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The obscured mid-infrared continuum of NGC 4418: a dust- and ice-enshrouded AGN

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WE report the detection of absorption features in the 6–8 μm region superimposed on a featureless mid-infrared continuum in NGC 4418. For several of these features this is the first detection in an external galaxy. We compare the absorption spectrum of NGC 4418 to that of embedded massive protostars and the Galactic center, and attribute the absorption features to ice grains and to hydrogenated amorphous carbon grains. From the depth of the ice features, we infer that the powerful central source responsible for the mid-infrared emission must be deeply enshrouded. Since this emission is warm and originates in a compact region, an AGN must be hiding in the nucleus of NGC 4418.

5.1 Introduction

The ISO mission has considerably enhanced our knowledge of the mid-IR properties of normal, starburst, Seyfert and Ultra-luminous Infrared Galaxies (ULIRGs). The spectra of most sources are dominated by ISM emission features, the most prominent of which are the well-known PAH emission bands at 6.2, 7.7, 8.6, 11.3 and 12.7 μm. The PAH features and the emission lines have been used qualitatively and quantitatively as diagnostics for the ultimate physical processes powering galactic nuclei (Genzel et al. 1998; Lutz et al. 1998; Rigopoulou et al. 1999; Tran et al. 2001). A broad absorption band due to the Si–O stretching mode in amorphous silicates, centered at 9.7 μm, is also commonly detected in galaxies. Since the center of the silicate absorption coincides with a gap between the 6.2–8.6 μm and 11.3–12.8 μm PAH complexes, it is not readily apparent whether a 9.7 μm flux minimum should be interpreted as the "trough" between PAH emission features or as strong silicate absorption, or as a combination of the two. In spectra of heavily absorbed Galactic lines of sight, a strong silicate feature is often accompanied by ice absorption features in the 6–8 μm region (e.g. Whittet et al. 1996). Until recently this combination had not been reported in equally extincted extragalactic sources, despite detections of ice features at shorter wavelengths (Chapter 3; Sturm et al. 2000). In this Chapter we report on the detection of ices in the strongly absorbed, ISO–PHT–S spectrum of NGC 4418, a nearby (D=29 Mpc; $1''$=140 pc) luminous ($L_{IR}=10^{11}\ L_\odot$) bright IRAS galaxy. NGC 4418 and the distant ULIRG IRAS 00183–7111 (Tran et al. 2001) are the first detections of these ice features in external galaxies.

NGC 4418 is well-known for its deep 9.7 μm silicate feature (Roche et al. 1986). Additional evidence for strong extinction is the weakness (Hα) and absence (Hβ, Brα, Brγ) of hydrogen recombination line emission (Kawara et al. 1989; Ridgway et al. 1994; Lehnert & Heckman 1995, L.Kewley, priv. comm.), commonly detected in galaxies. HST–NICMOS images (Scoville et al. 2000) show hardly any structure in the inner 400 pc$\times$400 pc, except for large scale extinction ($\Delta A_V \sim$2). The IRAS colors of NGC 4418 indicate that — unlike most other galaxies — the 12–100 μm emission is dominated by a warm dust component, peaking shortward of 60μm (see Fig. 5.1). VLA radio maps at 6 and 20 cm (Condon et al. 1990; Eales et al. 1990) show NGC 4418 to be compact (70 pc$\times$50 pc at most). This, as well as the presence of large quantities of warm dust, has been taken as evidence for the presence of an otherwise hidden AGN in NGC 4418. In this Chapter we present mid-IR spectral evidence lending further support for the presence of an AGN in NGC 4418.

5.2 Observations

A low resolution ($\lambda/\Delta\lambda \sim$90) ISO–PHT–S spectrum of the central $24''\times24''$ of NGC 4418 was obtained on 1996 July 14 as part of a project on the interstellar medium of normal galaxies (Helou et al. 2000). The measurement was carried out in triangular chopped mode, using a chopper throw of $150''$. The resulting spectrum is thus free of contributions from zodiacal light. The ISO–PHT–S data were reduced using PIA 8.2. The absolute calibration is accurate to within 20%. The resulting spectrum is shown in Fig. 5.3.1.

In Fig. 5.1 we compile the 1–3000 μm (spectro)photometric observations of NGC 4418, including the new, standard reduced, ISO–PHT–S, ISO–CAM and ISO–LWS observations. Stellar emission probably dominates the near-IR regime up to 4μm, beyond which a strong mid-infrared continuum sets in. The SED reveals that a substantial part of the emission emanates from optically thick warm dust (Roche & Chandler 1993; Lisenfeld et al. 2000),

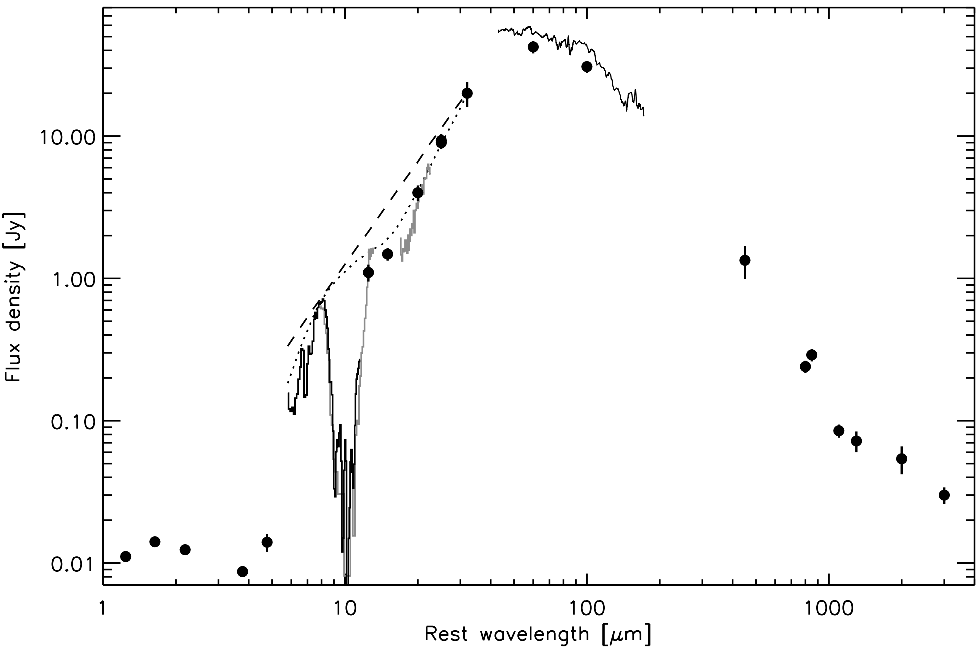

FIGURE 5.1 — The 1–3000 μm spectral energy distribution of NGC 4418, including the new ISO–PHT–S, ISO–CAM and smoothed ISO–LWS data. The data shown in grey is the spectrophotometry of Roche et al. (1986). Other data shown has been taken from Dudley (1997), Lisenfeld et al. (2000), Roche & Chandler (1993), Soifer et al. (1989) and Wynn-Williams & Becklin (1993). The *dotted and dashed curves* show two choices for the local mid-IR continuum. The *dotted line* interpolates the peaks of the observed data, whereas the *dashed line* assumes a stronger 18 μm silicate absorption.

peaking at 40–60 μm. Also shown in Fig. 5.1 are two equally possible choices of local continuum which we have adopted to analyse the ice, hydrogenated amorphous carbon (HAC) and silicate absorption. This will be discussed in detail in Sect. 5.3.2.

5.3 The mid-IR spectrum of NGC 4418

5.3.1 Spectral features

The mid-IR spectrum of NGC 4418 (Fig. 5.3.1) bears little resemblance to the spectrum of (almost) any other galaxy obtained by ISO. The spectra of normal and starburst galaxies (Rigopoulou et al. 1999; Helou et al. 2000) are dominated by strong PAH emission features. Seyfert galaxies with a clear line of sight to AGN-heated hot dust, on the other hand, are dominated by a strong mid-IR continuum with PAHs barely recognizable (Clavel et al. 2000). The mid-IR spectrum of NGC 4418 is rich in features but does not resemble PAH spectra. Rather it is similar to spectra observed towards heavily extincted Galactic lines of sight, such as deeply embedded massive protostars or the Galactic center (Fig. 5.3.1). These show no evidence for PAH emission features but do show strong absorption features. A simple criterion for the role of PAH emission and absorption features is based on the location of maxima in

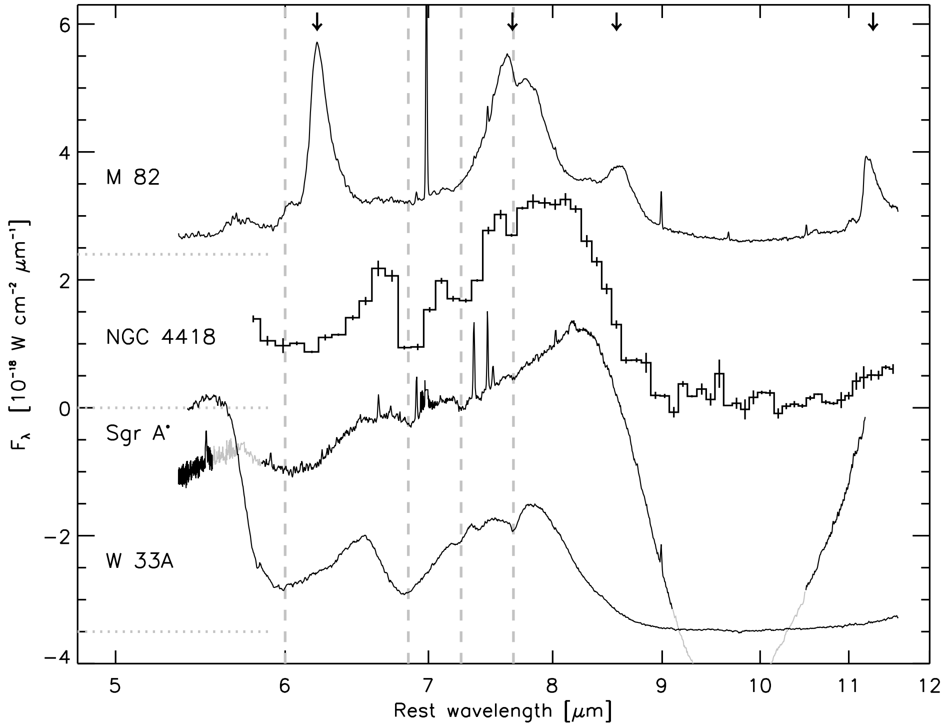

FIGURE 5.2 — A comparison of the ISO spectra of NGC 4418, M 82, the embedded massive protostar W 33A and the Galactic center (Sgr A*). Except for NGC 4418, the spectra have been scaled and offset. We removed the strong 7μm [Ar II] line from the Sgr A* spectrum. The *vertical dashed lines* facilitate comparision between the four spectra with well known Galactic absorption features. The *arrows* mark the rest wavelengths of the 6.2, 7.7, 8.6 and 11.3μm PAH features. The zero flux levels for M 82, NGC 4418 and W 33A are indicated with *horizontal dotted lines*.

the 6–7 μm region: PAH spectra show the 6.2 μm emission feature, whereas absorption spectra show a peak at 6.5–6.7 μm, which is not an emission feature but a window of reduced absorption between two features.

A detailed comparison of the absorption features with Galactic templates may be able to shed further light on the origin of the extinction in NGC 4418. The absorption features were determined by fitting a local polynomial to the peaks of the 5.8–8 μm spectrum of NGC 4418. The absence of the 6.2 μm PAH feature indicates that emission features are very weak in the spectrum, and justifies this simple procedure to derive the shape and depth of the absorption features. Fig. 5.3.1 shows the resulting NGC 4418 optical depth spectrum along with the optical depth spectrum of ices towards the massive protostar W 33A (Gibb et al. 2000) and the spectrum of the Galactic center (Sgr A*), which displays absorptions due to ices as well as features due to dust in the diffuse ISM (Chiar et al. 2000). The spectrum of NGC 4418 shows absorption features at 6.0, 6.8, 7.3, 7.6, 10 and 18 μm (Table 5.1). The 6.0 μm feature in NGC 4418 is similar to that in the Galactic sources but with a perhaps more pronounced long

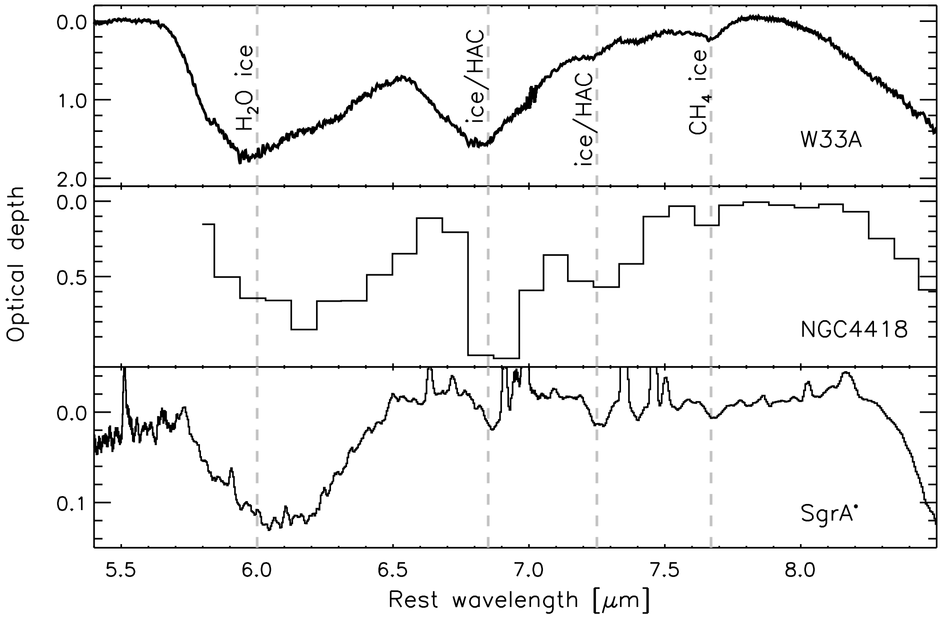

FIGURE 5.3 — The optical depth spectra for W 33A, NGC 4418, and Sgr A*. The *vertical lines* indicate the positions of the 6.0, 6.85, 7.3, and 7.6 μm ice and HAC absorption bands seen toward Galactic lines of sight.

wavelength wing. The 6.85 μm feature is considerably narrower than the molecular cloud feature but is similar in width to the diffuse ISM feature. The band at 7.3 μm is substantially broader than the molecular cloud and diffuse ISM features. The absorption band near 7.6 μm is similar to that observed locally.

The presence of ice along the line of sight toward NGC 4418 is suggested by the identification of the 7.6 μm band with CH_4 (Boogert et al. 1996, 1997) and by the presence of the 6.0 μm band due to H_2O ice (Keane et al. 2001; Chiar et al. 2000). The origins of the 6.85 μm and 7.3 μm bands in NGC 4418 are unclear. Interstellar ices also show features at these wavelengths, however, their relative strengths as well as widths are markedly different in NGC 4418. The 6.85 μm and 7.3 μm band ratios are consistent with the features observed towards Sgr A*, which have been attributed to CH deformation modes in HAC-like dust grains (Chiar et al. 2000). Thus, as for the Galactic center, both ice characteristics for shielded dense molecular cloud environments and HAC-like grain characteristics for diffuse ISM dust seem to be present along the line of sight. This conclusion could be tested through observations in the 3 μm window, which contains the strong 3 μm H_2O ice band and the 3.4 μm CH stretching modes of HAC materials. Guided by variations seen for the Galactic center region (Chiar et al. 2000), and between M 82 and NGC 1068 (Sturm et al. 2000), we speculate that the relative weight of ice and HAC components may vary considerably among galaxies.

TABLE 5.1 — Observed parameters for the NGC 4418 features.

λ [μm]	τ	$\tau_{\rm int}$ [cm^{-1}]	carrier	N [10^{17} cm^{-2}]
6.0	0.8	87	H_2O	73
6.85	1.1	27	HAC?	~200
7.3	0.6	12	HAC?	~200
7.67	0.12	1.2	CH_4	1.6
9.7	7	—	silicates	—
18	~1.5	—	silicates	—
			atomic H	$\sim 2\times 10^{6\,*}$

(*) Column to the mid-IR dust source calculated assuming Galactic gas to dust ratios. Note that the X-ray absorbing column to the central engine may be even higher.

5.3.2 Dust and ice column densities

The column densities of the ice species can be derived by dividing the integrated optical depth ($\tau_{\rm int}$) by the molecular band strength (Gerakines et al. 1995; Boogert et al. 1997). Table 5.1 summarizes the computed column densities of CH_4 and H_2O ice. The column densities are consistent with those derived for embedded massive protostellar objects in molecular clouds (Boogert et al. 1996; Keane et al. 2001). Also shown in Table 5.1 are the calculated HAC column densities for the 6.85 and 7.3 μm bands, assuming the intrinsic integrated band intensities for saturated aliphatic hydrocarbons from values by Wexler (1967). These integrated intensities are stronger than other current literature values (Sandford et al. 1991; Furton et al. 1999). For NGC 4418 a substantial fraction of the carbon is locked up in HAC (~20%) as compared to the Galactic center (a few % in Sgr A*, Pendleton et al. 1994).

As mentioned previously (Sect. 5.2), two continua, differing only longward of 8 μm were considered for NGC 4418 (Fig. 5.1). The effect of the different continua on the silicate feature is noticable when fitting the silicate profile by the Galactic Center Source GCS 3, a pure absorption feature, i.e. no intrinsic emission (Figer et al. 1999). However, the exact optical depth is still difficult to determine due to saturation of the silicate feature in NGC 4418. Adopting the dotted line in Figure 5.1 results in a NGC 4418 silicate profile in which the blue wing is well matched but the red wavelength wing is poorly fitted by the GCS 3 profile. If, however, the dashed line is adopted, then the fit to the red wing improves while still maintaining a reasonable match to the blue wing of the 9.7 μm silicate band. The 9.7 μm and 18 μm optical depths for the second case are $\tau_{9.7}$ ~7 (corresponding to A_V ~130) and τ_{18} ~1.5. These numbers, along with the derived hydrogen column density, are shown in Table 5.1. The apparent optical depth ratio of the 9.7/18 μm silicate bands, regardless of adopted continuum, is significantly larger than the ratio determined by Demyk et al. (1999) for two Galactic protostars. This might suggest that complex radiative transfer effects are important, which are however beyond the scope of this publication.

5.4 Discussion and conclusions

We have compared the ISO–PHT–S spectrum of NGC 4418 with spectra of our template sources and found no sign of PAH emission, neither from the nucleus, nor from that part of the disk contained within the 24″×24″ ISO–PHT–S aperture. Instead we found deep absorption features imposed upon a featureless mid-IR continuum. We identify the 6–8μm absorption features with foreground ices and HAC-like grains.

The nature of the central source in NGC 4418 cannot be infered from the observed mid- to far-IR spectrum alone, given the absence of any "signposts", like the 6.2 μm PAH emission feature ($F_{PAH}<6\times10^{-20}$ W/cm^2), and of fine structure lines ([O I], [C II] and [O III], Malhotra et al. (1999); $F_{[Ne\,II]}<2.3\times10^{-20}$ W/cm^2, from archival ISO–SWS data). Both a heavily enshrouded AGN or a similarly obscured nuclear starburst could be responsible for the observed continuum. Even if a starburst could be accomodated within the compact central source (<70 pc in the mid-IR (Scoville et al. 2000) and 25–70 pc at 6 and 20 cm (Eales et al. 1990; Kawara et al. 1990)), it would be highly unlikely to block the escape of any mid-IR starburst indicator from a region of that size. The most likely origin is therefore a heavily enshrouded AGN as suggested previously by Roche et al. (1986), Kawara et al. (1990) and Dudley & Wynn-Williams (1997). The 0.1″ point source (5 mJy) detected with the Parkes Tidbinbilla Interferometer (PTI) at 13 cm (Kewley et al. 2000, L.Kewley, priv. comm.) may actually pinpoint the AGN itself. Far-IR to millimetre sizes are less well constrained but the warm IRAS colours suggest that the emission in this range also arises in the nuclear region.

Our finding of strong absorptions due to cold silicates and ices in NGC 4418 leads us to believe that the same absorptions may be present in the mid-IR spectra of other galaxies. Indeed, we have found similar absorptions in 17 out of ∼250 galaxies observed spectroscopically by ISO (Chapter 2). Spectral identifications have to be done with great care since simultaneous presence of PAH emission makes other spectra more complex than the one of NGC 4418.

Since the overall shape of the NGC 4418 6–11 μm spectrum with its maximum near 8 μm mimicks at first glance a PAH spectrum, we point out the need for high S/N spectra to clearly identify the indicators for bona fide PAH spectra or absorption dominated spectra. The most obvious discriminator is the 6.2μm PAH peak to be contrasted with the 6.5–6.7 μm pseudo-maximum in absorption spectra, which is due to a window between two absorption features. In Chapter 2 this issue is addressed for our large ISO galaxy sample.

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