SPECTROPHOTOMETRY OF DUST

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I INTRODUCTION

In recent years there have been a number of extensive review papers and books on interstellar dust (e.g. Savage and Mathis, 1979, and references therein). This short review deals only with the spectral properties of dust within the wavelength range 3-25μm, with particular emphasis on recent results.

Infrared spectral features provide information on the chemical composition and structure of dust grains, by comparison with likely laboratory materials and the expected vibrational frequencies of atomic groups in the solid state.

The first observation of a broad infrared emission feature at 10μm in oxygen rich giants and supergiants was made by Woolf and Ney (1969), and attributed to the stretching resonance of the Si-O bond. Since then a total of 13 infrared bands, resolved with moderate resolving power and attributed to solid state transitions, have been discovered in the wavelength regions 3-13.5 and 16-25μm. Plausible laboratory counterparts exist for some of these features but in no case is there a completely unambiguous identification.

II INDIVIDUAL FEATURES

A. The 9.7μm Feature

This feature, with a full width at half maximum of 2-3μm, is seen in emission in the circumstellar shells of oxygen rich giants and supergiants (e.g. Merrill and Stein, 1976a) and also in emission, absorption or a combination of these in a variety of stellar objects (Russell et al 1975; Cohen, 1980), compact H II regions and the interstellar medium (Forrest et al, 1978), molecular clouds (Capps et al, 1978), some planetary nebulae (Aitken et al, 1979a), and presumed progenitors of planetary nebulae (Puetter et al, 1978, Aitken et al, 1980b) and comets (Hackwell, 1971; Merrill, 1974). It has not been

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observed in the spectra of carbon stars or novae. For brevity references are given only to recent work or if not referenced in earlier review articles.

The commonly accepted interpretation of this feature is that it is due to the stretching vibration of the Si-O bond in grains of disordered silicates. Crystalline forms of silicate minerals such as quartz, olivine and orthopyroxene can be ruled out on the basis of positional mismatch, lack of structure and independently by polarisation observations between 8-13μm of the BN object and the galactic centre (Capps and Knacke, 1976; Dyck and Beichman, 1974). The band strength required by the polarisation observations are an order of magnitude smaller than in terrestrial silicates, but are consistent with those of amorphous silicates. Amorphous silicates produced in the laboratory (Day and Donn, 1978; Day, 1979; Stephens and Russell, 1979) in fact provide a very good fit to the smooth astronomical feature as also do the structurally disordered hydrous silicates found in type I carbonaceous chondrites (e.g. Penman, 1976; Rose, 1979). The material in the meteorites has not been subjected to temperatures in excess of 500K since their formation and contains material from early in the history of the solar system. The correspondence between laboratory measurements of the optical properties of these materials and the astronomical feature must be regarded as very strong evidence for the correctness of the silicate identification.

Silicates also are expected to have band structure in the 20μm region due to bending of the Si-O-Si bond, and such a feature near 18μm has been observed in emission and absorption (Treffers and Cohen, 1974; Forrest _et al_, 1978; Forrest _et al_, 1976; Forrest and Soifer, 1976).

The feature can also be fit arguably well by a number of other materials or mixtures: a) Mixtures of particles of the diatomic oxides Si-O and Mg-O have been suggested by Duley _et al_, 1979. This model accounts for the 9.7μm and 18μm features, though not so convincingly as disordered silicates, and also the 2200Å feature. b) Mixtures of high molecular weight organic compounds can also be constructed to fit the data (Hoyle and Wickramasinghe, 1979; Khare and Sagan, 1979). Probably the strongest arguments against such a mixture being representative of a significant part of the interstellar medium is the observed appearance of the feature in oxygen rich but not carbon rich stars, and that it requires a correlation which is not observed between the absorption feature at 3.07μm and the 9.7μm feature.

B. The 11μm Broad Feature

This feature is characterised by emission increasing fairly sharply from near 10.5μm to a broad maximum in the 11μm region with a less well defined long wavelength turn off at around 12.7μm. These wavelengths correspond respectively to the longitudinal and transverse optical phonon frequencies in silicon carbide, which define the well known forbidden gap for propagation of electromagnetic waves. The spectral shape of the feature depends on the shape and size distribution of the grains.

This broad feature is seen in emission in circumstellar shells around carbon stars (Merrill and Stein, 1976a) and some planetary nebulae (Willner *et al*, 1979a; Aitken *et al*, 1979a). The feature is rarely seen in absorption (Jones *et al*, 1978), and in the general interstellar extinction $\tau_{SiC}/\tau_{sil} < 0.1$. Band strengths for silicon carbide grains are likely to be somewhat greater ($\beta m \backsim 1.4 \times 10^4 cm^2 g^{-1}$, Dorschner *et al*, 1977) than for amorphous silicates ($\beta m \backsim 3 \times 10^3 cm\ g^{-1}$, Penman, 1976); the ratio of silicon carbide to silicates in the interstellar medium must be less than a few percent by mass.

C. Phenomenology of the Oxygen-Rich and Carbon-Rich Features

Irrespective of arguments about the precise nature of these grain materials, observationally they are present in circumstellar environments according to whether the abundance ratio of carbon to oxygen atoms is greater or less than some number close to unity and in the range 1.0-1.8. In addition to often displaying the silicon carbide feature, carbon stars also show a featureless excess emission with characteristic temperature near 1000K which is usually attributed to graphite grains.

Thus on the basis of 8-13μm spectroscopy it is possible to categorise objects according to whether grains formed in an oxygen or carbon rich environment. This can be of particular value in nebular studies where optical and UV data relevant to the important ionic species of carbon may be scarce and the interpretation complicated by temperature dependence and theoretical uncertainties. For example the bright planetary nebula IC418 has recently been demonstrated to have N(C)/N(O) = 1.8±0.8 from optical and UV studies (Harrington *et al*, 1980), compared with N(C)/N(O) = 0.6 for the sun. In IC418, NGC6572 (Willner *et al*, 1979a); NGC6790 (Aitken *et al*, 1979a) and IC5117 (Grasdalen, 1979) the 11μm silicon carbide emission feature is readily seen and it can be inferred that the nebular composition in these objects is enriched in carbon due to nucleosynthesis. Some other planetary nebulae show the 9.7μm feature in emission (Aitken *et al*, 1979a) and at least the formation of grains must have taken place in an oxygen rich environment.

The gas phase of the interstellar medium and H II regions has N(C)/N(O) close to solar values (e.g. Salpeter, 1977) and it is perhaps gratifying to find the silicate feature ubiquitous in these regions. The archetype of this feature is often taken to be that of the Trapezium region of the Orion nebula. Here complications due to a photospheric component are avoided because the nebular feature can be spatially separated from the hot stars in the Trapezium. A simple two component dust model in which emission from warm isothermal dust is attenuated by cold Trapezium material has been remarkably successful in matching the observed 8-13μm spectra of H II regions, protostellar objects and the galactic centre sources, and it can be asserted that in some cases the underlying emission is from optically thin Trapezium like material. This is true for a number of 'moderately' obscured sources such as BN and some of the galactic centre sources. When the depth of the absorption feature approaches or exceeds an order of magnitude the match becomes insensitive to the form of the underlying emission and introduces an uncertainty in the derivation of the extinction optical depth to the source. Nevertheless the good fits obtainable for a wide variety of sources and optical depths is evidence for the universality of this extinction curve at 10μm.

Estimates of the ratio $A_V/A_{9.7}$ are difficult because few sources have well determined values of A_V large enough to give significant optical depths at 10μm. Table I gives values of $A_V/A_{9.7}$, obtained for three sources.

TABLE I Comparison of visual and infrared extinction

Source	A_V	$\tau_{9.7}$	$A_V/A_{9.7}$	N(Si)/N(H)	
G333.6-0.2	20±1	1.15	17.4±1	3.9×10^{-5}	Rank et al, 1978
VI Cyg #12	10	0.65	15	4.6×10^{-5}	Gillett et al, 1975b
IRS 7 in SgrA	30	3.5	8.5±3	8.1×10^{-5}	Becklin et al, 1978
				3.3×10^{-5}	Solar value; Allen, 1973

The value of $\tau_{9.7} = 1.15$ used for G333.6-0.2 differs from that used by Rank et al, 1978 and is more appropriate to the Bα and Hα beam sizes used to determine A_V since it has been found that the silicate optical depth is a function of beam size in this source. The range of about a factor two between the various determinations of $A_V/A_{9.7}$ may in part be due to the assumptions made in the derivations. The required silicon abundance is calculated assuming that 3/4 of $A_{9.7}$ is due to silicates with mass absorption coefficient $3\times10^3\text{cm}^2\text{g}^{-1}$ and that the hydrogen column density is $2\times10^{21}\text{cm}^{-2}\,A_V^{-1}$. The required abundance is rather high, as noted by Hong and Greenberg (1978), especially for the galactic centre for which the extinction is predominantly interstellar (Becklin et al, 1978).

A few heavily obscured sources refuse to yield good fits with the two component model. One of these, OH 0739 (Gillett and Soifer, 1976), exhibits a broad long wavelength wing to the extinction and this is presently without adequate explanation. The source IRC4 in BNKL has its minimum shifted to near 9.3μm, but this is due to failure of the two component model in a source with strong temperature gradients (Aitken et al, 1980c).

The Trapezium spectrum is more dilute than the excess observed in oxygen rich giants. In particular this is seen for μ Cep (Russell et al, 1975) and compared with that of the Trapezium and other oxygen rich giants in Fig 1. It seems that H II regions and the interstellar

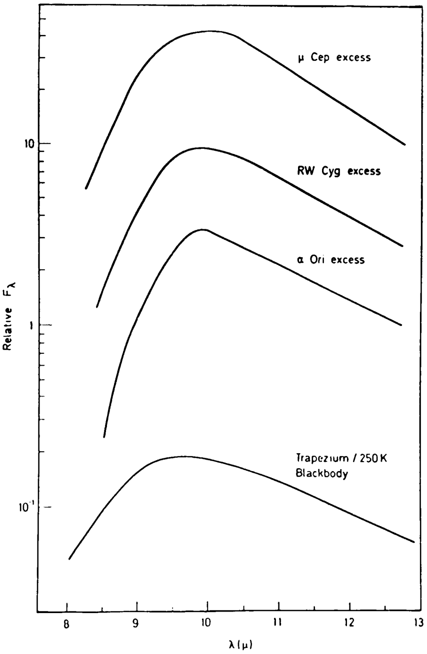

Figure 1. Comparison of the 8-13μm excess from μ Cep, RW Cyg and α Orion with that of the Orion Trapezium region. Data from Merrill et al, 1976; Russell et al, 1975; Forrest et al, 1975.

medium require an additional featureless component to that observed in the oxygen rich giants, and dust injection to the medium from carbon stars, planetary nebulae and novae is a likely cause. This difference also suggests that observationally one might be able to distinguish generally between oxygen rich regions in which grain formation has or is taking place and emission from H II regions. Certainly the eruptive variables HM Sge and V1016 Cyg, often considered to be protoplanetary nebulae, show 8-13μm spectra typical of recent grain formation (Puetter et al, 1978; Aitken et al, 1980b) in an oxygen rich environment.

D. The 3.07μm Absorption Feature

The presence of an absorption feature near 3.07μm due to interstellar water ice has been found in sources deeply embedded within molecular clouds but not in the general interstellar medium. The observed feature is narrow with a width at half maximum of about 0.3μm and while agreeing qualitatively with calculations using Mie theory and laboratory optical constants for H_2O ice, is different in details. In particular the observed feature has more extinction shortwards of 3.07μm and an additional long wavelength wing than required by theory. These difficulties can be reconciled by allowing a range of sizes and an admixture of NH_3 ice to produce the shorter wavelength extinction (Merrill et al, 1976a) and hydrocarbon ices (Hagen et al, 1980) to produce the long wavelength wing. The presence of C-H bond contamination has also been suggested by Soifer et al, (1979). A further difficulty exists however in that the broad feature expected in the 10μm ice spectrum (Bertie et al, 1969) is not observed even in sources showing very deep 3.07μm features.

Water ice also has a feature near 45μm and this has been searched for in KL. Detection of this band is reported by Papoular et al. (1978) in emission in a 4' beam, and in absorption in a 50" beam by Erickson et al. (1980). A temperature gradient in KL can explain this apparent discrepancy; however, these observations are extremely difficult and may be subject to systematic uncertainties.

The 'ice' feature is not to be confused with an absorption at the same wavelength seen in carbon stars and which has been definitively identified in high spectral resolution observations as molecular band absorption by hydrogen cyanide and acetylene (Ridgway et al, 1978). At the lower resolution typical of filter wheels the two features may be distinguished observationally with some care since the carbon star feature is slightly narrower and lacks the long wavelength wing. In practice distinction between the two features is often made on the basis of prior knowledge of the nature of the source.

In molecular clouds the ice and silicate features are essentially uncorrelated with $0.2 < \tau_{ice}/\tau_{sil} < 2$; in the interstellar medium ice absorption is not observed and $\tau_{ice}/\tau_{sil} < 0.04$ for VI Cyg No. 12 (Gillett et al, 1975b). Using a band strength $\beta_m = 1.4\times10^4 cm^2 g^{-1}$ for ice implies a molecular cloud ratio of mass of ice/silicate in the range 4-40%, well short of abundance constraints. Greenberg (1976), has suggested that ambient starlight in the medium converts H_2O to free OH radicals.

III OTHER EMISSION FEATURES

In 1973 Gillet et al reported the observation of two narrow but resolved features in the 8-13μm spectrum of the planetary nebula NGC7027. Since then other features have been observed and presently there are 7 narrow ($\Delta\lambda<1$μm) emission features at the wavelengths 3.28, 3.4, 3.5, 6.2, 7.7, 8.6 and 11.25μm. None of these, with the possible exception of that at 3.4μm, have ever been observed in absorption, and all save the 3.5μm feature were first discovered in NGC7027 (Fig. 2). The features have been seen in a wide range of objects encompassing a range of chemical abundances and evolutionary status (Table II) with the one apparent common feature of a plentiful supply of UV photons. The features do not break up into lines or bands at higher resolution (Tokunaga and Young, 1980; Bregman, 1977)

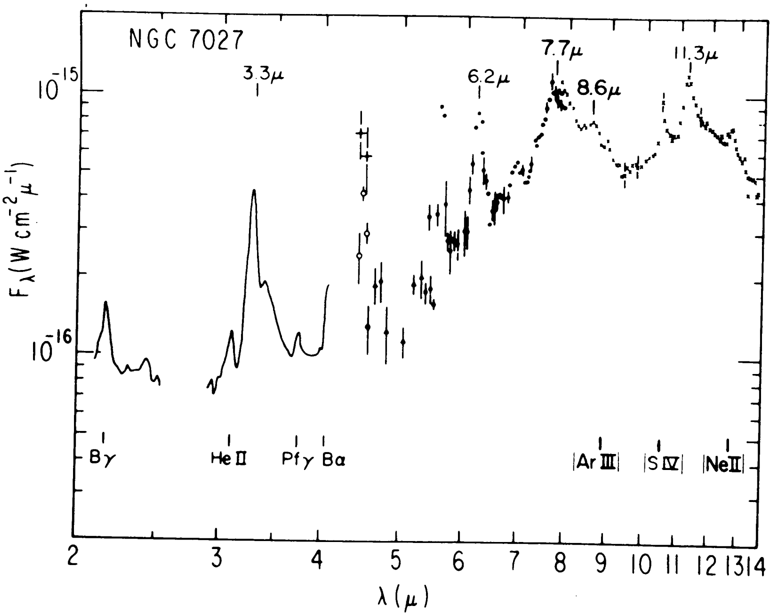

Figure 2. 2-14 μm spectrum of NGC 7027 showing the unidentified emission features together with atomic transitions. From Russell et al, (1977b).

and it is therefore assumed that the features arise from solid grains or grain mantles.

Apart from the 3.4 and 3.5μm feature there is a general tendency for the features to occur together; this is a qualitative statement, there being clear differences in the ratio of the strengths of the features although this is never very large (Table II). So far there is no agreed identification for any of the features, but while they do not necessarily arise from the same material or process it is clear that the environment which produces one of them also favours the production of others. The table reveals that there is no significance to the non-observance of the 8.6 and 11.25μm features in most H II regions.

Observations of the ionization front near θ^2 A in the Orion nebula indicate that the 11.25μm feature (Aitken et al, 1979b) and the 3.28μm feature shown in Fig 3 (Aitken and Roche, unpublished) arise from just outside the H II region. Maps of Orion (Sellgren, 1980) in the 3.28μm feature and 3.5μm continuum show that the feature distribution is different and more extended than that of the continuum and that the line to continuum ratio has a maximum close to the ionization front. Wynn-Williams et al (1980) show that in AFGL 437 the feature is similarly more extended than its H II region. All

TABLE II NARROW EMISSION FEATURES

	Band Centre and Width (μm)							
	3.28	3.4	3.5	6.2	7.7	8.6	11.25	
Source	0.05	0.08	0.08	0.2	0.5	0.3	0.25	References
PLANETARY NEBULAE								
NGC 7027	21	5	x	150	300	45	140	1,2,3,4
IC 418	1.2	x	x	-	-	-	<3	2,21
BD +30°3639	4.0	1	<0.1	✓	✓	7	18	2,3,4,5
NGC 6790	0.4	x	x	-	-	<0.5	1	22,27
SwSt1	0.4	?	x	-	-	<0.5	<0.5	22,27
M1-11	0.5	?	x	-	-	1	1	24
NGC 6572	0.5	<0.2	x	-	-	-	<1.5	21
H II REGIONS								
NGC 7538	✓	?	x	-	-	x	x	2
M17	✓	✓	x	-	-	-	-	17
Orion Bar 7"	2	0.5	x	✓	✓	4	9.5	8,9,10,28
GL 3053	(1)	(0.3)	<(.1)	(22)	(55)	(4.5)	(4.5)	11,12
G 333.6-0.2	2	x	x	-	-	<20	<20	28
G 45.1+0.1	✓	x	x	-	-	<10	<10	28
STELLAR OBJECTS								
He 2-113	4	<0.6	1?	-	-	9	20	25,26
CPD-56°8032	8	4	2?	-	-	<9	20	25,26
γ^2 Vel	✓	x	x	-	-	-	-	26
MWC 922	✓	x	x	-	-	?	?	19
HD 97048	1	3.5	6	-	-	?	3.3	20,24
EXTRA GALACTIC								
NGC 253	1	0.2	x	-	-	1.5	2	4,15
M 82	4	2	x	32	72	8	9	15,16
3C 273	.05	-	-	-	-	-	-	23
UNCLASSIFIED								
HD 44179	60	<6	<2	160	500	90	90	4,6,7,18
AFGL 437	2	0.4	<.2	-	-	8	11	13
GL 4029	✓	✓	✓	✓	✓	✓	✓	14

Table is representative rather than comprehensive.
Approximate intensities are given in units of 10^{-18} W cm^{-2}.
Approximate intensities relative to 3.28μm given in brackets.
✓ feature observed x not observed - no observations

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6 Russell *et al* 1978
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8 Sellgren 1980
9 Soifer *et al* 1980
10 Aitken *et al* 1979b
11 Russell 1979
12 Merrill 1977
13 Kleinmann *et al* 1977
14 Willner *et al* 1980
15 Gillett *et al* 1975a
16 Willner *et al* 1977
17 Grasdalen & Joyce 1976
18 Tokunaga & Young 1980
19 Merrill & Stein 1976b
20 Blades & Whittet 1980
21 Willner *et al* 1979a
22 Aitken *et al* 1979a
23 Allen 1980a
24 Aitken & Roche 1980
25 Aitken *et al* 1980a
26 Allen 1980b
27 Jones 1979
28 Aitken & Roche, unpubl.

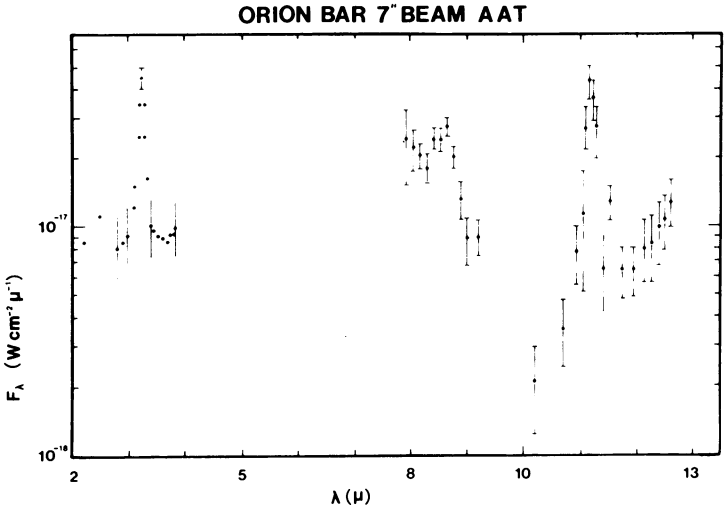

Figure 3. 3-4 μm and 8-13 μm spectrum of position 4 in the Orion bar taken with a 7" dia beam. From Aitken et al, 1979b, and Aitken and Roche, unpublished.

other observations appear to be consistent with the conclusion that the features arise just outside an H I — H II interface.

The distance from the ionizing source in Orion to the ionization front, and in AFGL 437 to the outer bound of the observed 3.28μm emission, is sufficiently large to rule out heating of normal sized grains to temperatures required to give the observed feature fluxes.

Presently there are two main ideas regarding the excitation mechanism of the features:

A Infrared Fluorescence

Allamandola et al (1979) have suggested that in sufficiently cold grains or grain mantles, UV radiation can lead to excited vibrational states which decay radiatively, i.e. IR fluorescence. They associate some of the observed bands with ices of H_2O, NH_3, CH_4 and C_2H_2. A high efficiency of conversion of UV photons to IR feature photons is required in this model and needs to approach unity for some of the features. The efficiency to all IR bands apparently exceeds unity for the Orion bar source, for instance. Such seemingly implausible efficiencies are not a fundamental problem, but a detailed theory of infrared fluorescence will need to explain them, and clearly laboratory measurements will be of value. This model naturally accounts for emission occurring from outside an H II region and may even require this constraint since grains in H II regions may not be cold enough to suppress thermal relaxation of the lattice. Absence of the features in absorption is explained since the emission process is efficient and the optical depth need only be small.

B UV Heating of Very Small Grains

Dwek et al (1980) have proposed that the features arise by thermal emission from a population of very small grains (a $\simeq$ 0.01μm) which are heated by UV radiation. They show that grains of radius $\simeq$ 0.01μm would reach temperatures $\simeq$ 300K within the ionization front in Orion, and that the temperature reached by the grains is a strong function of the UV content of incident radiation. Essentially the ratio of cross sections in the UV to the IR is kept large by making the grains small and on the order of the characteristic wavelength of the UV field from an early O star. The relatively small variation of the observed flux ratios (in features widely separated in wavelength) from source to source implies that the features are emitted only over a narrow range of temperatures. If the grain mantles are volatile an upper bound to the emission temperature will exist, but would not explain why the 11.3μm is never observed without the 3.28μm feature. The features do not appear in absorption because the emission process is efficient due to relatively high temperature and only a small optical depth of emitting material is required.

The 3.5μm feature, unresolved with resolving power of 50, has so far been observed in only one object, HD 97048, a likely pre-main-sequence star of spectral type B9-AO Ve in the Chameleon dark cloud (Blades and Whittet, 1980), which has a variable circumstellar shell on a time scale of months. The 3.28μm and 3.4μm features are also evident but with band strengths remarkably reversed from other sources, and the 3.5μm feature is dominant. The feature is very tentatively identified with formaldehyde following Allamandola and Norman (1978) and it is pointed out that the polymerised form of formaldehyde, polyoxymethylene, retains the 3.5μm signature and additionally shows infrared activity at 10.37μm and 11.76μm (Whittet et al, 1976). The 8-13μm spectrum (Aitken and Roche, to be published) shows no evidence of such activity although the 11.25μm feature is seen.

The sequence of emission features 7.7, 8.6 and 11.25μm can mimic the shape of the silicate absorption as can be seen in Figs. 2 and 3 where the silicate optical depth is expected to be small or negligible. Thus care is needed in evaluating extinction corrections to objects in which these emission features are seen or where observations have been made by narrow band photometry.

IV OTHER ABSORPTION FEATURES

Narrow but resolved absorption features are seen at 4.61μm, 6.0μm and 6.8μm, the latter two being observed only in molecular cloud sources. These are typified by the predominantly interstellar absorption seen to the galactic centre (Fig 4a, from Willner et al, 1979b)

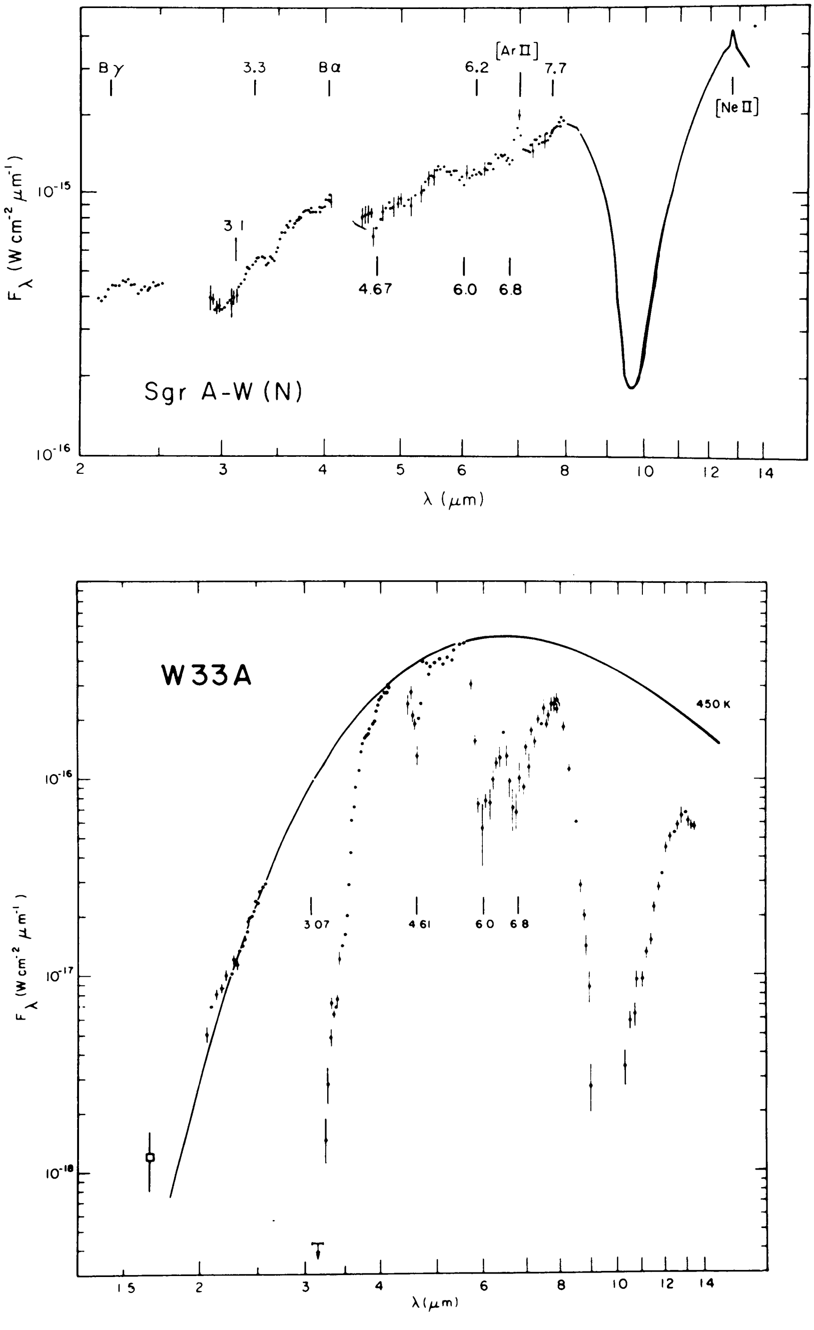

Figure 4. a) Absorption features in the interstellar medium to Sgr A; b) molecular cloud absorption features to W33A. Data from a) Willner et al, 1979a, and b) Soifer et al, 1979.

and the heavily obscured molecular cloud source W33A (Fig 4b, from Soifer et al, 1979).

The 4.67μm fundamental vibration band of CO has been suggested to be associated with the 4.61μm feature, although there are some admitted problems with width and wavelength shift of the observed feature (Soifer et al, 1980).

The strength of the 6.0 and 6.8μm absorption feature implies they must be due to abundant elements. Refractory materials appear to be ruled out as the features only appear in sources in molecular clouds and the presence of hydrated materials is unlikely for a number of reasons (Soifer et al, 1980). Although hydrated minerals do exhibit a band between 6.1 and 6.2μm this is significantly different from the 6.0μm band observed, which does not in any case occur in other situations where hydrated minerals would be expected. Hagen et al (1980) have shown that condensates from the gas phase of a mixture of H_2O, CH_3OH, NH_3 and CO at 10 K exhibit spectra which can account for all the absorption features seen between 3 and 8μm.

The stretching vibration of the C-H band expected between 3.3-3.5μm has been suggested as the reason for the skewed shape of the 3.07μm ice feature to larger wavelengths. It has also been searched for in absorption in the interstellar medium where the ice feature is not observed. Soifer et al (1976) observed a feature in the spectrum of the galactic centre, but it is not clear whether this is an emission feature at 3.3μm or the expected absorption near 3.4μm. Allen and Wickramasinghe (1980) have recently observed the galactic centre source IRS7; their data favours an absorption feature at 3.4μm with an optical depth of 0.2. An estimate of the column density of hydrocarbon material required to give this feature depends on the chemical class of the organic compounds, but if this result and interpretation is correct hydrocarbon material is not an insignificant part of the interstellar medium.

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DISCUSSION FOLLOWING PAPER PRESENTED BY D. K. AITKEN

RIEKE: The scatter in quoted values of $A_V/\tau_{silicates}$ in the literature is partly due to different definitions of τ_{sil}: if it is measured relative to a continuum joining the spectral points at 8 and 12 μm, VI Cyg No. 12 has $A/\tau_{sil} \simeq 23$; if a Trapezium-type spectrum is fitted, the fitted curve requires a significant optical depth at 8 and 12 μm, which gets added to τ_{sil} as it would be defined the other way, then VI Cyg No. 12 has $A/\tau_{sil} \simeq 15$. Similar discrepancies would be expected for other sources.

AITKEN: For the first two examples in Table 1, Trapezium-like emission was assumed. For IRS 7 in Sgr A something very similar was taken, so that this source of discrepancy is avoided in the table. We have used $\tau_{9.7}$ to refer to the total Trapezium-like optical depth since this may not be due solely to silicates.

RUSSELL: The Cornell group, using Houck's spectrometer and an amorphous silicate sample (Stephens and Russell, Astrophys. J. 228, 780, 1979) have obtained a fit to the Trapezium emission from 16 to 30 μm with a $\chi^2 = 1.4$.

MOORWOOD: Is the silicon carbide identification well accepted?

AITKEN: It has not been seriously challenged, but it cannot be taken as a definite identification.

HILDEBRAND: The Chicago group, in collaboration with Gatley, Sellgren, and Werner, has measured the ratio of near ultraviolet (0.25 μm) and far infrared (125 μm) extinction efficiencies of the reflection nebula NGC 7023. This is the subject of Stan Whitcomb's thesis. The measured ratio is much too low to correspond to bare graphite, silicate, or silicon carbide grains, but, on the basis of Aanestad's calculations, is in agreement with expected ratios for grains with ice mantles having mantle/core volume ratios $\lesssim 1$.