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A model for the infrared continuum spectrum of NGC 1068

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ABSTRACT

We present a model for the nuclear infrared (IR) continuum spectrum of the Seyfert galaxy NGC 1068. The torus emission is modelled in terms of the tapered disc models of Efstathiou & Rowan-Robinson, which give a good fit to the global infrared properties of active galactic nuclei. The models include the effects of a distribution of grain species and sizes and multiple scattering from dust.

Our analysis is constrained by the inclination of the torus predicted by optical spectropolarimetry. We assume in particular that our line of sight is inclined to the axis of symmetry by about 35°, and that the half-opening angle of the cone is 30°. We find that the torus emission alone cannot account for the whole of the IR continuum spectrum. While this is in agreement with recent mid-IR imaging observations, which show that up to 60 per cent of the flux is not originating from the torus, our model suggests that the difference between the observed and predicted torus emission is actually much greater at near-IR wavelengths. We attribute this excess IR emission to a component of optically thin dust (A_V=0.1–0.5 mag) located in the ionization cone between the BLR and the NLR. This dust must be distributed as r^{-2} in order to produce the required spectrum. Flatter density distributions peak at longer wavelengths and also produce a strong emission feature at 10 μm, contrary to observations. Even with an r^{-2} distribution, the grain mixture in the cone needs to be modified in order to suppress further the silicate emission feature. We suggest that this may be due to either destruction of silicate grains by shocks or the clumping of NLR dust.

In addition, our model requires that the flux radiated by the central source towards the cone is at least a factor of 6 higher than that directed towards the bulk of the torus, which is naturally explained if the central source is an accretion disc. This conclusion depends mainly on the assumed inclination and opening angle of the torus, but is rather insensitive to other geometrical parameters.

Key words: polarization – galaxies: active – galaxies: individual: NGC 1068 – galaxies: nuclei – galaxies: Seyfert – infrared: galaxies.

1 INTRODUCTION

Most discussion on active galactic nuclei (AGN) in recent years has centred around the idea of a geometrically and optically thick dusty disc or torus surrounding the nucleus. The presence of such a torus and the inclination of our line of sight with respect to its axis have profound effects on the observed properties of AGN, and largely determine their classification. Type 1 (broad-lined) AGN are assumed in this picture to be seen along the polar axis of the torus, while type 2 (narrow-lined) AGN have edge-on viewing angles (see Antonucci 1993). The development of this picture is mainly due to optical spectropolarimetry (Antonucci & Miller 1985; Bailey et al. 1988) and X-ray observations (Lawrence & Elvis 1982). One of the great challenges for the torus model is to account satisfactorily for the infrared (IR) emission of AGN, which must be mainly nuclear radiation reprocessed by the torus. Recently, some progress has been made in predicting the spectra emitted by dusty reprocessing discs or tori by means of detailed radiative transfer calculations (Efstathiou & Rowan-Robinson 1990, 1995; Pier & Krolik 1992; Granato & Danse 1994, hereafter ER90, ER95, PK and GD respectively). Calculations show that the predicted spectra are strongly dependent on orientation, but also on the assumed density distribution and geometry of the disc (i.e. whether it is a cylinder, a flared or tapered disc).

There are a number of reasons that make the comparison of theoretical models with observed spectral energy distributions (SEDs) difficult in general. First, there is a lack of good-quality IR data to constrain the models, especially in the near- and mid-IR. The spectra of model tori invariably show considerable structure at around 10 μm. The spectral shapes, for different inclinations are characterized by deep absorption features, featureless continua or emission features (ER90; ER95). Weaker emission and absorption features are also predicted at the 18-μm bending resonance of silicates. Spectrophotometry in this wavelength range, available only for bright sources (Roche et al. 1991), is therefore essential for constraining the models. Secondly, the spatial resolution of the observations is such that the emission of the nucleus cannot be separated from that of the circumnuclear (star-forming) material. A third problem is that generally we do not know the inclination of the torus. In the case of AGN in which we see the broad lines in polarized flux, the inclination of the system can be estimated with the method proposed by Young et al. (1995a).

NGC 1068 is one of a small number of AGN that lend themselves at present to the kind of detailed comparison with theoretical models of the torus suggested above. In this paper, we use all available data and the predictions of detailed radiative transfer calculations to develop a model for the IR emission of this AGN.

2 THE INFRARED EMISSION OF NGC 1068

Because of its proximity, it is possible to observe NGC 1068 from the near- to far-IR with sufficient spatial resolution to discriminate between the emission from the nucleus and that of the colder circumnuclear environment (Rieke & Low 1975; Telesco et al. 1984). The nuclear spectrum peaks at about 20–25 μm and shows a clear 10-μm feature in absorption. One of the most surprising recent observations is the discovery that a large fraction (possibly approaching 60 per cent) of the mid-IR emission of NGC 1068 comes from an extended (arcsec-scale) region which coincides with the ionization cone (Cameron et al. 1993; Braatz et al. 1993). A fraction of up to 40 per cent of the near-IR emission has also been found to extend over similar scales (McCarthy et al. 1982; Chelli et al. 1987). It is not known whether this trend continues to longer wavelengths, or indeed whether the extended emission dominates completely, as suggested by Pier & Krolik (1993). However, it is easy to show that the inclination we predict by spectropolarimetry and the opening angle of the torus imply that the torus must dominate at longer wavelengths.

The [O III] image of NGC 1068 (Pogge 1989) suggests that the opening half-angle of the cone Θ_c is about 30°. Assuming this geometry for the cone, and a degree of intrinsic polarization of 16 per cent (Antonucci & Miller 1985), Young et al. (1995a) find that the viewing angle θ_v (measured from the equatorial plane) is 56°. Assuming that the emission by the central engine is isotropic, the torus intercepts about 86.6 per cent ($\cos\Theta_c$) of its energy output. It is now well established that in order to produce spectra consistent with the IR observations (i.e. 10-μm absorption features in type 2 objects, *but* flat spectra in type 1 objects), the torus must be optically thick even to far-IR wavelengths (PK; ER95). Another result, which is also model-independent, is that for these thick tori the emission of reprocessed nuclear radiation is highly anisotropic. For the opening angle and orientation we suggest for NGC 1068, we find that the tapered discs of ER95 predict $S_t/(L/4\pi)\geq 1$, where S_t is the integrated observed flux from the torus for $\theta_v=56°$, and $L/4\pi$ is the nuclear flux seen from an unobstructed view. A similar result is found by PK (see their fig. 4) for cylinders of the same opening angle as the one assumed here. In fact, any axisymmetric system that is sufficiently optically thick to minimize the 10-μm feature from face-on directions is expected to show a similar property.

Assuming that dust in the ionization cone intercepts all of the radiation from the central engine directed towards it, because it is optically thin, it should radiate it more or less isotropically. Furthermore, we can see only the emission from the cone that is pointing towards us. It follows that

$$S_c \leq \frac{(1-\cos\Theta_c)}{2}\,\frac{L}{4\pi}$$

or $S_c/(L/4\pi)<0.066$, where S_c is the integrated observed flux from dust in the ionization cone. We can therefore deduce that $S_c/S_t<0.066$. Since there is already evidence for extended near- and mid-IR emission, it is very unlikely that the fraction of extended emission at wavelengths longer than say 15 μm is significantly higher than the above limit. We will therefore assume that the torus dominates in the longer wavelength part of the spectrum.

This argument, of course, breaks down if a significant part of the observed extended IR emission is not due to reprocessed nuclear radiation but, for example, due to star formation in the ionization cone. Also, if the viewing angle is more edge-on or Θ_c is greater than 30°, S_c/S_t can be higher. On the other hand, not all of the radiation directed towards the cones could be absorbed and reradiated by dust, because that would mean that the nucleus is obscured from all solid angles!

Because the torus and the cones have a density contrast of at least two orders of magnitude, we first examine them separately in the next two sections to establish the properties needed for a broad fit to the IR continuum. In Section 5, we discuss a composite model and compare its predictions with observations.

3 THE TORUS MODEL

ER95 presented arguments – based on the shape of the IR continuum spectrum of typical type 1 and 2 objects, the appearance of the 10-μm silicate features and the statistics of the two types of Seyfert galaxies – supporting the idea that the most likely geometry for the obscuring material is that of the tapered disc (a tapered disc, shown schematically in Fig. 1, is one whose thickness increases with distance from the central source in its inner part but tapers off to a constant height in its outer part). Flared discs (ER90; GD) block the view to the inner hot part of the disc, whereas cylinders (PK) must have very high equatorial optical depths, and consequently a very narrow range in temperature over which the torus is emitting most of its energy, in order to suppress the 10-μm features

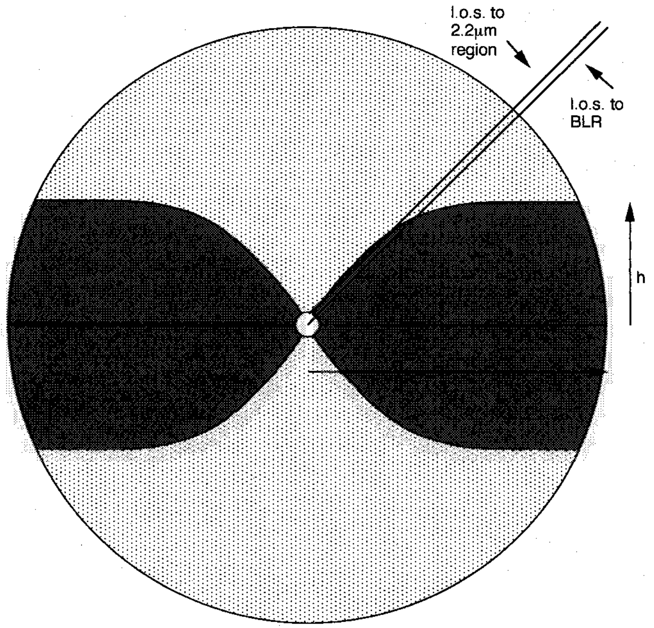

Figure 1. Schematic diagram of the assumed tapered disc and (optically thin) conical dust geometry. The inner region is drawn approximately to scale, but note that r_2 is about one order of magnitude larger than shown on the figure. Also shown are the lines of sight to the BLR (which on this scale is small enough to be considered a point source) and the 2.2-μm emitting region.

from face-on views. ER95 also argue that the most likely density distribution in the disc is one following r^{-1}.

We model the torus emission of NGC 1068 in terms of the tapered discs of ER95.

3.1 Computational details

The grain mixture used in these calculations is that of Rowan-Robinson (1992), which leads to a very good agreement with the interstellar extinction curve and observations of interstellar clouds. The mixture invokes the minimum number of grain types (total of seven) that can explain most of the observational evidence. It includes (i) 0.1-μm amorphous carbon grains with optical properties derived from models of circumstellar dust shells around carbon stars, (ii) 0.1-μm amorphous silicate grains with properties derived from circumstellar dust shells around M stars, (iii) 0.03-μm graphite grains, (iv) 0.03-μm silicate grains, (v) 0.01-μm graphite grains, (vi) 0.01-μm silicate grains, and (vii) 30-μm amorphous grains. The optical properties of the 0.03- and 0.01-μm grains have properties as calculated by Draine & Lee (1984).

We assume that the melting temperature of all grains is the same, T_1, but note that the radius at which each grain type in the mixture reaches this temperature is different (Efstathiou & Rowan-Robinson 1994). The model does not assume a value for the inner radius of the cloud but of the ratio r_1/r_2, where r_1 is the sublimation radius of the 0.1-μm silicate grains, and r_2 is the outer radius of the cloud (which is the same for all grain species). We also assume that the relative abundances of all grains remain constant throughout the cloud, except in the inner part where some species may be completely extinct.

The dust content of a model cloud is determined by the form of the density distribution and the ultraviolet (1000-Å) equatorial optical depth to the centre of the cloud, ${}^{e}\tau_{uv}$. The spectral energy distribution of the central source is assumed to follow a broken power law that approximates the average spectrum of PG quasars derived by Rowan-Robinson (1995).

The solution of the equation of radiative transfer is carried out by the ray tracing method, i.e. by defining a grid of rays, and for each one following the interaction of radiation with dust both in the form of absorption and scattering. The intensity in a given direction is given by the superposition of radiation directly from the central source (where appropriate), thermal emission from grains and scattered light from grains. As in ER90, the solution proceeds iteratively until the radiative balance equation is satisfied to within 1 per cent for every grain species and at every point in the cloud. The flux constancy condition provides an additional test for the accuracy of the solution.

The tapered disc models of ER95 assume five parameters: (1) the opening angle of the disc, Θ_1, (2) the ratio of inner to outer radii, r_1/r_2, (3) the ratio of the maximum half-thickness of the disc to the outer radius, h/r_2, (4) ${}^{e}\tau_{uv}$, and (5) the melting temperature of the grains, T_1.

3.2 The best-fitting torus model

As we have seen, the appearance of the ionization cone and the inferred intrinsic degree of polarization allow us to constrain the opening angle of the disc ($\Theta_1 = 60°$) and the viewing angle ($\theta_v \approx 55°$). A characteristic of tori with large opening angles, such as the one inferred for NGC 1068, is that they are very weak in the near-IR. This is because the near-IR-emitting region of the torus is very close to its inner radius, and therefore its emission suffers considerable self-absorption by the torus for most viewing angles. Even for face-on viewing angles, because the inner walls of the torus are concave, not much near-IR radiation is visible. These results seem to be a feature of all torus geometries explored to date. For the viewing angle appropriate to NGC 1068, the near-IR flux increases with decreasing h/r_2 as more of the inner core of the torus is revealed.

We find that we cannot fit simultaneously the entire spectrum, including a good fit to the 10-μm feature, with any combination of input parameters. Efstathiou, Hough & Rowan-Robinson (1994) and GD presented models for NGC 1068 that fit the whole spectrum but have a low ${}^{e}\tau_{uv}$. Such a torus viewed face-on would show an emission feature at 10-μm which has never been observed in a type 1 object. Also, the ${}^{e}\tau_{uv}$ (about 150) predicted by these models is probably too low compared with that predicted by the X-ray column (Elvis & Lawrence 1988), and the HCN observations of Jackson et al. (1993), who imply an A_V in excess of 70 (i.e. an ${}^{e}\tau_{uv}$ of about 350). Optically thicker tapered disc models that approximately fit the overall spectrum either predict too shallow an absorption feature or the mid-IR flux is in excess of that observed. For these reasons, and those discussed in Section 2, we conclude that at least one more IR-emitting component must be present which is probably related to the narrow-line region (NLR). We will refer to this dust as conical dust.

A point worth noting is that because the conical dust component cannot produce an absorption feature at 10 μm (see Section 4), the torus must show an absorption feature which is at least as deep as that observed, so that the addition of the conical dust emission will not dilute it. However, the depth of the 10-μm feature is constrained by the geometry of the torus and our viewing angle. The viewing angle through which we view the torus in NGC 1068 makes it very difficult to see a very deep absorption feature at 10 μm. The reason for this is that the 10-μm radiation is coming from the curved surface of the other side of the disc and is therefore viewed directly. The 10-μm feature is the result of the absorption of radiation, emitted by the bulk of the torus, by overlaying material which has only a slightly different temperature. This situation contrasts strongly with that for edge-on views, where emission by the hotter inner part of the torus is absorbed by the much colder outer part. The feature does not become appreciably deeper by increasing the overall density of the torus while, as argued by ER95, this has an effect on the width of the infrared continuum.

The torus that best fits the constraints we have imposed on it assumes the following parameters: $r_1/r_2=0.01$, $h/r_2=0.1$, ${}^{e}\tau_{uv}=1200$, and $T_1=950$ K. The predicted viewing angle is 45°, which is consistent with the value found by Young et al. (1995a). Also, the predicted diameter of the torus is 178 pc (assuming $D=22$ Mpc), which is in excellent agreement with *HST* observations of dusty discs in M51 and NGC 4261 (Jaffe et al. 1993). By subtracting the predicted torus SED from the observed spectrum, we can infer the spectrum of the postulated conical dust component. We find that this is approximately a blackbody peaking at about 3–5 μm.

4 THE CONICAL DUST MODEL

There are a number of arguments supporting the idea that the ionization cones are not completely dust-free. First, the NLR clouds themselves may contain dust (Rowan-Robinson 1995). It has also been suggested (Braatz et al. 1993; Cameron et al. 1993) that the extended mid-IR emission is due to optically thick discrete clouds that are heated by the optical–UV continuum.

It is also well known that the emission lines of type 1 AGN and quasars are reddened by an A_V which ranges from fractions of a magnitude to 2–3 mag (Ferland & Osterbrock 1986; Netzer 1990; Rowan-Robinson 1995). Ward et al. (1987) also find that there is evidence for the A_V to the broad lines being higher than that to the narrow lines, suggesting the presence of optically thin dust well down to the sublimation radius. Further evidence for obscuration in the NLR comes from imaging of the ionization cone (Unger et al. 1992).

The distribution of conical dust, i.e. whether it is concentrated in clouds or distributed more uniformly, has profound effects on the shape of the spectrum at around 10 μm. If the conical dust is optically thin and its composition is similar to that of interstellar dust in the Milky Way (and that assumed for the torus), then it will produce an emission feature that will dilute the absorption feature produced by the torus. The only way to minimize this dilution is to concentrate the dust as close to the illuminating source as possible. This is also the dust distribution needed to produce a spectrum peaking at about 3–5 μm. We find that an r^{-2} density distribution produces the required overall spectrum, but still produces a very strong 10-μm feature. We also find that if the central UV source is isotropic, then the conical dust does not produce enough near-IR flux. In view of the discussion in Section 2, this is not surprising. The beaming factor (defined in Section 5) needed to boost the near-IR output of the cones to the required level is of the order of a few. This is, of course, expected if the central source is an accretion disc and does *not* invalidate the torus model. Robinson et al. (1994) find that the ionizing continuum of NGC 4151 may be beamed by up to a factor of 10.

If the dust is concentrated in clouds, then the shape of the 10-μm spectrum will depend on the details of radiative transfer, with the optical depth across the cloud probably being the most crucial parameter. Rowan-Robinson (1995) approximated these clouds with shells and found that the 10-μm feature of clouds with an A_V of about 5 is very weak. It is therefore likely that the emission feature predicted by conical dust is so strong, because a significant fraction of the effective optical depth is due to these clouds.

Unfortunately, it is very difficult at present to calculate the emission of these clouds in a self-consistent manner, as they involve the solution of a three-dimensional radiative transfer problem. In the next section, we suggest a way of treating these clouds with our present model under some simplifying assumptions.

5 COMPOSITE MODEL

Having discussed the required characteristics of the best-fitting torus model and the most desirable distribution for the conical dust, we here consider both components together and compare the emission of the whole system with that of NGC 1068.

The model is shown schematically in Fig. 1. As discussed in Section 4, in order to produce enough near-IR flux, the radiation intensity emitted by the continuum source towards the optically thin conical dust should be a factor of a few higher than that directed towards the torus. If the anisotropy is due to the fact that the continuum source is an accretion disc, then there could be a smooth variation of the intensity from axial to equatorial directions. However, for simplicity, we parametrize the anisotropy of the central source with the beaming factor f_b, defined by

$$f_b=\frac{S_\nu(\Theta>\Theta_1)}{S_\nu(\Theta\leq\Theta_1)},$$

and which is assumed to be constant with wavelength.[1]

There are essentially three free parameters in the model that determine the luminosity of the near-IR component relative to that of the torus: the beaming factor f_b, the covering factor of dust in the ionization cone f_c, and the optical depth along the polar axis ${}^{p}\tau_{uv}$. The last is constrained by estimates of reddening in quasars and type 1 AGN (Rowan-Robinson 1995, and references therein), and we have there-

[1]Note that Θ is measured from the equatorial plane.

fore only explored models in which ${}^{\mathrm{P}}\tau_{\mathrm{uv}}$ does not exceed 2.5 (corresponding to an A_V of about 0.5). Fortunately, the shape of the near-IR spectrum does not depend very much on the optical depth in this range.

For a given value of ${}^{\mathrm{P}}\tau_{\mathrm{uv}}$, $S_{\mathrm{c}} \propto f_{\mathrm{c}} f_{\mathrm{b}}$. The assumed opening angle of the torus puts an upper limit to f_{c} of approximately 13 per cent. Because ${}^{\mathrm{P}}\tau_{\mathrm{uv}}$ is very low, we can neglect radiative transfer effects due to a partly filled cone, and so we can assume for simplicity that f_{c} takes its maximum value. Note, however, that a partly filled cone will allow illumination of dust to larger radii and may explain why a significant fraction of the near- and mid-IR emission is extended over arcsec scales (see Section 6). The inferred value of f_{b} will therefore be only a lower limit.

As noted in Section 4, if the conical dust has the same composition and size distribution as dust in the torus, then a very strong 10-μm feature is predicted. We therefore need to explore the possibility that the NLR dust mixture is different from the average interstellar one.

One possibility is that the silicate grains are preferentially destroyed by shocks by the mechanism proposed by Seab & Shull (1983). GD suggested that this mechanism is responsible for destroying the silicates in the torus and therefore eliminating the silicate emission features for face-on views of the torus. This is not necessary for our torus model (whose bulk in any case could be self-shielded for shocks to change its composition drastically), but it is possible that the mechanism could be operating in the diffuse environment of the ionization cone. There is also evidence (for example, the absence of PAH features in the spectra of AGN) that the smaller grains are destroyed by the high UV–X-ray intensities expected in the vicinity of the AGN.

Proper treatment of these effects is beyond the scope of the present paper. We instead attempt to model them by increasing the abundance of the 30-μm grains in the mixture of Rowan-Robinson (1992). These grains are assumed to have an absorption efficiency following λ^{-1} for $\lambda > 4\pi a$, where a is the grain radius, but being independent of λ for shorter wavelengths. We also note that these large grains can approximate the emission of individual optically thick NLR clouds. Proper treatment of the latter will again require further work, but to a first approximation each cloud will emit as a blackbody at a constant temperature (the side of the cloud facing the central source would obviously be hotter than the bulk of the cloud, but the amount of dust at this higher temperature is likely to be very small). However, calculation of even the average temperature of these clouds is not trivial, as we have to include contributions in the energy balance equation from the central source, the torus and other clouds.

We find that a reasonable fit to the 10-μm feature (see Fig. 2) is obtained if the abundance of the 30-μm grains is increased so that the extinction due to these large grains is just 2.5 per cent of that due to the whole mixture. The model assumes ${}^{\mathrm{P}}\tau_{\mathrm{uv}} = 2.5$ and $f_{\mathrm{b}} = 6$. As noted earlier, the inferred value of f_{b} is only a lower limit, and will have to be higher if ${}^{\mathrm{P}}\tau_{\mathrm{uv}}$ or f_{c} are lower than 2.5 and 0.134 respectively. Unger et al. (1992) presented [O III] images of NGC 1068 which show limb-brightening along the edges of the cone. While the scale of these observations is of the order of tens of arcseconds, they are consistent with our model if the conical dust is concentrated on the axis of the cone.

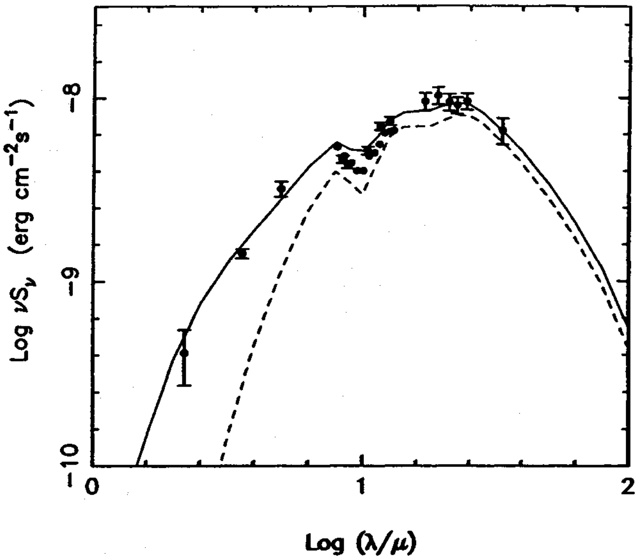

Figure 2. Fit to the infrared continuum of NGC 1068 with a torus and optically thin conical dust model. Also shown (dashed line) is the spectrum predicted by a model that does not include the conical dust component. Data from Rieke & Low (1975) and Roche et al. (1991).

6 DISCUSSION

6.1 Spatial extent of the infrared emission

A complete model for NGC 1068 should explain the spatial extent of the IR emission as well as its spectral energy distribution. The idea of the conical dust component is attractive, because it is consistent with the near- and mid-IR imaging observations which show that a large fraction of the emission is co-spatial with the [O III] emission. An important limitation of our model is that, although the predicted emission appears to agree qualitatively with observations, it is actually less extended than observed. In Fig. 3, we plot intensity maps of the central 0.16×0.16 arcsec^2 of both the composite and 'torus only' models at 2.5, 10 and 12.5 μm. The 2.5-μm emission is the most centrally concentrated, as it maps the hot inner core of the torus. Note that it is conical in shape, reflecting the projected opening angle of the torus. The addition of the conical dust makes the emission appear more extended. The images at 10 μm, which appear very similar in the 'torus only' and composite cases, are more extended than the 2.5-μm ones, and appear to be a superposition of a conical component and a more isotropic component. This isotropic component, which is a result of the mid-IR-emitting dust being less centrally concentrated, and therefore less obscured, appears to be more dominant in the 12.5-μm maps.

It is likely that the problem in fitting the extent of the IR emission may be related to that of fitting the 10-μm absorption feature. As discussed in Section 4, if the conical dust is concentrated in discrete optically thick clouds, then a very weak emission feature will be produced. In this case the clouds can be more uniformly distributed and can also 'see' radiation directly from the central source at greater distances. Both of these factors will tend to make the near- and mid-IR emission appear more extended.

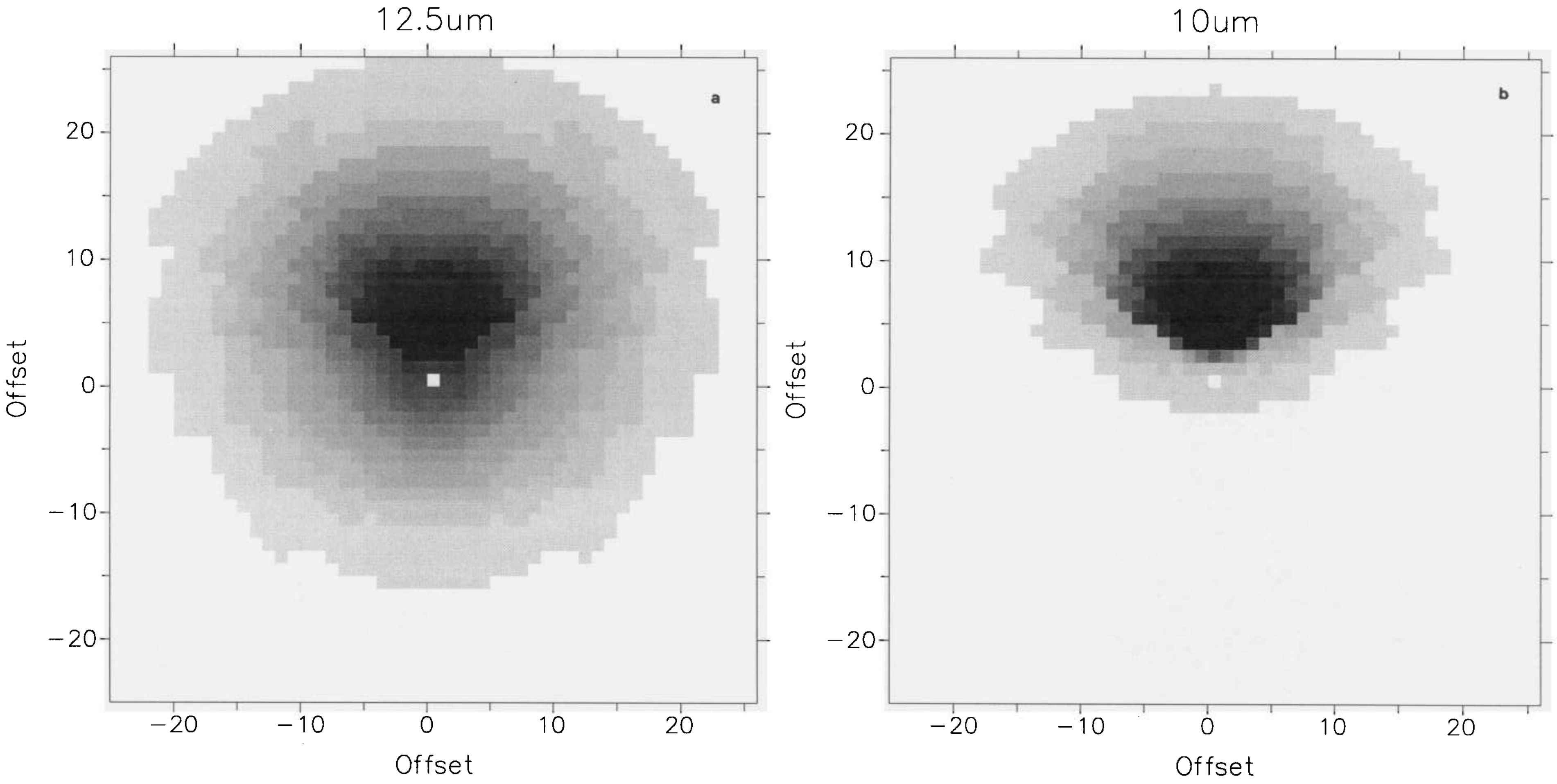

Figure 3. Intensity maps of the central 0.16 × 0.16 arcsec^2 region of the torus model at 12.5, 10 and 2.5 μm (a–c) and the composite model at the same wavelengths (d–f). Each pixel is about 0.003 25 arcsec.

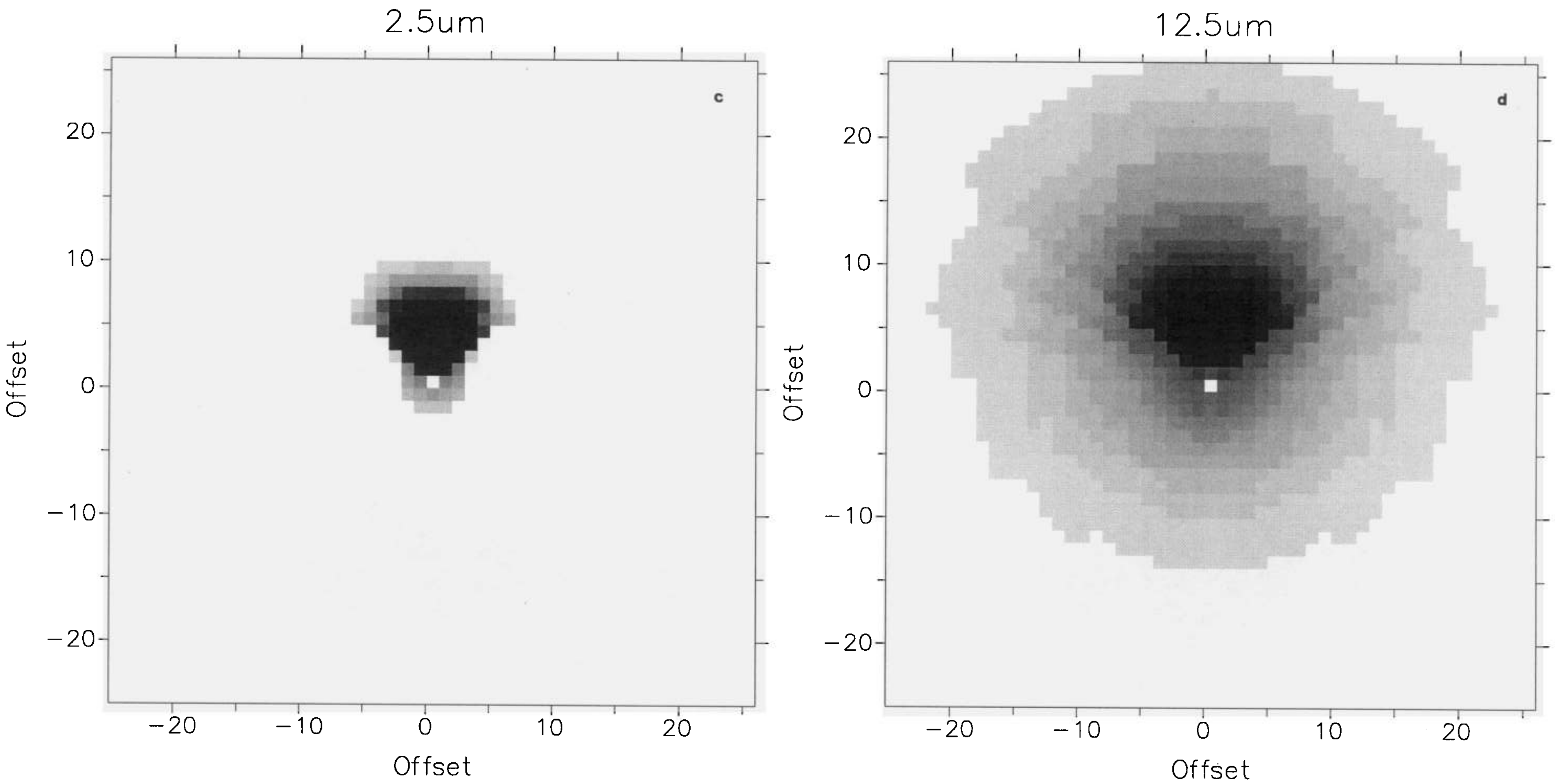

Figure 3 – *continued*

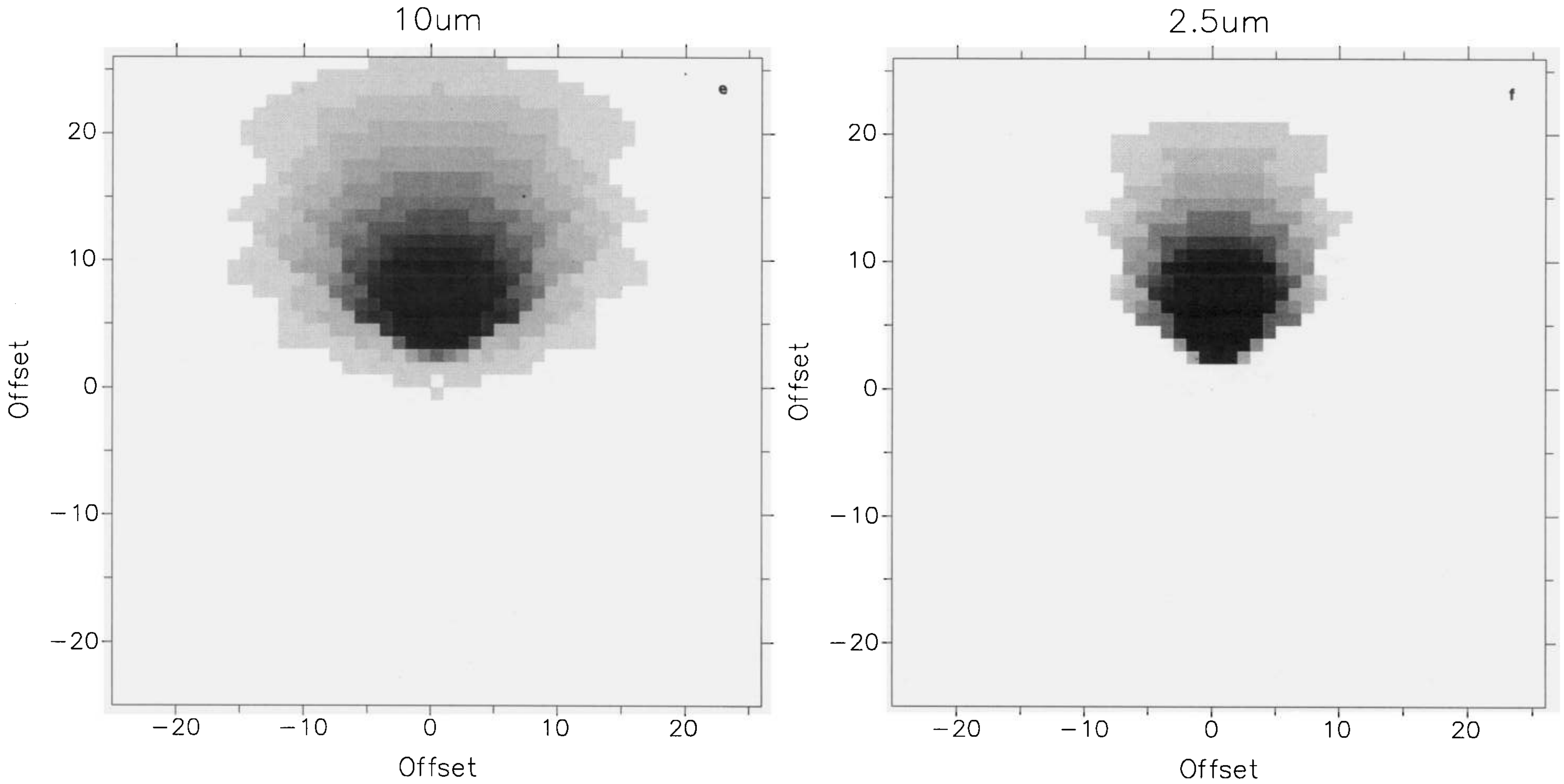

Figure 3 – *continued*

Throughout this paper we have assumed that the primary source of radiation is a point source at the centre of the system. Our calculation of the temperature distribution in the cones could significantly underestimate the temperature in the cones if local heating, in the form of star formation or shocks for example, is important. Again this would have the effect of producing a more extended distribution of mid-IR emission.

6.2 SEDs for other viewing angles

While we have found that the addition of optically thin conical dust is essential for explaining the spectrum of NGC 1068, it is interesting to examine its effect on the predicted SEDs from other viewing angles, and whether the latter agree with those obeserved in other AGN. In Fig. 4, we compare the SEDs predicted for different viewing angles for the 'torus only' model and the best-fitting composite model for NGC 1068. There are two problems with the 'torus only' model that are solved with the addition of the conical dust. First, the face-on SEDs predicted by the torus model do not produce the near-IR bump seen in type 1 objects (Edelson & Malkan 1986; Robson et al. 1986). This result is again a feature of all torus geometries explored to date, and is due to the fact that the hot dust in the torus is not visible because of either geometrical or obscuration effects. Note also that the near-IR flux does not increase monotonically with viewing angle. Contrary to intuition, the near-IR flux from $\theta_v = 90°$ is less than that for $\theta_v = 60°$. The addition of conical dust eliminates the latter feature and also produces a stronger 3–5 μm continuum. If the conical dust is a feature of AGN in general, and its covering factor is proportional to the opening angle of the cone, then our model predicts that the 3–5 μm bump will be stronger in objects with large cone opening angles.

A second problem with the 'torus only' model is that the SEDs predicted for edge-on views show very deep 10-μm features, in contrast with observations. Considering the large equatorial optical depths predicted for the tori, it is surprising that the 10-μm optical depths of type 2 objects are in the range 0–0.5 (Roche et al. 1991). This has led Roche et al. to question whether the dust responsible for the silicate absorption is the same as that providing the obscuration of the type 1 nucleus. As shown in Fig. 4(b), the addition of conical dust has the effect of 'filling in' the edge-on absorption feature at 10 μm to a level consistent with the observations. The shallow silicate absorption feature seen in the face-on SED is also filled in by the emission from the conical dust but remains in absorption, i.e. also consistent with the observations. As shown by ER95, shallow silicate features in absorption for face-on views are predicted only for tori with large opening angles.

6.3 Polarization

It is now well established that the polarization of the broad lines and the optical–UV continuum in NGC 1068, as well as in other AGN that exhibit the same phenomenon, is due to electron scattering of radiation from the nucleus escaping along the polar axis of the torus (Antonucci & Miller 1985; Miller, Goodrich & Mathews 1991; Young et al. 1995a,b). The presence of conical dust does not invalidate this interpretation because of the low optical depth and the fact that it is centrally concentrated. The conical dust could be responsible, however, for the polarization of type 1 objects, which is both at a lower level and at a different position angle to that seen in type 2 objects.

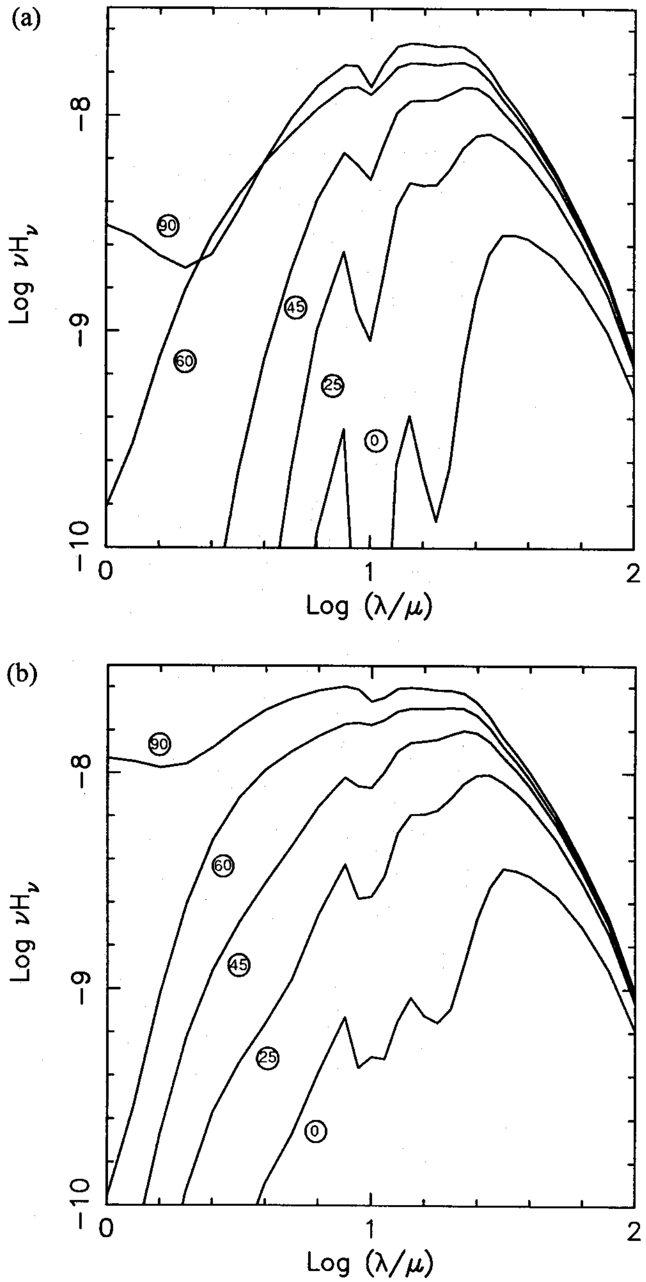

Figure 4. Spectral energy distributions of the torus model (a) and of the composite model (b) from different viewing angles. The inclination of the line of sight to the equatorial plane is indicated on the short-wavelength side of each curve.

It is not yet clear what mechanism causes the polarization in the near-IR. If electron scattering were responsible, then one would expect the polarization (after starlight subtraction) to remain constant with wavelength, but instead a rise in polarization is observed (Young et al. 1995a,b). Evidence that another polarization mechanism is at work is also provided by the change in position angle between the optical (where it is perpendicular to the parsec-scale radio jet) and the near-IR (where it is perpendicular to the large scale [O III] and radio structure).

Young et al. (1995a,b) have proposed a model that assumes that the near-IR polarization is produced by the dichroic absorption of nuclear light through the torus. In order to produce the polarization at K in the case of NGC 1068, Young et al. (1995a) require an extinction corresponding to an A_V of about 45 mag, and assuming a Serkowski law (Serkowski 1973), with $\lambda_{max} = 0.55$ μm and $P_{max} = A_V$. As this is less than the extinction to the BLR, Young et al. argue that the geometrical thicknesses to the BLR and to the near-IR-emitting regions are different.

This interpretation of the rise in near-IR polarization is entirely consistent with our model. Most of the near-IR flux in our model comes from the cone which suffers much less extinction than radiation emitted by the BLR or by the inner walls of the torus. In fact, one of the reasons we have introduced the optically thin, near-IR component is because the hot walls of the torus are too heavily obscured to produce the required near-IR flux. Our model predicts that the A_V to the near-IR-emitting region of the conical dust is 20 mag. This picture is also consistent with the estimate of the extinction to the 3.4-μm emitting region by Bridger, Wright & Geballe (1994), who find that the 3.4-μm dust absorption feature implies an A_V of 22 mag.

The predicted low A_V to the near-IR-emitting regions can also explain the observed 90° swing in polarization position angle that is seen for NGC 1068 at a wavelength between 4 and 5 μm (Bailey et al. 1988), and which is attributed to a change from absorption to emission polarization. If the optical depth at these wavelengths were large, then the polarization would still be seen in absorption. Similarly, the 10-μm polarization has a position angle almost perpendicular to that of the 1–2 μm polarization (Aitken et al. 1984). It has been suggested by a number of authors that this is due to optically thin emission by aligned grains. This is again consistent with our model as a large fraction of the 10-μm flux is due to optically thin conical dust emission. Since polarization is seen in emission from the conical dust grains, these grains must be aligned. The direction of polarization requires the long axis of the grains to be parallel to the cone axis. For Davis–Greenstein-type alignment processes, this would imply that the direction of the magnetic field is perpendicular to the cone axis. However, in the physical environment of the NLR the most likely alignment mechanism is by streaming, and not Davis–Greenstein, in which case the magnetic field will be parallel to the grain axis (Lazarian 1995). It would be very interesting to test these ideas with detailed polarization calculations in future work.

6.4 Comparison with other models of NGC 1068

GD presented a flared disc model that fits the SED of NGC 1068. The ${}^{e}\tau_{uv}$ assumed by the model is about 150. As already remarked, models with such low ${}^{e}\tau_{uv}$ produce strong emission features at 10 μm from face-on views. Such features have not yet been detected in type 1 objects. This model is therefore inconsistent with unified schemes, as it suggests that we have not yet observed a face-on analogue of NGC 1068.

Pier & Krolik (1993) proposed a three-component model for NGC 1068: torus emission viewed at an angle of about 15°, emission by cold (133-K), optically thin dust, and 'pole-ward' torus emission which is reflected in our line of sight by the same electron cloud that scatters the broad lines. It is also assumed that hot clouds orbiting in the plane of the torus, but closer to the central engine than the bulk of the torus, are also contributing in the near-IR, but their emission is obscured by the torus in the case of type 2 objects.

The torus in the Pier & Krolik model contributes about 90 per cent of the flux in the near-IR (the rest is due to the scattered component), whereas the 133-K component dominates in the far-IR. This is in contrast to our model in which the torus dominates in the far-IR. Although the Pier & Krolik model assumes that the optically thin dust is too cold (to avoid too much dilution of the 10-μm absorption feature produced by the torus), it predicts a very strong 18-μm silicate feature. By contrast, our model predicts a rather flat 18-μm spectrum (the torus actually produces a slight absorption feature which is filled in by emission by the NLR dust). We strongly encourage high-resolution spectroscopy of the 18-μm wavelength range as a possible test of the two alternative models.

7 CONCLUSIONS

Our main conclusions can be summarized as follows.

(1) In order to fit the SED of NGC 1068 we need to supplement the emission from the torus with a component peaking in the near-IR. We suggest that this is due to optically thin ($A_V = 0.1$–0.5) dust in the ionization cone distributed as r^{-2}.

(2) The radiation of the central source must be 'beamed' by at least a factor of 6.

(3) To obtain a detailed fit to the 10-μm feature, the dust mixture in the optically thin component must be depleted in silicates, or the dust must be concentrated in discrete clouds. It would be very interesting to calculate the emission from such clouds with detailed radiative transfer calculations in future work.

(4) The model proposed here is consistent with the rise in polarization in the near-IR and the change in position angle in the near- and mid-IR. It is important to test these ideas with detailed polarization calculations in future work.

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