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A Model for the Infrared Polarization of NGC 1068

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Abstract. We present a method for calculating the polarization due to absorption and emission by aligned grains distributed in a disk or a torus. The temperature distribution in the torus is calculated self-consistently with the axially symmetric radiative transfer code of Efstathiou & Rowan-Robinson (1990, 1995). The polarization patterns predicted for models that provide good fits to the spectral energy distributions of Active Galactic Nuclei (AGN) show a flip in position angle in the infrared. This effect has already been observed in the case of NGC 1068. We show that the model of Efstathiou et al. (1995) for the torus in NGC 1068 is consistent with the observed polarization pattern.

1. Introduction

The idea and implications of an optically and geometrically thick dusty torus in AGN has been widely discussed in recent years (e.g. Antonucci 1993). One of the great challenges for the torus model is to satisfactorily account for the infrared 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 disks or tori by means of detailed radiative transfer calculations (Efstathiou & Rowan-Robinson 1990, 1995; Pier & Krolik 1992; Granato & Danese 1994). Calculations show that the predicted spectra are strongly dependent on the orientation of the line of sight to the system's axis of symmetry but also on the assumed density distribution and geometry of the disk (i.e. whether it is a cylinder, a flared or tapered disk).

The presence of magnetic fields appears to be a prerequisite for the formation of a geometrically thick torus (Krolik & Begelman 1988; Königl & Kartje 1994). The alignment of grains with magnetic processes similar to those operating in the interstellar medium is therefore possible. Other possibilities for alignment (e.g. by streaming) are also possible (Lazarian 1996). If grains are aligned in the torus then their infrared emission should be polarized. So far NGC 1068 is the only AGN for which the polarization in the near and mid-infrared has been measured (Aitken et al. 1984; Bailey et al. 1988). These observations show a dramatic 90° switch in the position angle of polarization between 4 and 5 μm, which suggests that the polarization mechanism is due to absorption/emission by aligned grains.

Recently Efstathiou et al. (1995) presented a model that fits the spectral energy distribution (SED) of NGC 1068. The model involves a torus, which contributes most of the flux at wavelengths longer than 10 μm, and optically thin conical dust which dominates in the near-IR part of the spectrum. The spectra emitted by each component are calculated with the detailed radiative transfer code of Efstathiou & Rowan-Robinson (1990, 1995) which treats a distribution of grain sizes and species and multiple scattering from them.

In this paper we discuss how the technique of Efstathiou & Rowan-Robinson can be adapted to calculate the polarization due to absorption/emission by aligned grains. We subsequently show that the model of Efstathiou et al. can naturally explain the wavelength dependence of IR polarization of NGC 1068.

2. The Computational Method

2.1. Radiative Transfer in Dusty Discs

The iterative procedure for calculating the equilibrium temperature distribution in an axisymmetric dusty medium is described in detail in Efstathiou & Rowan-Robinson (1990, 1995). Once convergence is achieved the emergent spectrum is calculated for a number of viewing angles from a point outside the cloud, typically at a distance two orders of magnitude larger than the largest scale in the torus to avoid distortion by geometrical effects.

The grain mixture used in the calculations of Efstathiou et al. (1995) 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 μm and 0.01 μm grains have properties as calculated by Draine & Lee (1984).

All the grains in the above mixture are assumed to be spherical in shape. For the calculations reported here we assume that they are in fact oblate spheroids with a ratio of major to minor axes equal to 2:1. All the grain species can be (partially) aligned with an efficiency which depends on material and size. Strictly speaking, the temperature distribution of these spheroidal particles will be different from that of the spherical particles in the mixture of Rowan-Robinson (1992) but the effect should be small compared to other effects that determine the temperature distribution of grains. The efficiency of alignment can also be a function of position.

2.2. Dichroic Absorption and Emission by Aligned Grains

The problem of calculating polarization due to absorption/emission by aligned grains in a torus is much simplified if the rotation axis of all the aligned grains is the same, or at least is precessing about the same axis. This situation is not as idealized as it may appear at first sight. It could arise for example if the alignment mechanism is paramagnetic relaxation with the magnetic field being

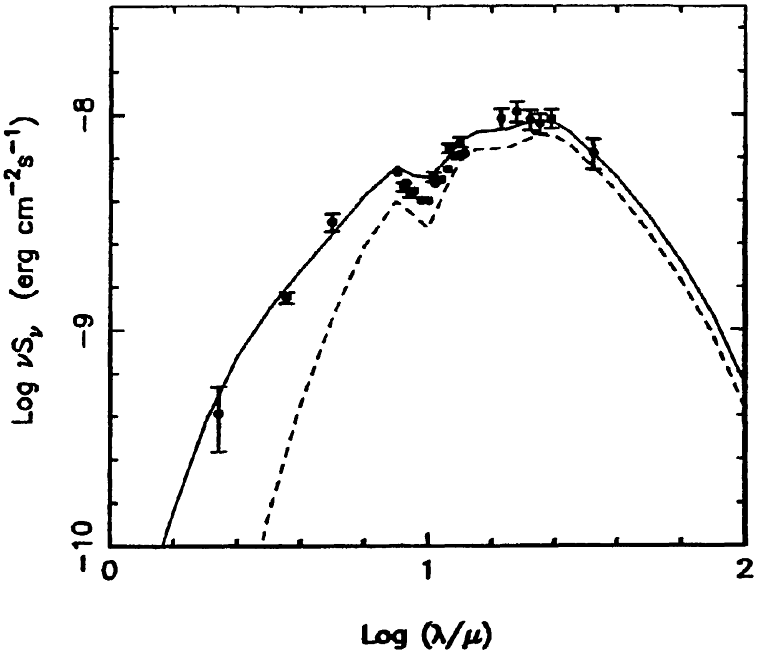

Figure 1. Model fit to the spectrum of NGC 1068 with a combination of a dusty torus and an optically thin conical dust. The emission by the torus is shown separately as a dashed line. The data are taken from Rieke & Low (1975) and Roche et al. (1991).

approximately poloidal (Königl & Kartje 1994). Other alignment configurations (e.g. one resulting from magnetic alignment in the case of a toroidal field) can also be approximated in this way. So for the sake of simplicity we initially explore models in which a certain fraction of the oblate spheroids are perfectly aligned with the semiminor axis parallel to the torus axis of symmetry.

We choose a coordinate system so that z is in the direction of propagation of radiation and x, y lie along the projected minor and major axes of the spheroids respectively. For a ray traversing the cloud the optical depths in the x and y planes correspond to the minimum and maximum values, respectively. The flux in the x and y directions (Hildebrand 1988) F_x and F_y can be calculated with two separate runs of the code of Efstathiou & Rowan-Robinson, each one tracing radiation traversing the cloud in the x or y directions. In each case the corresponding cross sections C_x and C_y are used (see below) for the aligned particles. For the randomly orientated particles we use the cross sections derived from the mixture of Rowan-Robinson (1992) in both runs. In the above discussion the frequency subscript has been dropped for simplicity.

The polarization is then given by the usual relationship

$$P = (F_x - F_y)/(F_x + F_y). \tag{1}$$

The effective cross sections of the perfectly aligned spheroids in the x and y directions are given by

$$C_x = C_{\|} \tag{2}$$

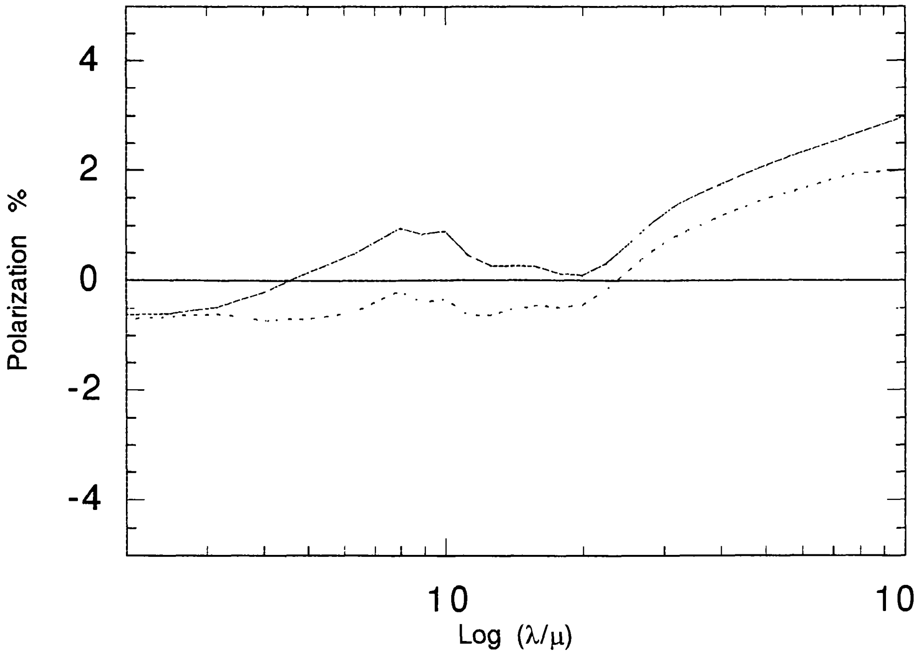

Figure 2. Predicted infrared polarization of NGC 1068 for the model described in Fig. 1 (see the text for more details).

and

$$C_y = C_{\|} - (C_{\|} - C_{\perp}) \cos^2(\theta_v) \tag{3}$$

where θ_v is the viewing angle measured from the equatorial plane, and $C_{\|}$ and $C_{\perp}$ are the cross sections for light polarized parallel and perpendicular to the grain symmetry axis, calculated according to the prescription of Draine & Lee (1984).

3. Results

In Fig. 1 we give the fit to the 2–34 μm spectrum of NGC 1068 obtained by Efstathiou et al. (1995). The torus is assumed to have the tapered disk geometry suggested by Efstathiou & Rowan-Robinson (1995). The dust number density in the torus is assumed to follow r^{-1} and the total A_V in the equatorial direction is 240 mag. The dust in the cone (which has a half-opening angle of 30°) is assumed to be distributed as r^{-2} and has a total A_V of 0.5 mag. The model requires that the abundance of the 30 μm grains in the cones be significant. The presence of these large grains is intended to approximate the emission from dusty clumps or metallic (carbon) dust grains.

We also show in Fig. 2 the polarization produced by a model assuming the same parameters as in Fig. 1 but with two different alignment configurations. In the first case (dotted line), one sixth of the 0.1 μm silicates in both the torus and cone are aligned. In the second case, two thirds of the 30 μm grains in the cones are also assumed to be aligned. In both cases, a cutoff of 500 K (above which grains can not align at all) is assumed. The effect of the aligned 30 μm grains on the wavelength at which the position angle changes sign is self-evident.

4. Conclusions

We present a method of adapting a full radiative transfer code to include a component of grains polarizing with absorption and emission. The code has been used to model the flip in position angle of polarization in the near-IR in the case of NGC 1068. The model indicates that the polarizing properties of dust in the cones and torus must be distinct. Further work on refining this model and applying it to other objects is in progress.

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