



Fig. 2 The 2.0–4.0  $\mu\text{m}$  spectrum of IRS7. The solid curve is the estimated position of the continuum (see text). The dashed curve is the July 1980 spectrum where it deviates from the May 1981 spectrum.

bands stretching from 2.9 to 3.6  $\mu\text{m}$ . Two dominant bands lie at 3.03 and 3.40  $\mu\text{m}$ , and have optical depths of 0.41 and 0.32 respectively. The increased optical depth of the 3.4  $\mu\text{m}$  feature relative to our previous result<sup>1</sup> reflects the improved definition of the continuum. This optical depth would be further increased if the redness between 3.6 and 3.95  $\mu\text{m}$  were due to absorption rather than to the addition of cool dust.

Figure 2 shows all of the absorption features we believe to be real, and a few (marked?) which are less certain. The absorption clearly breaks up into many discrete features and two of these (at 3.192 and 3.295  $\mu\text{m}$ ) are quite narrow. Whilst the broad features centred at 3.03  $\mu\text{m}$  and 3.40  $\mu\text{m}$  presumably arise in solid grains, the narrow features may have a gaseous origin. We have found no convincing identification for either, although many hydrocarbons have stretching absorptions in this spectral range. However, laboratory data are not available for even quite simple, incompletely bonded molecules (for example  $\text{CH}_3$ ) such as might be found in the interstellar environment. Quite narrow absorption bands are found in the absorption spectra of some solids, such as methane<sup>4</sup> and methyl alcohol<sup>5</sup>.

Suitable data on the absorption properties of solid materials are not available, and laboratory work is needed to match the present spectra. We see no evidence for water ice in the available data. The absorption band at 3.03  $\mu\text{m}$  is displaced from that of water (3.06  $\mu\text{m}$ ) and is narrower. If water ice is present, it contributes little to the absorption. Similarly, solid ammonia (2.91  $\mu\text{m}$ ) is not present. Molecules involving carbon and hydrogen, on the other hand, can produce absorption near both 3.0 and 3.4  $\mu\text{m}$ , and are thus particularly attractive identifications. Organic molecules containing OH and NH bonds also cause absorption near 3.0  $\mu\text{m}$  (refs 6, 7). The wavelengths of CH, NH and OH vibrations depend critically on the composition of the solid and only a few cases<sup>5</sup> of astronomical interest have been discussed in the literature. The H bonded solid complex of  $\text{H}_2\text{O}$ ,  $\text{CH}_3\text{OH}$  and  $\text{NH}_3$  (ref. 5) has a feature due to NH at 2.97  $\mu\text{m}$  but there is no correspondence with the rest of the spectrum.

It has been suggested recently<sup>8</sup>, that surface functional groups attached to reactive sites on small carbon grains may be responsible for the IR features seen in IRS7. Although there are some interesting wavelength coincidences (aromatic  $-\text{CH}$  (3.3  $\mu\text{m}$ ),  $-\text{CH}_3$  (3.4, 3.5  $\mu\text{m}$ ),  $-\text{CHO}$  (3.5, 3.65  $\mu\text{m}$ )) no information has been given on band strengths and shapes to enable a detailed comparison.

We have looked at published spectra of specific grain models involving organic polymers which could be possibilities for the organic component of interstellar grains. The polymer-like material in carbonaceous chondrites<sup>9</sup> show absorption due to CH near 3.3  $\mu\text{m}$  and weak absorption at 3.0  $\mu\text{m}$ . Clearly this material will not produce a fit to the astronomical data even over a restricted wavelength region. However, hydrated silicates of

meteoritic origin show a broad absorption feature centred near 3  $\mu\text{m}$ <sup>10</sup>. This may be relevant in view of the possible identifications of the 9.7  $\mu\text{m}$  and 18  $\mu\text{m}$  features in the galactic centre with silicates. We consider it significant that the yellow component of UV tholin<sup>2,9</sup> looks qualitatively similar to that of IRS7 in the 3.4- $\mu\text{m}$  region. In particular the shoulder at 3.36  $\mu\text{m}$ , the central component at 3.4  $\mu\text{m}$  and the component at 3.48  $\mu\text{m}$  are present in the laboratory data with wavelengths agreeing to within  $\pm 0.02$   $\mu\text{m}$ . This could indicate the existence of complex organic molecules in grains<sup>2,11,12</sup>. However, this material does not produce significant absorption near 3  $\mu\text{m}$  as required by the IRS7 data. It is interesting that the satellite features at 3.36, 3.48  $\mu\text{m}$  are also seen in the spectrum of polyformaldehyde suggesting that  $\text{H}_2\text{CO}$  may be present as a structural unit<sup>13</sup>.

We cannot rule out the possibility that a mix of simple organics might match the observed spectrum. This requires further investigation using laboratory data. However, as our data are of relevance mainly to the properties of dust in the diffuse interstellar medium it will be more appropriate to look at refractory materials related to the UV component of tholins such as the non-volatile residue produced in the laboratory experiments designed to simulate conditions in the interstellar medium described by Greenberg<sup>12</sup> and with predictions from the Hoyle–Wickramasinghe model<sup>11</sup>. The latter comparison has shown a remarkable similarity between the spectrum of IRS7 and that of dried bacteria (*Escherichia coli*) which will be reported elsewhere<sup>14</sup>.

Finally emission features are found in this waveband in some H II regions and carbon-rich planetary nebulae (for example, NGC7027)<sup>15</sup>. These normally comprise a strong, narrow peak at 3.29  $\mu\text{m}$  and a weaker, broader feature peaking at 3.40  $\mu\text{m}$ . In this respect they mimic features in the relevant portion of the absorption spectrum of IRS7. However, the 3.03 and 3.192  $\mu\text{m}$  features are not seen in emission in any objects. An interpretation of the absorption spectrum of IRS7 which simultaneously predicted the more restricted range of the emission bands would be very satisfying.

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## Fractal dimensions of landscapes and other environmental data

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Mandelbrot<sup>1</sup> has introduced the term 'fractal' specifically for temporal or spatial phenomena that are continuous but not differentiable, and that exhibit partial correlations over many scales. The term fractal strictly defined refers to a series in which the Hausdorff–Besicovitch dimension exceeds the topological dimension. A continuous series, such as a polynomial, is differentiable because it can be split up into an infinite number of absolutely smooth straight lines. A non-differentiable continuous series cannot be so resolved. Every attempt to split it up into smaller parts results in the resolution of still more structure or

**Table 1** Estimated *D* values for various environmental series

Location	Property	Lag	<i>D</i> as lag → 0	<i>D</i> at max. slope	Ref.
Wales	Soil—sodium content	15.2 m	1.7–1.9*	—	7
	—stone content (both over four directions)	15.2 m	1.1–1.8*	—	7
England	Soil—thickness of cover loam	20 m	1.6*	—	7
England	Soil—electrical resistivity (4 directions)	1 m	1.4–1.6*	—	7
England	Surface of airport runway	30 cm	1.5†	—	8
Deserts in Africa and America	Soil—mean cone index	~1 km	1.9‡	—	9
	—silt + clay in 0–15 cm layer	~1 km	1.8‡	—	9
	—mean diameter of surface stones	~1 km	1.8‡	—	9
	—coarse sand fraction in 0–15 cm layer	~1 km	1.8‡	—	9
	Vegetation cover	~1 km	1.6‡	—	9
South Africa	Gold	Various	1.9*	—	2
Australia	Soil—phosphorus level	5 m	2.0‡	—	10
	—pH	5 m	1.5‡	—	10
	—potassium level	5 m	1.6‡	1.1‡	10
	—bulk density	5 m	1.5‡	—	10
	—0.1 bar water	5 m	1.5‡	—	10
France	Iron ore in rocks				
	—chlorite	15 μm	1.6*	—	11
	—quartz	15 μm	1.9*	—	11
	—quartz	5 cm	1.6*	—	11
	—iron	5 cm	1.5*	—	11
	—iron (E–W)	100 m	1.7*	—	11
	—iron (N–S)	100 m	1.8*	—	11
	—iron (E–W)	500 m	1.6*	—	11
	—iron (N–S)	500 m	1.9*	—	11
France	Sea anemones	10 cm	1.6§	—	12
Chad	Rainfall	1 km	1.7*	—	13
Mauritania	Iron ore	3 m	1.4*	—	2
Ivory Coast	Groundwater levels				
	Piezometer 1	1 day	1.6*	—	2
	2	1 day	1.7*	—	2
	3	1 day	1.8*	1.3*	2
	4	1 day	1.3*	1.1*	2
Canada	Oil grades	60 cm	1.7*	—	2
Chile	Copper grades	2 m	1.7*	—	2
France	Topographic heights	10 m	1.5*	1.1*	2
USA	Soil—sand content	10 m	1.6–1.8*	—	14
	—pH	10 m	2.0*	—	14
Worldwide	Crop yields	1–1,000 m	1.6–1.8‡	—	15
India	Water table depth	250 m	1.6*	—	16

\* Estimated from variogram. ‡ Estimated from block variance. † Estimated from power spectrum. § Estimated from covariance.

roughness. For a linear fractal function, the Hausdorff–Besicovitch dimension *D* may vary between 1 (completely differentiable) and 2 (so rough and irregular that it effectively takes up the whole of a two-dimensional topological space). For surfaces, the corresponding range for *D* lies between 2 (absolutely smooth) and 3 (infinitely crumpled). Because the degree of roughness of spatial data is important when trying to make interpolations from point data such as by least-squares fitting or kriging<sup>2</sup>, it is worth examining them beforehand to see if the data contain evidence of variation over different scales, and how important these scales might be. Mandelbrot’s work<sup>1</sup> suggests that the fractal dimensions of coastlines and other linear natural phenomena are of the order of *D* = 1.2–1.3, implying that long range effects dominate. I show here that published data on many environmental variables suggest that not only are they fractals, but that they may have a wide range of fractal dimensions, including values that imply that interpolation mapping may not be appropriate in certain cases.

Berry and Lewis<sup>3</sup> have shown that the Weierstrass–Mandelbrot fractal function (WMF)

$$W(t) = \sum_{n=-\infty}^{\infty} \frac{[(1 - e^{i\gamma^n t}) e^{i\phi_n}]}{\gamma^{(2-D)n}}$$

(1 < *D* < 2,  $\gamma > 1$ ,  $\phi_n$  = arbitrary phases)

has a power spectrum *P*( $\omega$ ) that varies approximately as  $\omega^{-(5-2D)}$ , and a variance of increments  $V(t) = \langle [W(t_0) - W(t_0 + t)]^2 \rangle$  that varies as  $t^{4-2D}$  at the origin. If *D* > 1.5, *V*(*t*) is itself a fractal function. These results allow us to

estimate the fractional dimension *D* of a real series, either from the slope of the log–log plot of the power spectrum as *t* → 0, or from

$$\frac{d \log V(t)}{d \log t} = 4 - 2D \quad (t \rightarrow 0)$$

The variance of increments (or the half thereof, the semi-variance) is much used in geostatistical studies where, computed over distances, it is referred to as the variogram<sup>2</sup>. Computing the variogram is the first step in the interpolation procedure known as kriging which is used to assist estimation of mineral reserves, contouring groundwater surfaces, and so on. Thus many published data are available in this form and it is then a simple matter to calculate their dimensions *D* relative to the sampling interval used.

For a second-order stationary series, the variance of increments at a given lag is equal to twice the difference between the variance of the series and the covariance. Thus, *D* values may also be computed from covariances. In agriculture and soil science, many data have been published in the form of block variances; that is the variance within blocks of equal size plotted against block size. Because Yates<sup>4</sup> showed that the variance for a block of a given size *k* is

$$s_k^2 = \frac{2}{k(k+1)} \sum_{h=1}^k (k-h+1) Vh$$

where  $s_k^2$  is the block variance of block length *k*, and *Vh* the variance increment for lag *h*, the slope of log *Vh* versus log *h* (*h* → 0) can also be estimated from these data.

Table 1 presents a selection of data so analysed, giving the study location, the type of environmental variable, the lag interval used for sampling and the estimated  $D$  value assuming that the real data are but a series of regularly spaced samples of a realization of the Weierstrass–Mandelbrot function over one-dimensional space or time.

The data support Mandelbrot's<sup>1</sup> assertion that  $D$  values of landscape and other data may range over many values. It is evident that most of the values reported here exceed 1.5, and many are greater than 1.8. Note that one of the smoothest surfaces imaginable in a landscape, a new airport runway, has a relatively high  $D$ , presumably because variations over long distance are low in amplitude. These data do not conform to a single roughness model as proposed by Sayles and Thomas,<sup>5</sup> indeed, as Berry and Hannay<sup>6</sup> have commented, much wider ranges of roughness or randomness are to be expected.

These results should not be accepted uncritically, however. First, it is important to realize that the Weierstrass–Mandelbrot function is just one of a class of 'model' fractals. Its peculiarity is that it has a discrete and geometric spectrum, and this might make some of its properties non-universal among other fractals with the same  $D$  (M. V. Berry, personal communication).

Second, although some environmental data do appear to display the fractal property of statistical self-similarity at all scales, there are also many that show self-similarity over a limited range of scales, or over a few widely separated scales. For example, a variable with a highly regular spatial variability has a variogram that exhibits parabolic behaviour near the origin<sup>7</sup>. This is a good example where  $d \log V(h)/d \log h$  becomes less steep as  $h \rightarrow 0$ , and it indicates that the ultra-short, short and middle range variations are trivial compared with the main variations seen at larger scales. In fact, computing  $D$  as  $h \rightarrow 0$  will in this case estimate  $D$  for the ultra-short range scales of variation.

Third, the form of the variogram is often highly dependent on sampling direction and sampling interval. It is well known that when a particular sample spacing tends to match the scale of a spatial pattern, the variance of increments can fall rapidly. Accordingly, when a sampling interval matches a particular scale of a phenomenon in the landscape it perceives an apparently lower  $D$ . If this is so, it would seem more appropriate to estimate  $D$  values from the parts of the variogram showing maximum slope. Table 1 also contains these data for those phenomena showing a maximum slope at positions other than  $h \rightarrow 0$ .

The results presented here suggest that Mandelbrot's  $D$  can be used as a useful indicator of the complexity of autocorrelations over many scales for natural phenomena. However, although many natural phenomena do display certain degrees of statistical self-similarity over many spatial scales, there are others that seem to be structured and have their levels of variability clustered at particular scales. This behaviour does not exclude them from the fractal concept. Mandelbrot<sup>1</sup> considers that it is quite acceptable to have a series of zones of distinct dimensions connected by transition zones. If this is reasonable, it means that the examination of  $D$  values would be useful for trying to separate scales of variation that might be the result of particular natural processes. Moreover, identifying such scales could be of enormous practical value because one could then tailor sampling to a particular scale range of the phenomenon in question, thereby improving the efficiency of expensive field investigations and the resulting interpolations. The high level of the  $D$  values for some soil and geological data reported here would seem to question the wisdom of interpolation mapping in certain instances, however, and it would seem worthwhile to use  $D$  values as a guide to how further mapping and interpolation should proceed.

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## Reactor-released radionuclides in Susquehanna River sediments

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Three Mile Island (TMI) and Peach Bottom (PB) reactors have introduced <sup>137</sup>Cs, <sup>134</sup>Cs, <sup>60</sup>Co, <sup>58</sup>Co and several other anthropogenic radionuclides into the lower Susquehanna River. Here we present the release history for these nuclides (Table 1) and radionuclide concentration data (Table 2) for sediment samples collected in the river and upper portions of the Chesapeake Bay (Fig. 1) within a few months after the 28 March 1979 loss-of-coolant-water problem at TMI. Although we found no evidence for nuclides characteristic of a ruptured fuel element, we did find nuclides characteristic of routine operations. Despite the TMI incident, more than 95% of the total <sup>134</sup>Cs input to the Susquehanna has been a result of controlled low-level releases from the PB site. <sup>134</sup>Cs activity released into the river is effectively trapped by sediments with the major zones of reactor-nuclide accumulation behind Conowingo Dam and in the upper portions of Chesapeake Bay. The reported distributions document the fate of reactor-released radionuclides and their extent of environmental contamination in the Susquehanna–Upper Chesapeake Bay System.

During the past 14 yr, five nuclear power reactors have operated for varying lengths of time at two sites on the Susquehanna River (Fig. 1). The first reactor, PB 1, was a 40-MW, gas-cooled reactor and operated from March 1966 to October 1974. Three others, PB units 2 and 3 (boiling-water reactors), and TMI unit 1 (a pressurized-water reactor), began power production in 1974 and each produces ~1,000 MW. TMI unit 2, a twin of TMI 1, was activated on 30 December 1978 but shut down on 28 March 1979 after the loss-of-coolant incident. As with the other nuclear power stations, minor amounts of <sup>137</sup>Cs, <sup>134</sup>Cs, <sup>60</sup>Co, <sup>58</sup>Co and other radionuclides are released with the coolant-water effluent. The radionuclide release history of these reactors has been compiled using Nuclear Regulatory Commission documents<sup>1</sup> and is summarized in Table 1. The Peach Bottom plant has contributed most of the reactor-produced radionuclides introduced into the Susquehanna River, and from 1975 to 1979, the PB reactors have released >95% of the total <sup>134</sup>Cs input to the river.

In addition to reactor releases <sup>137</sup>Cs (half life of ~30 yr) has been introduced into the Susquehanna–Chesapeake Bay system as global fallout from atmospheric nuclear weapons testing. The major influx of fallout <sup>137</sup>Cs occurred between 1962 and 1964. Reil<sup>2</sup> used the distribution of fallout <sup>137</sup>Cs in Chesapeake Bay to study the hydrography of the estuary. Although other fission products and neutron activation nuclides, such as <sup>134</sup>Cs, <sup>60</sup>Co and <sup>58</sup>Co are also produced during weapons tests, their short half lives (~2, 5 and 0.2 yr, respectively) and low yields cause the