamond, along with graphite, is the main carbonaceous phase in ureilites (Lipschutz 1964, Vdovykin 1970). Meteoritic diamond ranges in size up to  $\sim 1 \mu\text{m}$  (Vdovykin 1970, 1972, Blake *et al.* 1988). XRD analysis of the diamond sample DIA101 reveals no detectable impurities.

Single crystal diamond transmission spectra indicate that absorption decreases gradually over the range 0.3 to 1.2  $\mu\text{m}$  with the appearance of various absorption bands in the visible region in colored specimens (Davies 1977, Orlov 1977, Woods and Collins 1986, Lifante *et al.* 1990). Absorption increases slightly over the range 1.5 to 2.6  $\mu\text{m}$

(Sutherland and Willis 1945, Orlov 1977). The reflectance spectrum of the powdered diamond sample (DIA101, Fig. 1) is consistent with these results: reflectance increases sharply in the visible, peaks near  $1.2 \mu\text{m}$ , and declines toward longer wavelengths. The DIA101 sample is colorless, consequently no absorption bands appear in the visible region. Its spectrum is a function of its crystal structure: a large band gap ( $\sim 5.4 \text{ eV}$ ) semiconductor (Meyerson and Smith 1980) and it differs significantly from the spectra of the other carbon polymorphs.

### Carbides

Silicon carbide (SiC) is widespread in carbonaceous chondrites and its abundance declines with increasing metamorphic grade (Bernatowicz *et al.* 1987, Ming and Anders 1988, Huss 1990). The cosmochemical importance of this phase is discussed below; however, isotopic anomalies seem to be related, at least in part, to SiC grain sizes and perhaps degree of structural order (Anders 1988, Ming and Anders 1988, Zinner *et al.* 1989, Ash *et al.* 1990).

The visible and near infrared spectral properties of silicon carbide have apparently not been measured previously. Two grain sizes of silicon carbide, from different sources (SIC101,  $<37\text{-}\mu\text{m}$  grain size; SIC102,  $<7\text{-}\mu\text{m}$  grain size), have been spectrally characterized in order to determine the effect of grain size variations on spectral properties (Fig. 2). Both spectra are similar in shape with the finer grain size exhibiting higher overall reflectance. The wavelength position of the reflectance maximum is located at  $\sim 0.51 \mu\text{m}$  in SIC102 and at  $\sim 0.42 \mu\text{m}$  in SIC101. Silicon carbide can occur in a large number of polymorphs (Thibault 1944, Adamsky and Merz 1959, Hannam and Shaffer 1969). XRD analysis of the two samples indicates that they are structurally similar but that the finer grain size sample exhibits a higher degree of disorder. This probably accounts for the SIC102 spectrum exhibiting a broader reflectance maximum and a more gradual reflectance decrease toward longer wavelengths. The cause of the  $0.95\text{-}\mu\text{m}$  absorption feature, most evident in the SIC102 spectrum, is unknown. The SiC spectra are distinctly different from the other carbonaceous phases but the overall shape most resembles that of diamond (Fig. 1), suggesting that this material may also be a large band gap semiconductor.

Cohenite ( $(\text{Fe},\text{Ni})_3\text{C}$ ) is most abundant in iron meteorites and enstatite chondrites (Brett 1967, Scott 1971). Cohenite and haxonite ( $\text{Fe}_{23}\text{C}_6$ ) are found only infrequently and sparsely in metal grains in carbonaceous chondrites and ureilites (Goodrich and Berkley 1986, Scott and Jones 1990).

The reflectance spectrum of synthetic cementite ( $\text{Fe}_3\text{C}$ ) (Fig. 2) is red sloped and featureless, similar to meteoritic metal powders (Johnson and Fanale 1973, Cloutis *et al.*

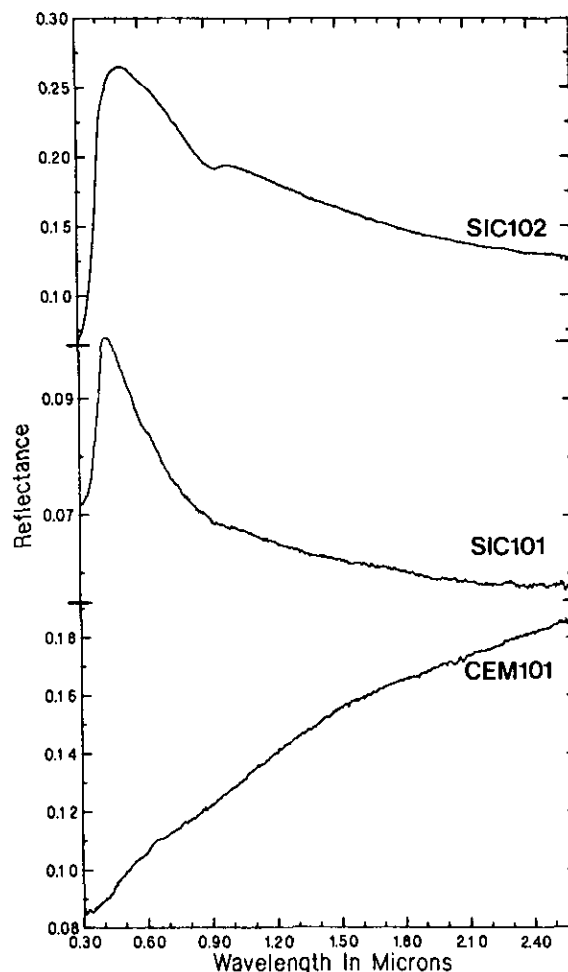


FIG. 2. Absolute reflectance spectra of powdered samples of carbides: silicon carbide  $<7\text{-}\mu\text{m}$  grain size (SIC102) and  $<37\text{-}\mu\text{m}$  grain size (SIC101), and iron carbide (cementite) (CEM101). Vertical scale varies for each sample.

1990), indicating that the material retains its metallic character with extensively delocalized electrons. Cementite is spectrally distinct from the other carbonaceous phases, but visible and near infrared spectroscopy is not suited for distinguishing it from metal.

### Macromolecular Carbon-Bearing Phases

The bulk of the carbon in carbonaceous chondrites (70 to  $>95\%$ ) is present in a form which is not solvent extractable (Vinogradov and Vdovykin 1964, Hayes 1967, Baker 1971, Nagy 1975, Cronin *et al.* 1982) and this has hampered efforts to characterize it (Kitajima and Masuda 1992). This material is carbon rich, containing a large amount of high molecular weight multiple ring heterocyclic aromatic components with extensive short aliphatic bridges and side chains (Hayatsu *et al.* 1977, Hayatsu and

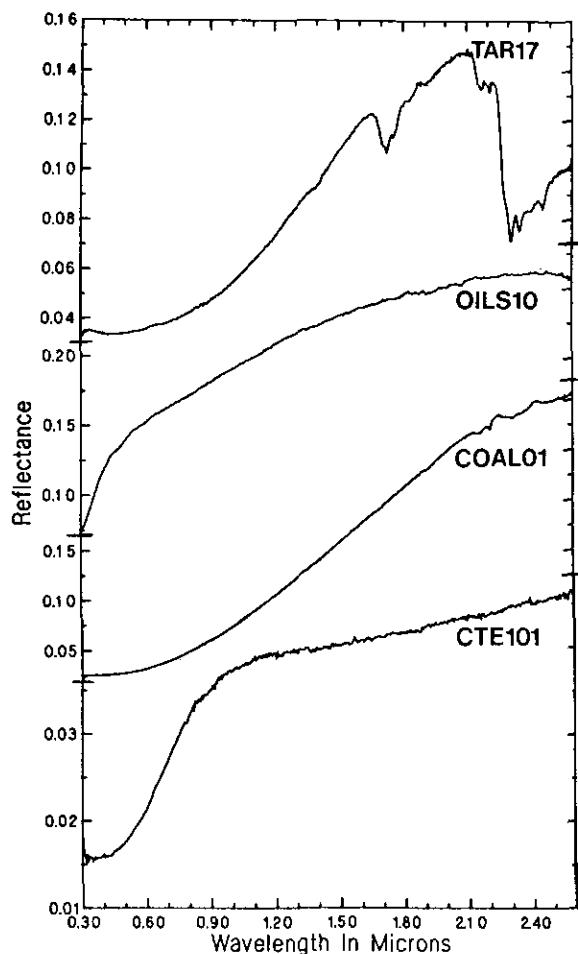


FIG. 3. Absolute reflectance spectra of powdered samples of macro-molecular organic-bearing materials: coal (COAL01), coal tar extract (CTE101), oil shale (OILS10), and oil sand (TAR17). Vertical scale varies for each sample.

Anders 1981, Cronin *et al.* 1982, Hayatsu *et al.* 1983, Cronin *et al.* 1988, Murae *et al.* 1990).

The reflectance spectra of a number of carbon-bearing geological materials with similar characteristics (coal, coal tar extract, oil sand, oil shale) are shown in Fig. 3. They exhibit variations in spectral properties due to compositional differences.

The organic fraction in coal is composed largely of heterocyclic aromatic hydrocarbons (Painter *et al.* 1985) which accounts for the red-sloped spectrum of coal. Coal spectra may also exhibit absorption bands in the 2.3–2.6  $\mu\text{m}$  region due to nonaromatic organic functional groups and/or mineral phases (Sutherland *et al.* 1944, Sill 1973, Fysh *et al.* 1985). The spectral slope varies as a function of metamorphic temperature or coal rank (van Vucht *et al.* 1955, Tschamler and de Ruiter 1963, Friedel *et al.* 1967, Painter *et al.* 1981, Donini and Michaelian 1986, McAskill 1987, Ito *et al.* 1988). The

large number of organic phases present in coal precludes the appearance of distinct absorption bands in the ultraviolet and visible regions (Gilbert 1960, Zerlia *et al.* 1990).

The reflectance spectrum of the coal sample (Fig. 3, COAL01) is red sloped as expected. The increase in slope toward longer wavelengths resembles the oil sand spectrum but the lack of absorption bands resembles the oil shale spectrum. The lack of C–H absorption bands is consistent with its low H/C ratio ( $\sim 0.8$ ) (Tibbetts 1976, Hunt 1979). XRD analysis of the sample indicates that the carbonaceous phase is composed largely of poorly ordered aromatic molecules; kaolinite and illite type clays are the predominant mineral species present.

The coal tar extract sample is coal tar with solvent extractable fractions removed (Gradie and Veverka 1980). Its reflectance spectrum (Fig. 3, CTE101) is relatively dark and flat ( $< 3\%$  reflectance variation) with an absorption feature centered near 0.4  $\mu\text{m}$ . XRD analysis indicates that this material is highly disordered with a broad weak peak near 3.6  $\text{\AA}$  and extensive low angle scattering. This suggests that the 0.4  $\mu\text{m}$  feature is attributable to electronic transitions in the aromatic molecules present in the sample (Tschamler and de Ruiter 1963, Ito *et al.* 1988). The low overall reflectance is also characteristic of a highly disordered material (O'Reilly and Mosher 1983, Robertson and O'Reilly 1987). The reflectance spectrum is similar to coal tar extract spectra measured by other investigators (Gradie and Veverka 1980, Bell *et al.* 1985, Cruikshank 1987).

Oil sand spectra have previously been measured by a number of investigators (Cloutis 1989, Dougan 1989, Cloutis 1990, Shaw and Kratochvil 1990). The oil sand spectrum (Fig. 3, TAR17) exhibits features attributable exclusively to the organic phase; the solid phase is 95% quartz, which is spectrally featureless (Hunt and Salisbury 1970). The organic phase results in a very red-sloped spectrum and intense C–H absorption bands in the 1.7  $\mu\text{m}$  and 2.3–2.6  $\mu\text{m}$  regions. This is consistent with the high H/C ratio ( $\sim 1.52$ ) and abundant high molecular weight polyaromatic molecules (Boyd and Montgomery 1962, Yen 1973, Bichard 1987).

The oil shale spectrum also exhibits a red slope but C–H bands are weak or nonexistent (Fig. 3, OILS10). XRD analysis of the sample indicates that the major crystalline phase is quartz with lesser amounts of chlorite and illite. The red slope of this sample is attributable to organic electronic absorptions. Oil shale spectra can exhibit absorption features attributable to the various phases composing the samples (McAskill 1987). The average H/C ratio of the oil shale is  $\sim 1.48$  (Anders and Robinson 1971) but the structure of the carbonaceous phase differs significantly from that found in the oil sand, consisting largely of aliphatic hydrocarbons (Tissot and Welte 1978). This

general lack of aromatic hydrocarbons probably accounts for the spectral differences between the oil shale and oil sand. The major mineral species in the oil shale is quartz. Small amounts of plagioclase feldspar, chlorite, and illite/muscovite are also present. None of these phases are apparent in the reflectance spectrum.

### DISCUSSION

Reflectance spectra of carbonaceous phases vary significantly among and within the carbon polymorph, carbide, and macromolecular organic-bearing groups. The spectral signatures of the various materials can be attributed to the compositional, structural, and crystallographic properties. The carbon polymorph and macromolecular organic-bearing sample spectra, with the exception of the diamond, are characterized by a broad absorption feature in the ultraviolet-visible region and red-sloped spectra. The absorption feature is attributable to molecular orbital transitions and/or delocalization of electrons located in aromatic structures (Tschamler and de Ruiter 1963, Silverstein and Bassler 1967, Painter *et al.* 1981, Fysh *et al.* 1985, Donini and Michaelian 1986, Ito *et al.* 1988) although contributions due to photon absorption by stable free radicals, mobile electrons, and charge transfer complexes may also be important (Tschamler and de Ruiter 1963 and references therein, Ito *et al.* 1988). The broadness and shape of this absorption feature is a function of the compositional complexity and crystallinity of the material (O'Reilly and Mosher 1983, Robertson and O'Reilly 1987); simple organic compounds do not exhibit red-sloped spectra (Holman and Edmondson 1956, Goddu 1957, Silverstein and Bassler 1967). The wavelength position of the absorption feature can be related to the average size of the aromatic molecules (Sutherland *et al.* 1944, Badger 1957).

Studies of organic materials, particularly coals, indicate that as the degree of aromatization (also referred to as coalification, carbonization, rank, or C/H ratio) increases, the ultraviolet-visible absorption feature becomes broader and more intense, particularly when carbon content exceeds ~91% (van Vucht *et al.* 1955, Friedel and Queiser 1956, Tschamler and de Ruiter 1963, Friedel *et al.* 1967, McCartney and Ergun 1967, Forrest *et al.* 1984, Donini and Michaelian 1986, Ito *et al.* 1988). These spectral and compositional changes also accompany increases in temperature of formation, heat treatment temperature, or degree of metamorphism (Kmetko 1951, Gavrillov and Ermolenko 1975, Rowan *et al.* 1991), which cause a loss of aliphatics, growth of aromatic complexes (ring condensation), loss of hydrogen, and decrease in the electronic energy gap (Gilbert 1960, Robertson and O'Reilly 1987, Moroz *et al.* 1991). This results in the wavelength position of the reflectance rise moving toward progressively longer

wavelengths (Kmetko 1951, Friedel 1966, Friel *et al.* 1982).

The samples containing complex mixtures of various hydrocarbons and significant amounts of hydrogen (H/C > ~0.2; i.e., coal, oil sand, oil shale) are more red sloped than the carbon-rich materials such as the coal tar extract, graphite, and amorphous carbon. The differences between the maximum and minimum reflectance for any one sample ranges from 12 to 31% in the former group and is <7% in the latter group. The shape of the ultraviolet-visible absorption feature has not been quantified but comparison of the two graphite spectra indicates that the band is broader in the less ordered sample (GRP102). An essentially amorphous material such as carbon black will exhibit low overall reflectance and an essentially flat or slightly blue slope because the lack of short and medium range order precludes the existence of well-defined electronic energy gaps (O'Reilly and Mosher 1983, Robertson and O'Reilly 1987). Average reflectance in the visible region increases as the degree of order increases (carbon black-"amorphous" graphite-natural graphite). The spectral differences between the two SiC samples and between the two graphite samples are attributable to differences in the relative degrees of crystallinity. This indicates that reflectance spectroscopy may be useful not only for identifying carbonaceous phases but also for assessing relative degrees of crystallinity of otherwise compositionally similar materials.

Comparison of the diamond, graphite, and carbon black spectra indicates that the electronic configuration of the carbon atoms will strongly affect the reflectance spectra. A largely amorphous structure results in a dark and relatively featureless reflectance spectrum (carbon black). If the material is more ordered, with carbon atoms in a hexagonal configuration, the reflectance spectrum will assume the characteristics expected for a semimetal with an absorption feature in the low wavelength visible region and a red-sloped spectrum (graphite). If the carbon atoms assume a tetragonal configuration, the reflectance spectrum will assume the characteristics of a large band gap semiconductor (diamond). Each material is spectrally unique (Fig. 1), permitting rapid spectral discrimination of these carbon polymorphs.

### POTENTIAL APPLICATIONS

As mentioned, the bulk of the carbon in carbonaceous chondrites is present as a macromolecular insoluble material, which hampers efforts to characterize it (Kitajima and Masuda 1992). The limited analyses available for this material indicate that it consists of a condensed aromatic network with short aliphatic bridges or side chains and substantial atomic substitutions (Hayes 1967, Simmonds *et al.* 1969, Baker 1971, Bandurski and Nagy 1976, Hay-

TABLE I  
Total Carbon Abundances in Various  
Meteorite Classes

Meteorite group	Total carbon (wt%)
Carbonaceous chondrites	
CI1	2.2–4.8
CM2	0.9–5.2
CR2	0.7–3.3
CV2	0.5–2.0
CV3	0.1–1.2
CV4	<0.1–0.2
CV5/6	0.1–0.3
CO3	0.1–1.0
CO4	<0.1–0.1
Adelaide	0.8
Ureilites	1.5–5.6
Ordinary chondrites	
H	<0.1–0.4
L	<0.1–0.9
LL	<0.1–0.6
E	<0.1–0.5

Note. Sources of data: Moore and Lewis 1965, 1967, Vdovykin 1970, Gibson *et al.* 1971 and references therein, Nagy 1975, Gibson 1976, 1980, Kerridge 1985, Wright *et al.* 1990, Murae *et al.* 1991.

atsu and Anders 1981, Zenobi *et al.* 1989, Murae *et al.* 1990). This material resembles terrestrial coal, oil shale, or kerogen in some respects but not in others (Schulz and Elofson 1965, Bitz and Nagy 1966, Nagy 1975, Bandurski and Nagy 1976, Cronin *et al.* 1982, Hayatsu *et al.* 1983, Wright *et al.* 1990). Comparisons of the meteoritic material with terrestrial carbonaceous materials are complicated by the compositional and structural variations of the former, which are a function of petrologic grade and meteorite class (Cronin *et al.* 1982, 1988, Hahn *et al.* 1988, Wright *et al.* 1990) (Table I). The fact that different organic-bearing geological materials exhibit spectral differences attributable to differences in the composition and structure of the organic phase suggests that visible and near infrared reflectance spectroscopy could fruitfully be applied to characterizing the insoluble organic material in meteorites, a capability that has been demonstrated using infrared spectroscopy (Blob *et al.* 1988, Murae *et al.* 1990, Murae 1992).

If the insoluble macromolecular material strongly affects carbonaceous chondrite reflectance spectra, the meteorite spectral slopes should most closely resemble the spectra of solvent insoluble materials such as graphite, carbon black, oil shale, and coal tar extract rather than coal, or oil sand. The available carbonaceous chondrite reflectance spectra have shapes ranging from slightly blue

to red sloped, although none are nearly as red sloped as the coal and oil sand spectra (Johnson and Fanale 1973, Salisbury *et al.* 1975, Gaffey 1976, Gaffey and McCord 1979, Larson *et al.* 1979, Wagner *et al.* 1987, Moroz and Pieters 1991). This indicates that the macromolecular phase in carbonaceous chondrites is spectrally similar to terrestrial solvent insoluble phases with carbon in hexagonal arrangements and that the latter may be useful for studying the spectrum altering effects of the former.

Of the various carbon-bearing phases found in meteorites, silicon carbide, diamond, amorphous carbon, and graphite have been singled out because they appear to be carriers of isotopically anomalous elements and primordial noble gases (e.g., Göbel *et al.* 1978, Bernatowicz *et al.* 1987, Zinner *et al.* 1987, Blake *et al.* 1988, Ming and Anders 1988, Zinner *et al.* 1989, Amari *et al.* 1990, Ash *et al.* 1990, Huss 1990). Most techniques currently used to study these materials involve extensive physical and chemical concentration procedures which may lead to undesirable compositional alterations (Murae 1992). Since these phases are spectrally distinct in the visible–near infrared region, microspectroscopy could be used to (non-destructively) identify, ascertain the degree of order, and map *in situ* distributions of these and other carbonaceous phases (Blob *et al.* 1988, Murae *et al.* 1990, Murae 1992). Microspectroscopy could also potentially be combined with other *in situ* analytical techniques (Kagi *et al.* 1991, USRA Quarterly 1992, Nittler *et al.* 1993) to map isotopic anomalies on a grain-by-grain basis and to identify and characterize the carrier in each case.

If the various SiC carriers of isotopic anomalies possess different degrees of crystallinity (Ash *et al.* 1990), spectroscopy may be useful for distinguishing them on this basis. SiC can also form a large number of polymorphs (polytypes) (Thibault 1944, Adamsky and Merz 1959, Hannam and Schaffer 1969). If these polymorphs are also spectrally distinct (a subject currently under investigation), spectroscopy may prove useful in this area as well, helping to determine whether isotopic anomalies are correlated with SiC structural variations. *In situ* analyses, relying largely on spectroscopy, should substantially clarify the nature of the various isotopic carriers.

Meteoritic diamonds and diamond-like phases are also carriers of isotopic anomalies and primordial noble gases in carbonaceous chondrites and ureilites (Blake *et al.* 1988, Ming and Anders 1988, Huss 1990). This material can apparently be somewhat disordered, hydrogenated, or nitrogenated (Vinogradov *et al.* 1966, Blake *et al.* 1988, Bernatowicz *et al.* 1989). Analysis of the diamond phases suffers from their generally low abundances in carbonaceous chondrites (Huss 1990). Given the spectral uniqueness of diamond, it should be possible to use visible–near infrared spectroscopy to identify diamond *in situ* or in separates.

The substitution of nitrogen for carbon in diamond leads to spectrally detectable changes in infrared absorption bands and wavelength position of the ultraviolet-visible absorption edge (Vinogradov *et al.* 1966, Orlov 1977). While the crystallographic siting of noncarbon phases in meteoritic diamonds is not known, the results of Orlov (1977) suggest that microspectroscopy may be useful for identifying diamonds which contain spectrally significant amounts of noncarbon elements and for potentially quantifying these amounts.

A large body of meteoritic and observational evidence exists which suggests that B, C, D, F, G, P, and T class asteroids possess abundant opaque (probably carbonaceous) phases on their surfaces (Gaffey *et al.* 1989). Asteroid reflectance spectra generally become more red sloped with increasing heliocentric distance (Gradie and Tedesco 1982, Hartmann *et al.* 1987, Cruikshank 1989, Jones *et al.* 1990, Mueller *et al.* 1992). The "big picture" scenario of Bell *et al.* (1989) suggests that the maximum temperature experienced by asteroids decreases with increasing heliocentric distance and decreasing size. The spectral data in conjunction with laboratory and field studies of thermal metamorphism of carbonaceous materials indicate that increasing the temperature of carbonaceous materials results in a number of compositional and structural changes which result in losses of aliphatics and hydrogen and the development of a progressively more ordered aromatic structure (van Vucht *et al.* 1955, French 1964, Friedel *et al.* 1967, Sugiura *et al.* 1986, Ito *et al.* 1988, 1990, Moroz *et al.* 1991, Ikeda 1992). Spectrally this will result in a decrease in overall reflectance, a possible increase in ultraviolet-visible absolute reflectance (Davis 1978), and a decrease in overall spectral slope with the wavelength position of the reflectance rise moving toward progressively longer wavelengths (Kmetko 1951, Friedel 1966, Friel *et al.* 1982). The increase in spectral slope is seen for the dark asteroid classes with increasing heliocentric distance (Mueller *et al.* 1992), consistent with the expected spectrum altering effects on carbonaceous phases subjected to a radially decreasing heat source (Bell *et al.* 1989) and consistent with the current spectral results indicating decreasing spectral slope accompanies progressive increases in temperature. A more comprehensive examination of the origin and evolution of carbonaceous materials on asteroids in light of the available spectral/compositional information for carbonaceous materials is currently in preparation.

The carbonaceous phases in IDPs have yet to be fully characterized (Gibson 1992 and references therein) but the diversity of identified materials suggests that microspectroscopy could be used to identify and map the distributions of carbon phases in these particles and assist in identifying the carriers of isotopic anomalies (McKeegan *et al.* 1985, Gibson 1992).

The increasing order and associated structural and compositional changes accompanying thermal metamorphism are usually amenable to X ray diffraction analysis (Mueller 1953, Rietmeijer and Mackinnon 1985a). If a correlation between diagnostic spectral parameters and the X ray diffraction data can be established it will open up the possibility of using spectroscopic techniques to conduct remote spectroscopic geothermometry on asteroids.

#### ACKNOWLEDGMENTS

This study was supported by a grant-in-aid from the American Association of Petroleum Geology (to E.A.C.) and a postdoctoral fellowship and research grant from the Alberta Oil Sands Technology and Research Authority (to E.A.C.) and NASA Planetary Geology and Geophysics Grant NAGW 642 (to M.J.G.). Thanks to Diane Caird for acquiring the X ray diffraction data of the samples. Thanks also to Carle Pieters and Stephen Pratt at the Reflectance Experiment Laboratory (RELAB) multiuser spectrometer facility in the Department of Geological Sciences at Brown University for measuring the sample reflectance spectra. Special thanks to the two anonymous reviewers for their insightful comments.

#### REFERENCES

- ADAMSKY, R. F., AND K. M. MERZ 1959. Synthesis and crystallography of the wurtzite form of silicon carbide. *Z. Kristallogr.* **111**, 350-361.
- ALLAMANDOLA, L. J., S. A. SANDFORD, AND B. WOPENKA 1987. Interstellar polycyclic aromatic hydrocarbons and carbon in interplanetary dust particles and meteorites. *Science* **237**, 56-59.
- AMARI, S., E. ANDERS, A. VIRAG, AND E. ZINNER 1990. Interstellar graphite in meteorites. *Nature* **345**, 238-240.
- ANDERS, E. 1988. Circumstellar material in meteorites: Noble gases, carbon and nitrogen. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, Eds.), pp. 927-955. Univ. of Arizona Press, Tucson.
- ANDERS, D. E., AND W. E. ROBINSON 1971. *Compositional Variations of the Organic Material of Green River Oil Shale- Colorado No. 1 Core*. Bureau of Mines Report of Investigations. U.S. Department of the Interior, Washington, D.C.
- ASH, R. D., J. W. ARDEN, M. M. GRADY, I. P. WRIGHT, AND C. T. PILLINGER 1990. Recondite interstellar carbon components in the Allende meteorite revealed by preparative precombustion. *Geochim. Cosmochim. Acta* **54**, 455-468.
- BADGER, G. M. 1957. *Structures and Reactions of the Aromatic Compounds*. Cambridge University Press, London.
- BAKER, B. L. 1971. Review of organic matter in the Orgueil meteorite. *Space Life Sci.* **2**, 472-497.
- BANDURSKI, E. L., AND B. NAGY 1976. The polymer-like organic matter in the Orgueil meteorite. *Geochim. Cosmochim. Acta* **40**, 1397-1406.
- BARBER, D. J. 1985. Phyllosilicates and other layer-structured materials in stony meteorites. *Clay Miner.* **20**, 415-454.
- BELL, J. F., D. P. CRUIKSHANK, AND M. J. GAFFEY 1985. The composition and origin of the Iapetus dark material. *Icarus* **61**, 192-207.
- BELL, J. F., D. R. DAVIS, W. K. HARTMANN, AND M. J. GAFFEY 1989. Asteroids: The big picture. In *Asteroids II* (R. P. Binzel, T. Gehrels, and M. S. Matthews, Eds.), pp. 921-945. Univ. of Arizona Press, Tucson.
- BERNATOWICZ, T., G. FRAUNDORF, T. MING, E. ANDERS, B. WOPENKA, E. ZINNER, AND P. FRAUNDORF 1987. Evidence for interstellar SiC in the Murray carbonaceous meteorite. *Nature* **330**, 728-730.



- BERNATOWICZ, T., P. GIBBONS, AND R. LEWIS 1989. Meteoritic diamonds: Nature of the amorphous component. *Lunar Planet. Sci. Conf. XX*, 65–66.
- BICHARD, J. A. 1987. *Oil Sands Composition and Behaviour Research*. AOSTRA Tech. Publ. Series #4, Alberta Oil Sands Technology and Research Authority, Edmonton.
- BISCOE, J., AND B. E. WARREN 1942. An X-ray study of carbon black. *J. Appl. Phys.* **13**, 364–371.
- BITZ, M. C., AND B. NAGY 1966. Ozonolysis of "polymer-type" material in coal, kerogens, and in the Orgueil meteorite: A preliminary report. *Proc. Natl. Acad. Sci. USA* **56**, 1383–1390.
- BLAKE, D. F., F. FREUND, K. M. F. KRISHNAN, C. J. ECHER, R. SHIPP, T. E. BUNCH, A. G. TIELENS, R. J. LIPARI, C. J. D. HETHERINGTON, AND S. CHANG 1988. The nature and origin of interstellar diamond. *Nature* **332**, 611–613.
- BLANFORD, G. E., K. L. THOMAS, AND D. S. MCKAY 1988. Microbeam analysis of four chondritic interplanetary dust particles for major elements, carbon, and oxygen. *Meteoritics* **23**, 113–121.
- BLOB, A. K., J. RULLKÖTTER, AND D. H. WELTE 1988. Direct determination of the aliphatic carbon content of individual macerals in petroleum source rocks by near-infrared microspectroscopy. *Org. Geochem.* **13**, 1073–1077.
- BOYD, M. L., AND D. S. MONTGOMERY 1962. *A Study of the Athabasca Bitumen from the Abasand Quarry, Alberta, Canada*. Report 104. Department of Mines and Technical Surveys, Ottawa, Canada.
- BRETT, R. 1967. Cohenite: Its occurrence and a proposed origin. *Geochim. Cosmochim. Acta* **31**, 143–159.
- BROOKE, T. Y., AND R. F. KNACKE 1986. The nucleus of Comet P/ Arend-Rigaux. *Icarus* **67**, 80–87.
- BROWNLEE, D. E., L. PILACHOWSKI, E. OLSZEWSKI, AND P. W. HODGE 1980. Analysis of interplanetary dust collections. In *Solid Particles in the Solar System* (I. Halliday and B. A. McIntosh, Eds.), pp. 333–342. Reidel, Dordrecht.
- CHRISTOFFERSON, R., AND P. R. BUSECK 1986. Mineralogy of interplanetary dust particles from the "olivine" infrared class. *Earth Planet. Sci. Lett.* **78**, 53–66.
- CLOUTIS, E. A. 1989. Spectral reflectance properties of hydrocarbons: Remote-sensing implications. *Science* **245**, 165–169.
- CLOUTIS, E. A. 1990. Identification, detection and characterization of individual tar sand phases using diffuse reflectance spectroscopy (0.35–2.6  $\mu\text{m}$ ). *AOSTRA J. Res.* **6**, 17–27.
- CLOUTIS, E. A., M. J. GAFFEY, D. G. W. SMITH, AND R. ST. J. LAMBERT 1990. Reflectance spectra of "featureless" materials and the surface mineralogies of M- and E-class asteroids. *J. Geophys. Res.* **95**, 281–293.
- CRONIN, J. R., S. PIZARELLO, G. U. YUEN, J. S. FRYE, AND S. CHANG 1982.  $^{13}\text{C}$  NMR spectroscopy of the insoluble carbon of carbonaceous chondrites. *Meteoritics* **17**, 200.
- CRONIN, J. R., S. PIZARELLO, AND D. P. CRUIKSHANK 1988. Organic matter in carbonaceous chondrites, planetary satellites, asteroids and comets. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, Eds.), pp. 819–857. Univ. of Arizona Press, Tucson.
- CRUIKSHANK, D. P. 1987. Dark matter in the solar system. *Adv. Space Res.* **7**, 109–120.
- CRUIKSHANK, D. P. 1989. Dark surfaces of asteroids and comets: Evidence for macromolecular carbon compounds. *Adv. Space Res.* **9**, 65–71.
- CRUIKSHANK, D. P., AND R. H. BROWN 1987. Organic matter on asteroid 130 Elektra. *Science* **238**, 183–184.
- CRUIKSHANK, D. P., W. K. HARTMANN, D. J. THOLEN, L. J. ALLAMANDOLA, AND R. H. BROWN 1990. Solid  $\text{C}\equiv\text{N}$  bearing material in the outer solar system. *Bull. Am. Astron. Soc.* **22**, 1098.
- DAVIES, G. 1977. The optical properties of diamond. *Chem. Phys. Carbon* **13**, 1–143.
- DAVIS, A. 1978. The reflectance of coal. In *Analytical Methods for Coal and Coal Products* (C. Karr, Jr., Ed.), Vol. II, pp. 27–81. Academic Press, New York.
- DI BROZOLO, F. R., T. E. BUNCH, AND S. CHANG 1985. Laser microprobe study of carbon in interplanetary dust particles (IDP). *Origins of Life* **16**, 236–237.
- DONINI, J. C., AND K. H. MICHAELIAN 1986. Near-infrared photoacoustic FTIR spectroscopy of clay minerals and coal. *Infrared Phys.* **26**, 135–140.
- DOUGAN, P. D. 1989. Near-infrared reflectance analysis: Its potential application in oil sand processing. *AOSTRA J. Res.* **5**, 203–210.
- ERGUN, S. 1968. Optical studies of carbon. In *Chemistry and Physics of Carbon 3* (P. L. Walker, Jr., Ed.), pp. 45–119. Dekker, New York.
- ERGUN, S., J. B. YASINSKY, AND J. R. TOWNSEND 1967. Transverse and longitudinal optical properties of graphite. *Carbon* **5**, 403–408.
- FORREST, R. A., H. MARSH, AND C. CORNFORD 1984. Optical properties of anisotropic carbon. In *Chemistry and Physics of Carbon 19* (P. A. Thrower, Ed.), pp. 211–330. Dekker, New York.
- FOSTER, P. J., AND C. R. HOWARTH 1968. Optical constants of carbons and coals in the infrared. *Carbon* **6**, 719–729.
- FRAUNDORF, P., R. I. PATEL, R. M. WALKER, J. J. FREEMAN, AND F. ADAR 1982. Raman spectroscopy of graphite and other phases in meteorites and interplanetary dust. *Lunar Planet. Sci. Conf. XIII*, 231–232.
- FRAUNDORF, P., R. I. PATEL, S. A. SANDFORD, AND R. M. WALKER 1983. Laboratory infrared spectroscopic measurements of interplanetary dust particles and comparison with astronomical observations of comet dust. *Lunar Planet. Sci. Conf. XIV*, 207–208.
- FRENCH, B. M. 1964. Graphitization of organic material in a progressively metamorphosed Precambrian iron formation. *Science* **146**, 917–918.
- FRIEDEL, R. A. 1966. Infrared in coal structure research. In *Applied Infrared Spectroscopy* (D. N. Kendall, Ed.), pp. 312–343. Reinhold, New York.
- FRIEDEL, R. A., AND J. A. QUEISER 1956. Infrared analysis of bituminous coals and other carbonaceous materials. *Anal. Chem.* **28**, 22–30.
- FRIEDEL, R. A., H. L. RETCOFSKY, AND J. A. QUEISER 1967. *Advances in Coal Spectrometry*. Bureau of Mines Bulletin 640, United States Department of the Interior, Washington, DC.
- FRIEL, J. J., S. MEHTA, AND D. M. FOLLWEILER 1982. Electron, optical and IR spectroscopic investigation of coal carbonization. In *Coal and Coal Products: Analytical Characterization Techniques* (E. L. Fuller, Jr., Ed.), pp. 293–309. Am. Chem. Soc., Washington, DC.
- FUKUNAGA, K., J. MATSUDA, K. NAGAO, M. MIYAMOTO, AND K. ITO 1987. Noble-gas enrichment in vapour-growth diamonds and the origin of diamonds in ureilites. *Nature* **328**, 141–143.
- FYSH, S. A., D. A. J. SWINKELS, AND P. M. FREDERICKS 1985. Near-infrared diffuse reflectance spectroscopy of coal. *Appl. Spectrosc.* **39**, 354–357.
- GAFFEY, M. J. 1976. Spectral reflectance characteristics of the meteorite classes. *J. Geophys. Res.* **81**, 905–920.
- GAFFEY, M. J., AND T. B. MCCORD 1979. Mineralogical and petrological characterizations of asteroid surface materials. In *Asteroids* (T. Gehrels, Ed.), pp. 688–723. Univ. of Arizona Press, Tucson.

- GAFFEY, M. J., J. F. BELL, AND D. P. CRUIKSHANK 1989. Reflectance spectroscopy and asteroid surface mineralogy. In *Asteroids II* (R. P. Binzel, T. Gehrels, and M. S. Matthews, Eds.), pp. 98–127. Univ. of Arizona Press, Tucson.
- GAVRILOV, M. Z., AND I. N. ERMOLENKO 1975. Spectroscopic study of the pyrolysis of hydrocellulose films and the formation of carbon film structure. *J. Appl. Spectrosc.* **23**, 955–957.
- GIBSON, E. K., JR. 1976. Nature of the carbon and sulphur phases and inorganic gases in the Kenna ureilite. *Geochim. Cosmochim. Acta* **40**, 1459–1464.
- GIBSON, E. K., JR. 1980. Carbon abundances in Antarctic meteorites. *Lunar Planet. Sci. Conf. XI*, 323–325.
- GIBSON, E. K., JR. 1992. Volatiles in interplanetary dust particles: A review. *J. Geophys. Res.* **97**, 3865–3875.
- GIBSON, E. K., JR., AND C. P. HARTMETZ 1991. Carbon-bearing phases and volatiles in interplanetary dust particles. *Lunar Planet. Sci. Conf. XXII*, 439–440.
- GIBSON, E. K., JR., C. B. MOORE, AND C. F. LEWIS 1971. Total nitrogen and carbon abundances in carbonaceous meteorites. *Geochim. Cosmochim. Acta* **35**, 599–604.
- GILBERT, L. A. 1960. The reflectivity spectra of coal vitrains in the visible and the ultra-violet. *Fuel* **39**, 393–400.
- GÖBEL, R., U. OTT, AND F. BEGEMANN 1978. On trapped noble gases in ureilites. *J. Geophys. Res.* **83**, 855–867.
- GODDU, R. F. 1957. Determination of unsaturation by near-infrared spectrophotometry. *Anal. Chem.* **29**, 1790–1794.
- GOODRICH, C. E., AND J. L. BERKLEY 1986. Primary magmatic carbon in ureilites: Evidence from cohenite-bearing metallic spherules. *Geochim. Cosmochim. Acta* **50**, 681–691.
- GRADIE, J., AND E. TEDESCO 1982. Compositional structure of the asteroid belt. *Science* **216**, 1405–1407.
- GRADIE, J., AND J. VEVERKA 1980. The composition of the Trojan asteroids. *Nature* **283**, 840–842.
- GREEN, H. W., S. V. RADCLIFFE, AND A. H. HEUER 1971. Allende meteorite: A high voltage electron petrographic study. *Science* **172**, 936–939.
- GRIFFIN, G. M. 1967. X-ray diffraction techniques applicable to studies of diagenesis and low rank metamorphism in humic sediments. *J. Sedim. Petrol.* **37**, 1006–1011.
- HAHN, J. H., R. ZENOBI, J. L. BADA, AND R. N. ZARE 1988. Application of two-step laser mass spectrometry to cosmogeochemistry: Direct analysis of meteorites. *Science* **239**, 1523–1525.
- HANNAM, A. L., AND P. T. B. SHAFFER 1969. Revised X-ray diffraction line intensities for silicon carbide polytypes. *J. Appl. Crystallogr.* **2**, 45–48.
- HANNER, M. S., D. K. AITKEN, R. KNACKE, S. MCCORKLE, P. F. ROCHE, AND A. T. TOKUNAGA 1985. Infrared spectrophotometry of comet IRAS-Araki-Alcock (1983d): A bare nucleus revealed? *Icarus* **62**, 97–109.
- HARTMANN, W. K., D. P. CRUIKSHANK, AND J. DEGEWIJ 1982. Remote comets and related bodies: VJHK colorimetry and surface materials. *Icarus* **52**, 377–408.
- HARTMANN, W. K., D. J. THOLEN, AND D. P. CRUIKSHANK 1987. The relationship of active comets, “extinct” comets, and dark asteroids. *Icarus* **69**, 33–50.
- HAYATSU, R., AND E. ANDERS 1981. Organic compounds in meteorites and their origins. *Topics Curr. Chem.* **99**, 1–37.
- HAYATSU, R., S. MATSUOKA, R. G. SCOTT, M. STUDIER, AND E. ANDERS 1977. Origin of organic matter in the early solar system-VII. The organic polymer in carbonaceous chondrites. *Geochim. Cosmochim. Acta* **41**, 1325–1339.
- HAYATSU, R., R. G. SCOTT, AND R. E. WINANS 1983. Comparative structural study of meteoritic polymer with terrestrial geopolymers coal and kerogen. *Meteoritics* **18**, 310.
- HAYES, J. M. 1967. Organic constituents of meteorites—A review. *Geochim. Cosmochim. Acta* **31**, 1395–1440.
- HENNIG, G. R. 1965. Optical transmission of graphite compounds. *J. Chem. Phys.* **43**, 1201–1206.
- HOLMAN, R. T., AND P. R. EDMONDSON 1956. Near-infrared spectra of fatty acids and some related substances. *Anal. Chem.* **28**, 1533–1538.
- HUNT, J. M. 1979. *Petroleum Geochemistry and Geology*. Freeman, San Francisco.
- HUNT, G. R., AND J. W. SALISBURY 1970. Visible and near-infrared spectra of minerals and rocks, I, Silicate minerals. *Mod. Geol.* **1**, 283–300.
- HUSS, G. R. 1990. Ubiquitous interstellar diamond and SiC in primitive chondrites: Abundances reflect metamorphism. *Nature* **347**, 159–161.
- IKEDA, Y. 1992. An overview of the research consortium, “Antarctic carbonaceous chondrites with CI affinities, Yamato-86720, Yamato-82162, and Belgica-7904”. *Proc. NIPR Symp. Antarct. Meteorites* **5**, 49–73.
- ITO, O., H. SEKI, AND M. IINO 1988. Diffuse reflectance spectra in near-i.r. region of coals: A new index for degrees of coalification and carbonization. *Fuel* **67**, 573–578.
- ITO, O., T. KAKUTA, AND M. IINO 1990. Optical absorption spectra of heat treated decacyclene during mesophase formation. *Carbon* **28**, 553–558.
- JOHNSON, T. V., AND F. P. FANALE 1973. Optical properties of carbonaceous chondrites and their relationship to asteroids. *J. Geophys. Res.* **78**, 8507–8518.
- JONES, T. D., L. A. LEBOSKY, J. S. LEWIS, AND M. S. MARLEY 1990. The composition and origin of the C, P, and D asteroids: Water as a tracer of thermal evolution in the outer belt. *Icarus* **88**, 172–192.
- KAGI, H., K. TAKAHASHI, H. SHIMIZU, F. KITAJIMA, AND A. MASUDA 1991. *In-situ* micro Raman studies on graphitic carbon in some Antarctic ureilites. *Proc. NIPR Symp. Antarct. Meteorites* **4**, 371–383.
- KERRIDGE, J. F., AND M. S. MATTHEWS (Eds.) 1988. *Meteorites and the Early Solar System*. Univ. of Arizona Press, Tucson.
- KERRIDGE, J. F. 1985. Carbon, hydrogen and nitrogen in carbonaceous chondrites: Abundances and isotopic compositions in bulk samples. *Geochim. Cosmochim. Acta* **49**, 1707–1714.
- KITAJIMA, F., AND A. MASUDA 1992. A comparative structural study of the carbonaceous macromolecular materials in carbonaceous chondrites with several synthetic polymers. *Symp. Antarct. Meteorites 17th*, 65–68.
- KMETKO, E. A. 1951. Infrared absorption and intrinsic semiconductivity of condensed aromatic systems. *Phys. Rev.* **82**, 456–457.
- KNACKE, R. F. 1977. Carbonaceous compounds in interstellar dust. *Nature* **269**, 132–134.
- LARSON, H. P., M. A. FEIERBERG, U. FINK, AND H. A. SMITH 1979. Remote spectroscopic identification of carbonaceous chondrite mineralogies: Applications to Ceres and Pallas. *Icarus* **39**, 257–271.
- LIFANTE, G., F. JAQUE, M. A. HOYOS, AND S. LEGUEY 1990. Testing of colourless natural diamonds by room temperature optical absorption. *J. Gemmol.* **22**, 142–145.
- LIPSCHUTZ, M. E. 1964. Origin of diamonds in the ureilites. *Nature* **143**, 1431–1434.
- LOCHMÜLLER, C. H., R. RÖHL, AND D. B. MARSHALL 1981. Use of

- carbon black as a reference material in photoacoustic spectroscopy. *Anal. Lett.* **14**, 41–46.
- MACKINNON, I. D. R. 1987. Secrets of black dust revealed. *Nature* **328**, 670–671.
- MARCHAND, A. 1987. Various kinds of solid carbon: Structure and optical properties. In *Polycyclic Aromatic Hydrocarbons and Astrophysics* (A. Léger, L. d'Hendecourt, and N. Boccara, Eds.), pp. 31–54. Reidel, Dordrecht.
- MATSUDA, M., K. FUKUNAGA, AND K. ITO 1991. Noble gas studies in vapor-growth diamonds: Comparison with shock-produced diamonds and the origin of diamonds in ureilites. *Geochim. Cosmochim. Acta* **55**, 2011–2023.
- MAURETTE, M., C. JÉHANNO, E. ROBIN, AND C. HAMMER 1987. Characteristics and mass distribution of extraterrestrial dust from the Greenland ice cap. *Nature* **328**, 699–702.
- MCASKILL, N. A. 1987. Near-infrared photoacoustic spectroscopy of coals and shales. *Appl. Spectrosc.* **41**, 313–317.
- MCCARTNEY, J. T., AND S. ERGUN 1967. *Optical Properties of Coals and Graphite*. Bulletin 641, U.S. Department of the Interior, Bureau of Mines, Washington, D.C.
- MCKAY, D. S., F. J. M. RIETMEIJER, AND I. D. R. MACKINNON 1985. Mineralogy of chondritic porous aggregates: Current status. *Lunar Planet. Sci. Conf. XVI*, 536–537.
- MCKEEGAN, K. D., R. M. WALKER, AND E. ZINNER 1985. Ion microprobe isotopic measurements of individual interplanetary dust particles. *Geochim. Cosmochim. Acta* **49**, 1971–1987.
- MCMICHAEL, B. D., E. A. KMETKO, AND S. MROZOWSKI 1954. An aromatic detector for the infrared. *J. Opt. Soc. Amer.* **44**, 26–30.
- MEYERSON, B., AND F. W. SMITH 1980. Electrical and optical properties of hydrogenated amorphous carbon films. *J. Non-Cryst. Solids* **35/36**, 435–440.
- MING, T., AND E. ANDERS 1988. Isotopic anomalies of Ne, Xe, and C in meteorites. II. Interstellar diamond and SiC: Carriers of exotic noble gases. *Geochim. Cosmochim. Acta* **52**, 1235–1244.
- MOORE, C. B., AND C. LEWIS 1965. Carbon abundances in chondritic meteorites. *Science* **149**, 317–318.
- MOORE, C. B., AND C. F. LEWIS 1967. Total carbon content of ordinary chondrites. *J. Geophys. Res.* **72**, 6289–6292.
- MOROZ, L. V., AND C. M. PIETERS 1991. Reflectance spectra of some fractions of Migei and Murchison CM chondrites in the range of 0.3–2.6  $\mu\text{m}$ . *Lunar Planet. Sci. Conf. XXII*, 923–924.
- MOROZ, L. V., C. M. PIETERS, AND M. V. AKHMANOVA 1991. Spectroscopy of solid carbonaceous materials: Implications for dark surfaces of outer belt asteroids. *Lunar Planet. Sci. Conf. XXII*, 925–926.
- MUELLER, G. 1953. The properties and theory of genesis of the carbonaceous complex within the cold bokevelt meteorite. *Geochim. Cosmochim. Acta* **4**, 1–10.
- MUELLER, B. E. A., D. J. THOLEN, W. K. HARTMANN, AND D. P. CRUIKSHANK 1992. Extraordinary colors of asteroidal object (5145) 1992 AD. *Icarus* **97**, 150–154.
- MURAE, T. 1992. Spectroscopic studies of major organic matter in carbonaceous chondrites by microscopic FT-IR. *Symp. Antarct. Meteorites 17th*, 63–64.
- MURAE, T., A. MASUDA, AND T. TAKAHASHI 1990. Spectroscopic studies of acid-resistant residues of carbonaceous chondrites. *Proc. NIPR Symp. Antarct. Meteorites* **3**, 211–219.
- MURAE, T., F. KITAJIMA, AND A. MASUDA 1991. Pyrolytic nature of carbonaceous matter in carbonaceous chondrites and secondary metamorphism. *Proc. NIPR Symp. Antarct. Meteorites* **4**, 384–389.
- MURRELL, M. T., P. A. DAVIS, K. NISHIZUMI, AND H. T. MILLARD 1980. Deep sea spherules from Pacific clay: Mass distribution and influx rate. *Geochim. Cosmochim. Acta* **44**, 2067–2074.
- NAGY, B. 1975. *Carbonaceous Meteorites*. Elsevier, Amsterdam.
- NITTLER, L. R., R. M. WALKER, E. ZINNER, P. HOPPE, AND R. S. LEWIS 1993. Identification of an interstellar oxide grain from the Murchison meteorite by ion imaging. *Lunar Planet. Sci. Conf. XXIV*, 1087–1088.
- NUTH, J. 1990. Diamonds are for everywhere. *Nature* **347**, 125–126.
- OBERLIN, A., J. L. BOULMIER, AND M. VILLEY 1980. Electron microscope study of kerogen microtexture. Selected criteria for determining the evolution path and evolution stage of kerogen. In *Kerogen: Insoluble Organic Matter from Sedimentary Rocks* (B. Durand, Ed.), pp. 191–241. Éditions Technip, Paris.
- O'REILLY, J. M., AND R. A. MOSHER 1983. Functional groups in carbon black by FTIR spectroscopy. *Carbon* **21**, 47–51.
- ORLOV, Y. L. 1977. *The Mineralogy of the Diamond*. Wiley, New York.
- PAINTER, P. C., R. W. SNYDER, M. STARSINIC, M. M. COLEMAN, D. W. KUEHN, AND A. DAVIS 1981. Concerning the application of FT-IR to the study of coal: A critical assessment of band assignments and the application of spectral analysis programs. *Fuel* **35**, 475–485.
- PAINTER, P., M. STARSINIC, AND M. COLEMAN 1985. Determination of functional groups in coal by Fourier transform interferometry. In *Fourier Transform Infrared Spectroscopy* (J. R. Ferraro and L. J. Basile, Eds.), pp. 169–241. Academic Press, New York.
- PELLA, P. A. 1986. X-ray spectrometry. In *Instrumental Analysis* (G. D. Christian and J. E. O'Reilly, Eds.), 2nd ed., pp. 412–450. Allyn and Bacon, Boston.
- PIETERS, C. M. 1983. Strength of mineral absorption bands in the transmitted component of near-infrared light: First results from RELAB. *J. Geophys. Res.* **88**, 9534–9544.
- PISCITELLI, J. R., D. P. CRUIKSHANK, R. H. BROWN, A. T. TOKUNAGA, AND J. F. BELL 1988. The search for solid macromolecular carbon on asteroids. *Bull. Am. Astron. Soc.* **20**, 864.
- RIETMEIJER, F. J. M., AND I. D. R. MACKINNON 1985a. Poorly graphitized carbon as a new cosmo thermometer for primitive extraterrestrial materials. *Nature* **315**, 733–736.
- RIETMEIJER, F. J. M., AND I. D. R. MACKINNON 1985b. A multi-stage history for carbonaceous material in extraterrestrial chondritic porous aggregate W7029\*A and a new cosmo thermometer. *Lunar Planet. Sci. Conf. XVI*, 700–701.
- RIETMEIJER, F. J. M., AND I. D. R. MACKINNON 1987. Metastable carbon in two chondritic porous interplanetary dust particles. *Nature* **326**, 162–165.
- ROBERTSON, J., AND E. P. O'REILLY 1987. Electronic and atomic structure of amorphous carbon. *Phys. Rev. B* **35**, 2946–2957.
- ROWAN, L. C., J. W. SALISBURY, M. J. KINGSTON, N. VERGO, AND N. H. BOSTICK 1991. Evaluation of visible and near-infrared and thermal-infrared reflectance spectra for studying thermal alteration of Pierre shale, Wolcott, Colorado. *J. Geophys. Res.* **96**, 18,047–18,057.
- SALISBURY, J. W., G. R. HUNT, AND C. J. LENHOFF 1975. Visible and near-infrared spectra: X. Stony meteorites. *Mod. Geol.* **5**, 115–126.
- SANDFORD, S. A. 1986. Acid dissolution experiments: Carbonates and the 6.8-micrometer band in interplanetary dust particles. *Science* **231**, 1540–1541.
- SANDFORD, S. A., AND R. M. WALKER 1985. Laboratory infrared transmission spectra of individual interplanetary dust particles from 2.5 to 25 microns. *Astrophys. J.* **291**, 838–851.
- SCHULZ, K. F., AND R. M. ELOFSON 1965. Electron spin resonance studies of organic matter in the Orgueil meteorite. *Geochim. Cosmochim. Acta* **29**, 157–160.

- SCOTT, E. R. D. 1971. New carbide,  $(\text{Fe,Ni})_{23}\text{C}_6$ , found in iron meteorites. *Nature* **229**, 61–62.
- SCOTT, E. R. D., AND R. H. JONES 1990. Disentangling nebular and asteroidal features of CO<sub>3</sub> carbonaceous chondrite meteorites. *Geochim. Cosmochim. Acta* **54**, 2485–2502.
- SHAW, R. C., AND B. KRATOCHVIL 1990. Near-infrared diffuse reflectance analysis of Athabasca oil sand. *Anal. Chem.* **62**, 167–174.
- SILL, G. T. 1973. Reflection spectra of solids of planetary interest. *Contrib. Lunar Planet. Lab* **184**.
- SILVERSTEIN, R. M., AND G. C. BASSLER 1967. *Spectrometric Identification of Organic Compounds*. Wiley, New York.
- SIMMONDS, P. G., A. J. BAUMAN, E. M. BOLLIN, E. GELPI, AND J. ORÓ 1969. The unextractable organic fraction of the Pueblito de Allende meteorite: Evidence for its indigenous nature. *Proc. Natl. Acad. Sci. USA* **64**, 1027–1034.
- SINGER, R. B. 1985. Spectroscopic observation of Mars. *Adv. Space Res.* **5**, 59–68.
- SMITH, P. P. K., AND P. R. BUSECK 1981. Carbon in the Allende meteorite: Evidence for poorly graphitized carbon rather than carbyne. *Proc. Lunar Planet. Sci. Conf. 12th*, 1167–1175.
- SUGIURA, N., J. ARKANI-HAMED, AND D. W. STRANGWAY 1986. Possible transport of carbon in meteorite parent bodies. *Earth Planet. Sci. Lett.* **78**, 148–156.
- SUTHERLAND, G. B. B. M., AND H. A. WILLIS 1945. Some new peculiarities in the infra-red spectrum of diamond. *Trans. Faraday Soc.* **41**, 289–293.
- SUTHERLAND, G. B. B. M., P. B. FELLGETT, AND H. A. WILLIS 1944. The infra-red spectrum of coal. In *Proc. Conf. on the Ultra-Fine Structure of Coals and Cokes*, pp. 330–333. British Coal Utilization Research Association.
- THIBAUT, N. W. 1944. Morphological and structural crystallography and optical properties of silicon carbide (SiC). *Am. Mineral.* **29**, 249–278.
- THOLEN, D. J. 1984. *Asteroid Taxonomy from Cluster Analysis of Photometry*. Ph.D. dissertation. University of Arizona.
- THOLEN, D. J., AND J. F. BELL 1987. Evolution of asteroid taxonomy. *Lunar. Planet. Sci. Conf. XVIII*, 1008–1009.
- TIBBETTS, T. E. 1976. *Evaluation of Canadian Commercial Coals: Saskatchewan, Alberta and British Columbia—1975*. CANMET Report 76-41, Canada Centre for Mineral and Energy Technology, Ottawa.
- TISSOT, B. P., AND D. H. WELTE 1978. *Petroleum Formation and Occurrence*. Springer-Verlag, Berlin.
- TSCHAMLER, H., AND E. DE RUITER 1963. Physical properties of coals. In *Chemistry of Coal Utilization*, (H. H. Lowry, Ed.), Suppl. Vol., pp. 35–79. Wiley, New York.
- USRA Quarterly 1992. Stellar astronomy with an ion microprobe. *USRA Q.* **Fall**, 4–5.
- VAN VUCHT, H. A., B. J. RIETVELD, AND D. W. VAN KREVELEN 1955. Chemical structure and properties of coal. VIII—Infra-red absorption spectra. *Fuel* **34**, 50–59.
- VDOVYKIN, G. P. 1970. Ureilites. *Space Sci. Rev.* **10**, 483–510.
- VDOVYKIN, G. P. 1972. Forms of carbon in the New Haverö ureilite of Finland. *Meteoritics* **7**, 547–552.
- VIDRINE, D. W. 1980. Photoacoustic Fourier transform infrared spectroscopy of solid samples. *Appl. Spectrosc.* **34**, 314–319.
- VINOGRADOV, A. P., AND G. P. VDOVYKIN 1964. Multimolecular organic matter of carbonaceous chondrites. *Geochem. Int.* **9**, 831–836.
- VINOGRADOV, A. P., G. P. VDOVYKIN, A. V. KARYAKIN, AND M. Y. ZUBRILINA 1966. An infrared absorption spectroscopy study of organic compounds and diamond in the Novyy Urey meteorite. *Geochem. Int.* **9**, 885–888.
- WACKER, J. F. 1986. Noble gases in the diamond-free ureilite, ALHA 78019: The roles of shock and nebular processes. *Geochim. Cosmochim. Acta* **50**, 633–642.
- WAGNER, J. K., B. W. HAPKE, AND E. N. WELLS 1987. Atlas of reflectance spectra of terrestrial, lunar, and meteoritic powders and frosts from 92 to 1800 nm. *Icarus* **69**, 14–28.
- WASSON, J. T. 1974. *Meteorites: Classification and Properties*. Springer-Verlag, New York.
- WEBER, H. W., H. HINTENBERGER, AND F. BEGEMANN 1971. Noble gases in the Haverö ureilite. *Earth Planet. Sci. Lett.* **13**, 205–209.
- WEBER, H. W., F. BEGEMANN, AND H. HINTENBERGER 1976. Primordial gases in graphite-diamond-kamacite inclusions from the Haverö ureilite. *Earth Planet. Sci. Lett.* **29**, 81–90.
- WEIDNER, V. R., AND J. J. HSIA 1981. Reflection properties of pressed polytetrafluoroethylene powder. *J. Opt. Soc. Am.* **71**, 856–861.
- WEISSMAN, P. R., M. F. A'HEARN, L. A. MCFADDEN, AND H. RICKMAN 1989. Evolution of comets into asteroids. In *Asteroids II* (R. P. Binzel, T. Gehrels, and M. S. Matthews, Eds.), pp. 880–920. Univ. of Arizona Press, Tucson.
- WOODS, G. S., AND A. T. COLLINS 1986. New developments in spectroscopic methods for detecting artificially coloured diamonds. *J. Gemm.* **20**, 75–82.
- WOPENKA, B. 1988. Raman observations on individual interplanetary dust particles. *Earth Planet. Sci. Lett.* **88**, 221–231.
- WOPENKA, B., AND S. A. SANDFORD 1984. Laser Raman microprobe study of mineral phases in meteorites. *Meteoritics* **19**, 340–341.
- WRIGHT, I. P., D. W. MCGARVIE, M. M. GRADY, AND C. T. PILLINGER 1990. The distribution of carbon in C1 to C6 carbonaceous chondrites. *Proc. NIPR Symp. Antarct. Meteorites* **3**, 194–210.
- YASINSKY, J. B., AND S. ERGUN 1965. Transmittance of single crystals of graphite in the infrared spectrum. *Carbon* **2**, 355–358.
- YEN, T. F. 1973. The charge-transfer nature of bitumens. *Fuel* **52**, 93–98.
- ZENOBI, R., J. M. PHILIPPOZ, P. R. BUSECK, AND R. N. ZARE 1989. Spatially resolved organic analysis of the Allende meteorite. *Science* **246**, 1026–1029.
- ZERLIA, T., G. PINELLA, M. ZAGHI, AND S. FRIGNANI 1990. U.V. spectrometry as a tool for rapid screening of petroleum products. *Fuel* **69**, 1381–1385.
- ZINNER, E. 1988. Interstellar cloud material in meteorites. In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, Eds.), pp. 956–983. Univ. of Arizona Press, Tucson.
- ZINNER, E., T. MING, AND E. ANDERS 1987. Large isotopic anomalies of Si, C, N and noble gases in interstellar silicon carbide from the Murray meteorite. *Nature* **330**, 730–732.
- ZINNER, E., T. MING, AND E. ANDERS 1989. Interstellar SiC in the Murchison and Murray meteorites: Isotopic composition of Ne, Xe, Si, C, and N. *Geochim. Cosmochim. Acta* **53**, 3273–3290.
- ZINNER, E., B. WOPENKA, S. AMARI, AND E. ANDERS 1990. Interstellar graphite and other carbonaceous grains from the Murchison meteorite: Structure, composition and isotopes of C, N, and Ne. *Lunar Planet. Sci. Conf. XXI*, 1379–1380.