Silicate absorption in heavily obscured galaxy nuclei

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ABSTRACT
Spectroscopy at 8–13 μm with T-ReCS on Gemini-S is presented for three galaxies with substantial silicate absorption features, NGC 3094, NGC 7172 and NGC 5506. In the galaxies with the deepest absorption bands, the silicate profile towards the nuclei is well represented by the emissivity function derived from the circumstellar emission from the red supergiant, μ Cephei which is also representative of the mid-infrared absorption in the diffuse interstellar medium in the Galaxy. There is spectral structure near 11.2 μm in NGC 3094 which may be due to a component of crystalline silicates. In NGC 5506, the depth of the silicate absorption increases from north to south across the nucleus, suggestive of a dusty structure on scales of tens of parsecs. We discuss the profile of the silicate absorption band towards galaxy nuclei and the relationship between the 9.7-μm silicate and 3.4-μm hydrocarbon absorption bands.

Key words: dust, extinction – galaxies: nuclei – infrared: galaxies.

1 INTRODUCTION
Observations of active galaxies have shown that there are very large columns of material along the line of sight to many nuclei. The standard picture is that Seyferts of type 2 suffer significantly greater obscuration than those of type 1, much of which probably arises in dusty circumnuclear structures with differing inclinations to the line of sight (e.g. Antonucci 1993). These columns can be investigated via the cut-offs at X-ray wavelengths, the extinction in the visible and near-infrared (near-IR) and dust absorption bands in the near and mid-IR, all of which probe to different depths. X-ray observations have shown that at least 50 per cent of nearby Seyfert 2 galaxies are obscured by column densities greater than 10^{24} cm^{-2} (Risaliti, Maiolino & Salvati 1999) and that this material is concentrated into relatively small volumes (< a few parsecs). Mid-IR observations have demonstrated that substantial silicate absorption depths at 9.7 μm are relatively common towards Seyfert 2 galaxies, but rare in Seyfert of type 1 (Aitken & Roche 1985; Roche et al. 1991), again suggesting large obscuring columns towards the underlying warm emitting dust.

Dust around active galactic nucleus (AGN) is likely to be affected by the hard photon flux from the active nucleus; for example, Aitken & Roche (1985) have argued that the absence of polycyclic aromatic hydrocarbon (PAH) emission bands in active nuclei can be explained by destruction of the small grains that carry the bands. On the other hand, the shape of the silicate absorption feature towards the most heavily extinguished galaxy known, NGC 4418 (Roche et al. 1986), is similar to that produced by the diffuse interstellar medium (ISM) in our Milky Way galaxy (Roche & Aitken 1984, 1985; Chiar & Tielens 2006). A weak absorption band at 3.4 μm, similar to that seen in the Galactic diffuse ISM, has been detected towards a number of nuclei (Imanishi 2000, 2003; Mason et al. 2004), again suggesting that the dust towards those objects is similar to that in the Galaxy. Observations with Spitzer have recently detected absorption features from crystalline silicates towards several deeply embedded galaxies and additional absorption bands from hydrocarbons at 6.85 and 7.25 μm and a number of molecular species (Spoon et al. 2006).

Here, we present mid-IR spectroscopy of NGC 3094, NGC 7172 and NGC 5506, three galaxies with significant silicate absorption features, and investigate the nature of the silicate absorption towards active nuclei at subarcsecond resolution.

2 OBSERVATIONS
Long-slit spectra between 8 and 13 μm were obtained at the 8-m Gemini South telescope in clearing skies with the facility mid-IR imager/spectrometer, T-ReCS (Telesco et al. 1998), in 2004 May under programme GS-2004A-C-2. The seeing was variable at the time of observations, so the resolution achieved in the acquisition images is not well defined, particularly for NGC 3094 which was observed as the skies cleared and conditions were changing rapidly. None the less, we show these short exposures in Fig. 1. We do not have accurate astrometric reference positions for the T-ReCS data and so adopt the bright core as the central reference position. The
between 9.2 and 10 μm the galaxy spectra. This only has a significant effect on the flux background. We therefore subtracted the residual signal from NGC 5506 and NGC 7172 are probably similar to those for the reference star. None the less, the calibration uncertainty is likely to be significant and we estimate for NGC 3094, NGC 5506 and NGC 7172, respectively. The chop direction was perpendicular to the slit, and so only the signal from the guided beam position was accumulated.

Correction for telluric atmospheric absorption is with respect to α Cen whilst wavelength calibration is with respect to the planetary nebula NGC 6302, which has a rich emission-line spectrum (see Casassus, Roche & Barlow 2000 for the spectrum and accurate wavelengths).

The spectra were straightened, registered in the dispersion direction with reference to the sharp structure in the absorption band due to atmospheric ozone at 9.6 μm, and the dispersion calibration from NGC 6302 was applied. The spectra were corrected for atmospheric absorption by straightening and growing the α Cen spectrum along the slit, dividing it into the galaxy spectra and multiplying by a blackbody at a temperature of 5770 K (Cohen et al. 1996). We extracted and smoothed the residual flux in regions ±5–10 arcsec along the slit from the spectra of the nuclei; this is at a very low level and presumably arises from beam imbalances between the chopped and nodded beams. The deep silicate absorption bands in NGC 3094 and NGC 7172 give rise to very low flux levels in the 9 to 10 μm region, and the shape of the minimum can be distorted by this residual background. We therefore subtracted the residual signal from the galaxy spectra. This only has a significant effect on the flux between 9.2 and 10 μm, but does appear to improve the match to the expected silicate profiles.

The cores of these galaxies are fairly compact and the slit losses for NGC 5506 and NGC 7172 are probably similar to those for the reference star. None the less, the calibration uncertainty is likely to be significant and we estimate ~20 per cent.

In order to search for spectral variations along the slit, spectra were extracted in a number of different spatial bins. For NGC 3094 and NGC 7172, the extracted spectra off the nuclei were of low signal-to-noise ratio (S/N), and no significant differences from the on-nuclei spectra were detected. NGC 5506 is significantly brighter, and its spectra do show spatial structure; the spectra are shown in Fig. 2. Spectra were extracted by summing detector rows together, and are shown in Fig. 3 at the position of the central peak, at ±0.3 and ±0.6 arcsec. The noise in the spectra increases between 9 and 10 μm because of low atmospheric transmission due to absorption by ozone in the upper atmosphere, while the fluxes at these wavelengths are decreased by silicate absorption in the source. These effects become increasingly apparent in the spatial positions furthest from the nucleus.

3 TARGETS

The galaxies observed all show significant silicate absorption bands in published mid-IR spectra with no evidence of the narrow emission bands attributed to emission by large PAH molecules that trace nuclear star-forming regions (Roche et al. 1991), and show other evidence of substantial obscuration. They are described briefly here.

3.1 NGC 3094

NGC 3094 is a nearby (z ∼ 0.008) Sb spiral galaxy hosting a Seyfert 2 nucleus, and inclined by ∼49° to the line of sight. Near-IR images show a bright bar with a compact nucleus extended over ∼1.7 arcsec (Zernek & Lenzen 1993) while the radio emission is fairly diffuse over 15 arcsec (Condon et al. 1990). The T-ReCS acquisition image indicates that the mid-IR source may be extended by about 1 arcsec at a position angle (PA) of ∼170°, but the variable seeing conditions make this rather uncertain. However, the spatial profile within the slit, which was at a PA of 0° for the spectroscopic observations also suggests a source extended on a scale of ∼1 arcsec. Despite the narrow slit, the T-ReCS spectrum has flux levels within 25 per cent of those obtained within a 4-arcsec aperture by Roche et al., who detected a deep silicate absorption band with τ 9.7μm ∼ 4.3. The 3-μm spectrum of NGC 3094 has been presented by Imanishi (2000) who found a weak 3.4-μm hydrocarbon absorption band with a peak optical depth, τ 3.4μm ∼ 0.04. Imanishi also claimed to detect a weak 3.3-μm PAH emission band; we see no evidence for the corresponding PAH emission features in the 8–13 μm spectrum.

3.2 NGC 5506

NGC 5506 is a Sa spiral galaxy hosting an intermediate Seyfert 1.9 nucleus at a redshift of 0.0062. The galaxy has a prominent dust
lane and is almost edge-on, with an inclination angle approaching 90°. The nucleus is very compact in the mid-IR, and has an optical depth \( \tau_{9.7 \mu m} \sim 1.4 \) and a prominent [S IV] emission line at 10.5 \( \mu m \) (Roche et al. 1991; Siebenmorgen, Kruegel & Spoon 2004). The nucleus is classed as a Seyfert 1.9 as broad wings are detected on the infrared lines (Blanco, Ward & Wright 1990; Nagar et al. 2002). The X-ray spectrum suggests substantial obscuration, with a column of material corresponding to \( \sim 3.4 \times 10^{22} \) cm\(^{-2} \) (Risaliti et al. 1999). The hydrocarbon absorption band at 3.4 \( \mu m \) is weak with an optical depth \( \tau_{3.4 \mu m} \sim 0.04 \) (Inamishi 2000). The TReCS acquisition image shows a bright compact core but the spectrum obtained at a PA of 0° has a flux level about 50 per cent lower than that detected by Roche et al. (1991) in a 4-arcsec aperture, consistent with a compact core within a more extended emitting region. The [S IV] line emission is more extended than the dust continuum emission along PA 0°, corresponding approximately to the ionization cone axis found by Wilson, Baldwin & Ulvestad (1985).

### 3.3 NGC 7172

NGC 7172 is a type 2 Seyfert in a nearly edge-on Sa spiral galaxy at a redshift of 0.0087 (Sharples et al. 1984). It displays a prominent dust lane running almost east–west and the Spitzer IRAC image shows mid-IR emission extending over several arcseconds in the same direction; there is a suggestion of extension along this same axis in the T-ReCS acquisition image. The nucleus of NGC 7172 is heavily obscured in the X-ray region with \( N(H) \sim 8.6 \times 10^{22} \) cm\(^{-2} \), and in the mid-IR with a silicate absorption band with \( \tau_{9.7 \mu m} \sim 2.8 \) (Roche et al. 1991). The hydrocarbon absorption band at 3.4 \( \mu m \) has an optical depth \( \tau_{3.4 \mu m} \sim 0.09 \) (Inamishi 2000). The T-ReCS image indicates that the core is extended on a scale of \( \sim 1 \) arcsec at a PA of 90°. The flux captured by the T-ReCS slit at a PA of 60° is about one-third that detected by Roche et al. (1991) in their 4-arcsec aperture, consistent with a compact core within the more extended emitting source detected by Spitzer.

### 3.4 Fits to the spectra

In order to quantify the behaviour of the mid-IR absorption, we have fit the spectra with different emission and absorption components. The fits cannot be physically realistic in this complex region, but do allow us to extract some quantitative data.

Following Aitken & Roche (1982), we have fit the spectra with emission spectra suffering extinction by cool silicate grains. In these galaxies, inclusion of a PAH emission component does not improve the fits as indicated by the \( \chi^2 \) values and so the results presented employ emission and absorption spectra consisting of blackbody and silicate grains. We used silicate grain profiles derived from the Trapezium in Orion and the M supergiant \( \mu \) Cephei, which are taken to be representative of molecular clouds and the diffuse Galactic ISM, respectively (Roche & Aitken 1984; Whittet et al. 1988). The goodness of fit is estimated from reduced \( \chi^2 \) values, with the errors estimated from the scatter in the data points. These allow us to differentiate between different combinations, but the range of values giving adequate fits can be quite large for some spectra. In particular, the depth of the silicate absorption depends critically on the assumed spectral properties of the underlying emission. Here, we assume that the underlying emission can be represented by grains with a blackbody emission spectrum.

For the most heavily obscured objects, NGC 3094 and NGC 7172, the reduced \( \chi^2 \) values indicate that a \( \mu \) Cep-like emissivity provides a much better fit than a Trapezium-like emissivity profile. The results are listed in Table 1 and inspection of Fig. 2 indicates that the \( \mu \) Cep curve provides a qualitatively much better fit to the curvature in the 8–9 \( \mu m \) region than the Trapezium curve. This is in line with previous conclusions for deeply embedded objects, e.g. for NGC 4418 (Roche et al. 1986) or IRAS 08572+3915 (Dudley & Wynn-Williams 1997) and from Spitzer results (Spoon et al. 2006). The dust towards the deeply embedded galaxies is well-represented by dust very similar to that in the diffuse ISM in the Galaxy (Roche & Aitken 1985; Chiar & Tielens 2006). However, the fit to NGC 3094 shows additional structure near 11 \( \mu m \) which may represent a contribution from crystalline grains. Spoon et al. (2006) have detected absorption features at 11, 16, 19, 23 and 28 \( \mu m \) which they attribute to crystalline silicates in the Spitzer IRS spectra of galaxies with deep silicate absorption bands with \( \tau_{9.7 \mu m} \sim 2.9 \). Unfortunately, the \( S/N \) of the present data are insufficient to determine whether the additional 11-\( \mu m \) crystalline absorption is distributed across the emitting region or it is centrally concentrated.

For NGC 5506, the silicate absorption feature is much shallower with \( \tau_{9.7 \mu m} \sim 1.4 \) with the Trapezium profile or 1.1 with the \( \mu \) Cep profile towards the nucleus. As found for several other galaxies with moderate silicate absorption (e.g. in the Circinus galaxy; Roche et al. 2006), the Trapezium curve provides the better fit.

### 4 DISCUSSION

#### 4.1 Spectral variations in NGC 5506

The dust continuum emission in NGC 5506 is compact but sufficiently bright to allow us to measure spectral differences in the line emission and silicate absorption depth over the central 1.2 arcsec. At the distance implied by the redshift of NGC 5506, this corresponds to a total distance of about 170 pc. The spectra to the north have shallower silicate absorption than on the nucleus with \( \tau_{9.7 \mu m} \sim 1.25 \) at 0.6 arcsec north, while the optical depth is higher at \( \tau_{9.7 \mu m} \sim 1.7 \) at 0.6 arcsec south using the Trapezium profile; the colour temperature of the underlying emission is \( \sim 300 \) K. The [S IV] emission line intensity decreases by a factor of 3 at 0.6 arcsec north and by a factor of 10 at 0.6 arcsec south compared to the central position, reflecting the changes in silicate absorption depth and the corresponding extinction. The continuum emission decreases more quickly than the line emission with distance from the nucleus so that the equivalent width of the [S IV] line increases. The [S IV] intensity is lower on the south side of the nucleus, consistent with greater extinction than to the north if the intrinsic distribution is symmetric.

The total [S IV] flux detected in the TReCS slit, 1.7 \( 10^{-20} \) W cm\(^{-2} \), is 30 per cent of that detected by ISO in a large (\( \sim 14 \times 20 \) arcsec\(^2 \)) aperture (Sturm et al. 2002) and about half that detected by Siebenmorgen et al. (2004) in a 3-arcsec slit. The 12.8-\( \mu m \) [Ne II] line is not detected in any of the TReCS spectra, suggesting that the [Ne II] emission line detected by ISO arises from more spatially extended, lower ionization gas than the [S IV] emission.

These spatial trends are consistent with an inclined obscuring layer that increases the extinction to both dust and line emitting regions to the south of the nucleus and results in lower extinction to the north, and which extends over at least 80 pc. The variations in the depth of the silicate absorption band and the [S IV] emission line are qualitatively similar to those found in NGC 1068 by Mason et al. (2006) and Rhee & Larkin (2006) and in Circinus by Roche et al. (2006) who also found variations in the silicate absorption depth on subarcsec scales and line-emitting regions more extended than the continuum emission. Adopting an \( A(V) \) to \( \tau_{9.7 \mu m} \) ratio of 18, as
Figure 2. The 8–13 μm spectra of NGC 3094 (left-hand panel) and NGC 7172 (right-hand panel). The solid lines represent fits to the spectra with the Trapezium silicate curve while the dashed lines use that obtained from the circumstellar shell of μ Cep. Flux is in units of $10^{-20}$ W cm$^{-2}$ μm$^{-1}$. The error bars plotted are estimated from the scatter of the points in narrow wavelength bins. The spectrum of NGC 7172 has been smoothed to improve the S/N per point.

Figure 3. The spectra of NGC 5506. Left-hand panel: the spectrum of the peak (top) and at positions 0.3 and 0.6 arcsec south. Right-hand panel: the spectrum at the peak and at positions 0.3 and 0.6 arcsec north of the centre. Flux is in units of $10^{-20}$ W cm$^{-2}$ μm$^{-1}$ and the dashed and solid lines represent fits as described for Fig. 2. The spectra at 0.6 arcsec south and north have been smoothed to improve the S/N per point, except in the vicinity of the [S IV] emission line.
found in the diffuse ISM in the Galaxy (Roche & Aitken 1984; Chiar & Tielens 2006) indicates that the corresponding visual extinctions at 0.6 arcsec south, on the nucleus and 0.6 arcsec north are $A_V \sim 30$, 25 and 22 mag, respectively.

4.2 Absorbing columns

The fits to the galaxy spectra hold only for simple models of a warm underlying emitting nucleus suffering extinction by cold layers. None the less, the match between the silicate absorption profile and the underlying emitting nucleus suffering extinction by cold layers is not complete in objects with the lowest absorbing columns. Alternately destroy small grains (Aitken & Roche 1985; Voit 1992), and so we might expect the grains with Trapezium-like emissivities to be found closest to the AGN, and small grain destruction to be most significant on scales of 3 and 10 μm in NGC 3094 and that of μ Cep, representing the profile in the diffuse ISM in the Galaxy, is remarkable. It is noteworthy that the galaxies with very deep silicate absorption bands have profiles similar to the diffuse ISM while those with shallower silicate absorption are better matched by the molecular cloud (Trapezium) curve. This is illustrated in Table 1, where the 9.7-μm absorption features in nearby galaxies.

| Galaxy | τ$_{9.7 \mu m}$ | μ Cep | τ$_{9.7 \mu m}$ Trap | χ$^2/N (\mu$ Cep) | χ$^2/N (\text{Trap})$ | τ$_{3.4 \mu m}$ |
|--------|---------------|--------|----------------------|--------------------|----------------------|----------------|
| NGC 4418$^b$ | 7.5 ± 0.2 | 6.6 ± 0.2 | 2.8 | 6.4 | 0.05 |
| NGC 3094 | 4.7 ± 0.1 | 5.0 ± 0.1 | 4.1 | 9.5 | 0.18 |
| NGC 7479$^c$ | 3.2 ± 0.2 | 3.3 ± 0.2 | 1.2 | 1.4 | 0.05 |
| NGC 7172 | 3.2 ± 0.1 | 3.2 ± 0.1 | 3.9 | 6.9 | 0.08 |
| Circinus$^a$ | 1.76 ± 0.1 | 2.4 ± 0.1 | 4.63 | 4.2 |
| NGC 5506 | 1.1 ± 0.05 | 1.4 ± 0.05 | 2.8 | 1.4 | 0.02 |
| NGC 1068$^d$ | 0.51 ± 0.02 | 0.69 ± 0.02 | 1.54 | 1.31 | 0.09 |
| NGC 5506 0.6 arcsec N | 1.00 ± 0.05 | 1.27 ± 0.05 | 2.3 | 2.2 |
| NGC 5506 0.3 arcsec N | 1.08 ± 0.04 | 1.40 ± 0.04 | 2.7 | 1.8 |
| NGC 5506 0.3 arcsec S | 1.33 ± 0.04 | 1.67 ± 0.04 | 2.5 | 1.6 |
| NGC 5506 0.6 arcsec S | 1.31 ± 0.05 | 1.70 ± 0.05 | 2.6 | 2.2 |

Notes. $^a$τ$_{3.4 \mu m}$ taken from Mason et al. (2004). Silicate absorption depths taken from Roche et al. (1986); $^b$Roche et al. (1991); $^c$Roche et al. (2006); $^d$Roche et al. (1984).

5 CONCLUSIONS

NGC 5506 shows variations in silicate absorption depth on scales of tens of parsecs. This could arise in a dusty structure extending over many tens of parsecs in the nuclear region. High spatial resolution observations of NGC 1068 and Circinus show similar effects, so that such structures appear to be a common property of circumnuclear material in nearby AGN. The 10-μm silicate absorption in galaxies with deep absorption closely resembles the silicate profile in the diffuse ISM in our Galaxy, as represented by the circumstellar emission from the red supergiant μ Cep while less heavily obscured nuclei appear to be better fit by the Trapezium emissivity curve, which is representative...
of silicates in molecular clouds. This could reflect preferential destruction of small grains in the galaxies with the lowest absorbing columns. However, the absorption depth of the 3.4-μm aliphatic hydrocarbon band, which is prominent in the Galactic diffuse ISM, is not well correlated with the silicate absorption depth, even in galaxies with diffuse-ISM-like profiles.

In common with many heavily obscured ultraluminous infrared galaxies, NGC 3094 shows evidence of spectral structure at 11 μm which may arise from a population of crystalline silicates; higher quality spectra may be able to determine whether these grains are confined to the nuclear region or are more widely distributed.

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