**Astronomy**
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# Discovery of 10 $\mu$m silicate emission in quasars

## Evidence of the AGN unification scheme

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**Abstract.** According to the unified scheme, AGN are surrounded by a dust-torus, and the observed diversity of AGN properties results from the different orientations relative to our line of sight. The strong resonance of silicate dust at 10 $\mu$m is therefore, as expected, seen in absorption towards many type-2 AGN. In type-1 AGN, it should be seen in emission because the hot inner surface of the dust torus becomes visible. However, this has not been observed so far, thus challenging the unification scheme or leading to exotic modifications of the dust-torus model. Here we report the discovery of the 10 $\mu$m silicate feature in emission in two luminous quasars with the Infrared Spectrograph of the Spitzer Space Telescope.

**Key words.** galaxies: active – galaxies: nuclei – galaxies: quasars: general – galaxies: quasars: individual: 3C 249.1 – galaxies: quasars: individual: 3C 351

## 1. Introduction

Observational evidence is mounting that most, if not all, quasars are surrounded by large quantities of dust (Sanders et al. 1989; Haas et al. 2003, 2004; Siebenmorgen et al. 2004a,b). According to the AGN unification model, a quasar, i.e. a type-1 AGN, is seen roughly pole-on allowing for a direct view of the nucleus, while a type-2 AGN is seen edge-on with most of the central region being hidden by the obscuring dust (Antonucci 1993). The most convincing support of the unification comes from spectro-polarimetric observations in those edge-on cases, where scattering particles located above and below the dust torus allow for viewing the AGN-typical broad spectral lines of the central region (Heisler et al. 1997). A further argument in favour of unification comes from the analysis of the isotropic far-infrared emission. The fraction of the nuclear luminosity that is absorbed by dust must be re-radiated in the infrared, and sensitive observations with the ISO satellite found similar far-infrared dust luminosities for radio loud type-1 and type-2 AGN, after normalisation by their likewise isotropic 178 MHz radio power. Hence, apart from possible starburst contributions and other small differences, which may be caused by the various evolutionary stages of these complex sources, the far-infrared observations corroborate the unified scheme (Meisenheimer et al. 2001; Haas et al. 2004).

Besides solid carbon, silicate minerals are a major component of dust not only in the Milky Way, but probably also around AGN. For a centrally heated optically thick torus viewed edge-on, the 10 $\mu$m silicate feature should be in absorption and, indeed, most type-2 AGN display such an extinction signature. On the other hand, when viewed face-on, the hot illuminated surface of the inner torus wall should display the silicates in emission. This was already predicted in the first studies of the dust radiative transfer in AGN tori (Pier & Krolik 1993). For young stellar objects with surrounding disks, which may be considered in many ways as scaled down versions of quasars, the 10 $\mu$m silicate emission is indeed also observed (Forrest et al. 2004; van Boekel et al. 2004). But contrary to the expectations, the 10 $\mu$m spectra of type-1 AGN so far showed no clear indication of the presence of silicates whatsoever, neither in emission nor in absorption. This poses a challenge to the AGN unification scheme.

For more than a decade, several research groups have therefore sought for ways to reconcile the straightforward model predictions with the observational fact of non-detection. This led to severe modifications of the dust torus models. As solutions, it was proposed that the silicon abundance in the AGN dust is very low, or that the grains are much bigger than what is usually adopted (Laor & Draine 1993). Then AGN would radiate like featureless blackbodies in the 10 $\mu$m region, but for what reason should dust grains coagulate to larger particles in the hostile environment of a luminous quasar? In another attempt, the geometry of the dust distribution was fine-tuned, resulting in sophisticated shapes; tapered disk configurations
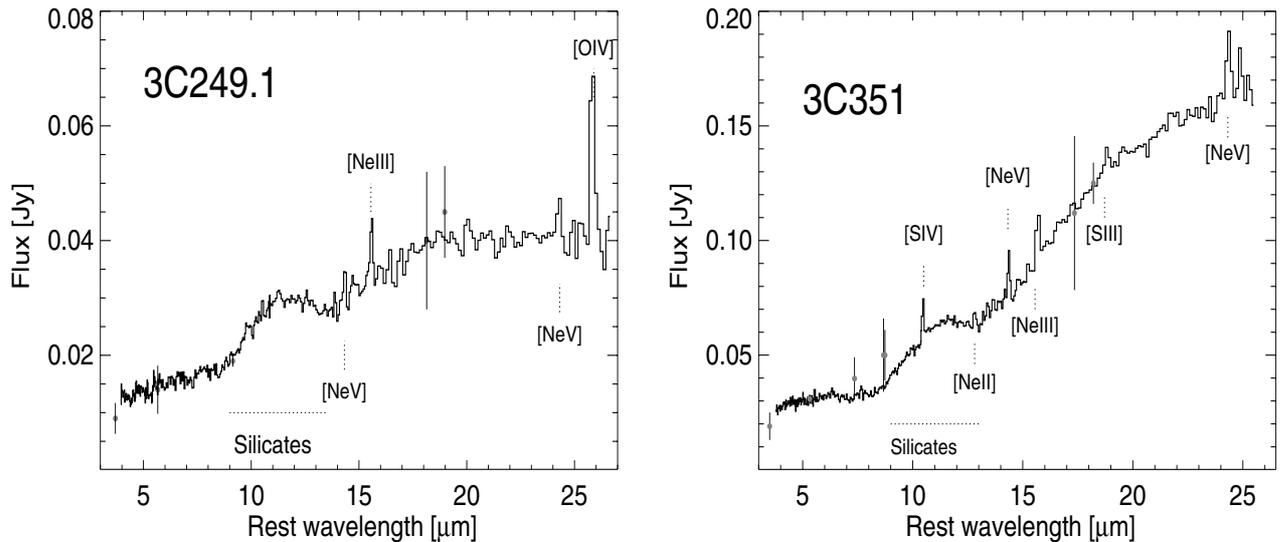
**Fig. 1.** Spectra of the quasars 3C 249.1 and 3C 351, obtained with the Infrared Spectrograph (IRS) of the Spitzer Space Telescope. The spectrum of 3C 351 is scaled by a factor 1.1 in flux, to match the broad band photometry from the literature (filled circles with $1\sigma$-error bars). The AGN-typical high-excitation emission lines like [ Ne V ] $\lambda = 14.3$ $\mu$m, $\lambda = 24.3$ $\mu$m are marked with vertical dotted lines. The broad bump in the wavelength range 9–13 $\mu$m, indicated by horizontal dotted lines, is the detected silicate emission.

were presented in order to allow for a reduction of the observable silicate emission up to large, close to face-on, viewing angles (Efstathiou & Rowan-Robinson 1995). Rowan-Robinson (1995) suggested that an ensemble of geometrically small but optically thick clouds would result in only a weak feature, due to the effective cancellation of absorption and emission processes in the 10 $\mu$m line. Similarly, clumped dust density distributions were investigated (Nenkova et al. 2002), however, the claimed reduction of the silicate 10 $\mu$m emission has recently been questioned (Dullemond & van Bemmel 2005).

## 2. Observations

Because the missing silicate emission presents a riddle of possibly fundamental importance, we observed a number of steep radio spectrum quasars and powerful radio galaxies using the infrared spectrograph (IRS) of the Spitzer Space Telescope (Werner et al. 2004). The sample contains the two luminous quasars 3C 249.1 (PG 1100+772) and 3C 351 (PG 1704+608), at redshift $z = 0.312$ and $z = 0.372$, respectively. They have a blue luminosity $M_B \sim -26$ mag, and an infrared dust luminosity estimated from ISO observations to be $4 \times 10^{45}$ erg/s assuming a $\Lambda$-cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$ and $\Omega_\lambda = 0.73$. ROSAT and ASCA X-ray data imply that the intrinsic absorption is negligible (Sambruna et al. 1999; Brandt et al. 2000). Hence, both sources are classified as powerful type-1 AGN with an almost unobscured line-of-sight towards the hot inner wall of the putative dusty torus. Therefore, these two quasars are well suited to search for the 10 $\mu$m silicate emission feature.

The objects were observed between 5 and 35 $\mu$m in the two IRS low-resolution ($64 < \lambda / \Delta\lambda < 128$) modules in staring mode. Our analysis starts with the two dimensional data frames from the Spitzer pipeline (Higdon et al. 2004) using the latest calibration files. At this point the major instrumental effects

are already removed. We subtracted the sky background, using pairs of frames, where the source appears at two different positions along the spectrometer slit. We interactively extracted the one dimensional spectra. Before averaging, parts with low reproducibility between integrations were discarded.

## 3. Results and discussion

Figure 1 depicts the IRS spectra shifted to the quasar rest frames (4–27 $\mu$m). Not only do they show the AGN-typical high-excitation lines like [ Ne V ] $\lambda = 14.3$ $\mu$m, $\lambda = 24.3$ $\mu$m and [ O IV ] $\lambda = 25.9$ $\mu$m, but they also exhibit a prominent broad bump in the wavelength range 9–13 $\mu$m. By comparison with the IRS spectra obtained for other sources of the sample (3CR radio galaxies), we rule out that the bump is an artifact. Furthermore, if it were produced by broadening of an atomic line, the velocity dispersion would have to be unacceptably large, about one fifth of the speed of light. Infrared emission bands in this wavelength range, such as features of polycyclic aromatic hydrocarbons, do also not fit. As the shape of the bump is explainable by optically thin emission of silicate minerals, we conclude that this is in fact their origin, and that we here detected this long sought for emission feature in quasars. We find that in both quasars the silicate emission contributes to about 20% of the total 9–13 $\mu$m luminosity.

The absorption coefficient of interstellar silicate dust, $\kappa_\nu$, has a local maximum around 9.7 $\mu$m producing the well-known broad band. The exact position depends on the choice of the optical constants. The emission feature detected here is centered around 11 $\mu$m. Such a shift in the local maximum can occur as a result of varying grain mineralogy or an increase in grain size ($2\pi \cdot a/\lambda \sim 1$) as suggested for circumstellar matter for young stars (Bouwman et al. 2001; Forrest et. 2004). In our case, where the emission is probably optically thin and therefore proportional to $\kappa_\nu \times B_\nu(T_d)$, the natural explanation for the
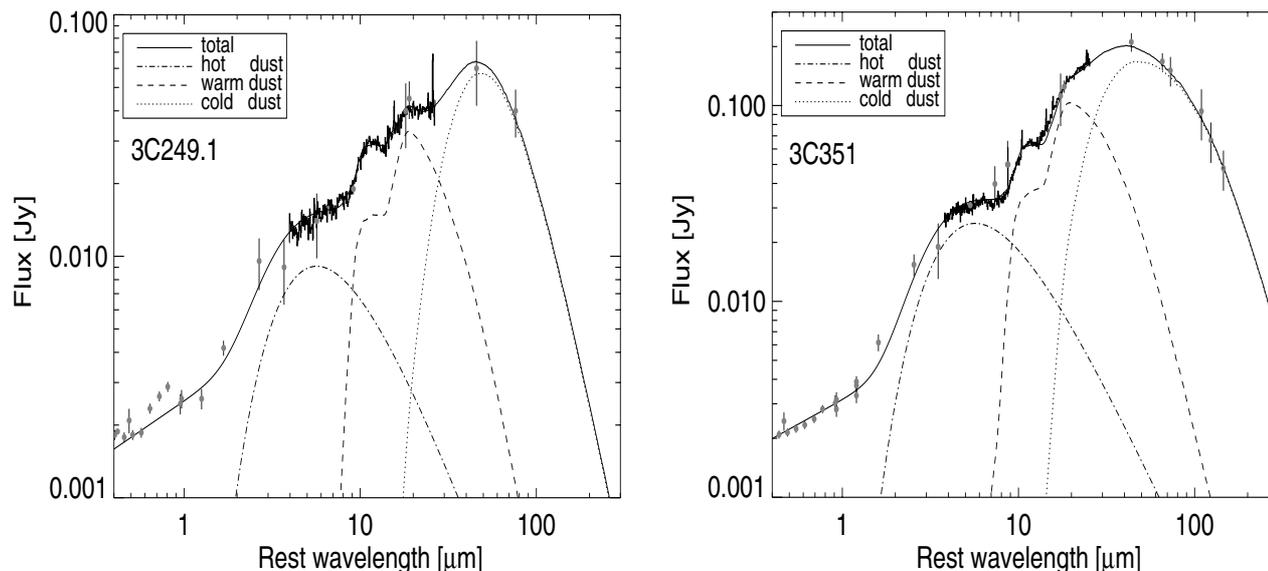
**Fig. 2.** Spectral data (see Fig.1) and model fit for the quasars 3C 249.1 and 3C 351. The models consist of a central heating source with an X-ray-to-infrared power-law spectrum, two dust components and a black body, their parameters being given in Table 1.

**Table 1.** Model components of the infrared emission. In both quasars, the infrared emission can be fitted by a superposition of a blackbody and a warm and a cold dust component (see Fig. 2). The temperatures, the surface area of the blackbody, the mass of the dust components and their distance assuming direct heating by the AGN are listed. For better agreement with the data, we used for 3C 351 two warm and two cold components.

| Name | Blackbody | | Warm dust | | | Cold dust | | |
|---|---|---|---|---|---|---|---|---|
| | $T$ [K] | Area [pc$^2$] | $T$ [K] | Mass [$10^3$ $M_\odot$] | Dist. [pc] | $T$ [K] | Mass [$10^6$ $M_\odot$] | Dist. [kpc] |
| 3C 249.1 | 900 | 180 | 180 | 3.3 | 30 | 60 | 1.4 | 1.0 |
| 3C 351 | 900 | 725 | 140 | 35 | 100 | 33 | 53 | 5.7 |
| | | | 195 | 5.3 | 30 | 70 | 2.3 | 0.6 |

local extrema is the folding of $\kappa_\nu$ with the steeply rising Planck function $B_\nu(T_d)$. The presence of carbon grains of about 180 K whose emission is included in the observed flux enhances the effect and broadens the bump.

We can reproduce the Spitzer observations, as well as the photometric data at other infrared wavelengths, by a model consisting of three components: cold dust, warm dust and a hot blackbody. The primary heating source has a power-law spectrum, $F_\nu \propto \nu^{-0.7}$, in the wavelength range 0.1 nm–15 $\mu$m. We assume that the dust in the quasar is similar to that of the Milky Way; it is a mixture of carbon and silicate spheres of fixed radius of 0.1 $\mu$m with optical constants by Zubko et al. (2004) and cross sections calculated from Mie-theory. The emission of the warm and cold component is optically thin which is a reasonable assumption for a face-on viewed quasar. The parameters of the dust components, i.e. their temperature, mass and characteristic distance to the AGN, are listed in Table 1,

together with the temperature and surface area of the blackbody. The emission of the latter may also be due to dust, but hot and optically thick. As shown in Fig. 2, this simple model fits the data and, in particular, the silicate emission bump quite well suggesting that it is not necessary to postulate a very low silicate abundance, exotic grain sizes or sophisticated torus geometries. Of course, this approach needs further refinement by a self-consistent axial-symmetric radiative transfer model of the quasar emission. Such studies are in progress and will be presented in a forthcoming paper.

Our detection of the silicate emission in two quasars poses the question why it has not been seen so far in other type-1 AGN sources. All previous spectroscopic observations which could suitably cover the 7–15 $\mu$m rest frame wavelength range necessary to unambiguously identify the broad emission bump, were of lower sensitivity and hence restricted to nearby AGN (Sturm et al. 2002). These Seyfert-1 sources, however, are

intrinsically a factor between ten and hundred less luminous than the two distant quasars investigated here. Therefore, our first guess is that the luminosity determines whether the silicate emission band is prominent or not. Further investigations may provide clues to a possible luminosity dependence of the silicate emission strength.

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