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Dusty discs in AGN

A. EFSTATHIOU

Division of Physical Sciences, University of Hertfordshire, Herts AL10 9AB, UK

Abstract

A modified version of the code of Efstathiou & Rowan-Robinson (1990), that solves accurately the axially symmetric radiative transfer problem in dust clouds, is used to model the infrared emission from dust in Active Galactic Nuclei. The method takes into account a distribution of grain species and sizes and includes treatment of multiple scattering from grains. Arguments are presented supporting the idea that tapered discs (discs whose height increases with distance from the central source but tapers off to a constant height in their outer part) with steep density gradients are the most successful in satisfying the observational constraints.

1. Introduction

The fundamental assumption of current unified theories of Active Galactic Nuclei (AGN) and quasars is that the continuum source and Broad Line Region are surrounded by a geometrically and optically thick torus of obscuring material. The most exciting consequence of the presence of such a torus in the vicinity of AGN is that it can lead to an understanding of the phenomenological differences between type 1 and 2 AGN (e.g. Antonucci 1993).

Observations (e.g. Roche et al 1990) require that a successful AGN model must fulfill the following three minimum requirements:

1. The predicted spectrum should be quite broad, at least for face-on views, and peak in the mid-infrared.

2. The model should also predict (moderate) absorption features at $10\mu m$ for edge-on views *but* featureless spectra for face-on views.

3. Requirements (1) and (2) must be satisfied for a range of torus opening angles Lawrence (1991).

For the purpose of assessing how well a given model satisfies the first requirement we compare it with 'typical' type 1 and 2 spectra. As a representative type 1 spectrum we use the average of the spectra of Seyfert 1s (with starlight and galactic contributions subtracted) in the sample of Granato & Danese (1994). As our typical type 2 spectrum (filled circles) we use that of the nucleus of NGC1068 (Rieke & Low 1975). The two spectra (compared with the predicted spectra in figures 2 and 3 are distinctively different and show the behaviour expected from an optically thick disc.

Granato & Danese (1994) considered flared discs and suggested that the lack of $10\mu m$ emission features in the spectra of type 1 objects may be due to the depletion of silicates by shocks in the innermost regions of the tori. Pier & Krolik (1992) presented models of homogeneous compact tori of high optical depth which almost eliminate emission features but produce too narrow spectra. The calculations reported here were carried out with the axially symmetric radiative transfer code of Efstathiou & Rowan-Robinson (1990) generalized to take into account a distribution of grain species and sizes. A full account of the results summarized in this paper is given in Efstathiou & Rowan-Robinson (1995).

2. Which type of torus?

A generic feature of the spectra emitted by dusty discs is that the $10\mu m$ silicate feature changes from absorption to emission as the angle the line of sight makes with the plane of the disc, θ_v, increases (Efstathiou & Rowan-Robinson 1990). This is because for edge-on views the $10\mu m$ radiation has to go through material in the plane of the disc whereas for face-on views it is seen directly. The emission feature seen face-on can be suppressed if the $10\mu m$ emitting region is optically thick to its own radiation. With ordinary interstellar dust, this implies that the ultraviolet optical depth perpendicular to the plane of the disc ${}^{\perp}\tau_{uv}$ ($A_V \approx \tau_{uv}/5$) at the radius where the dust temperature is about 500K must be ≥ 300.

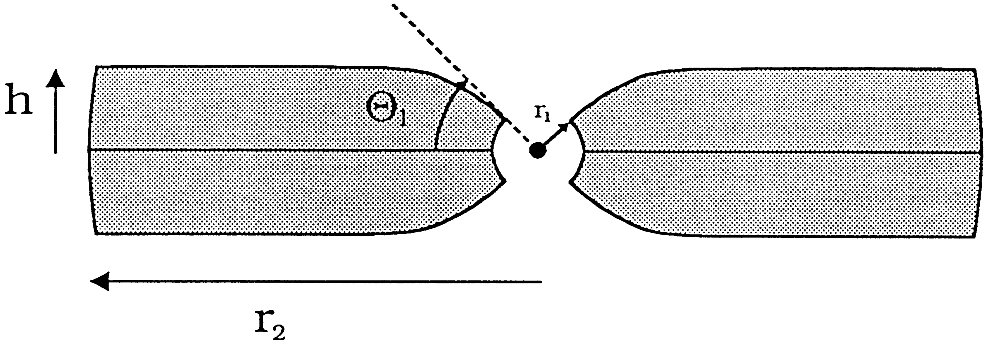

Figure 1. Cross section of a tapered disc.

In a flared disc (a disc whose thickness increases linearly with distance from the central source d) following an r^{-1} density distribution, ${}^{\perp}\tau_{uv}$ is easily shown to be constant with d and given by

$$ {}^{\perp}\tau_{uv} = 2\,{}^{e}\tau_{uv}\,\frac{\sinh^{-1}(\tan\Theta_1)}{\ln(r_2/r_1)} $$

where r_1/r_2 is the ratio of inner and outer disc radii and Θ_1 is its opening angle. It therefore follows that for $\Theta_1 = 45^0$ and $r_2/r_1 = 10, 100, 1000$, the equatorial optical depth ${}^{e}\tau_{uv}$ must be greater than about 400, 750 and 1200 respectively in order to suppress the $10\mu m$ emission feature. For a flared disc with uniform density, ${}^{\perp}\tau_{uv}$ increases linearly with d, with its maximum value (at $d = r_2\cos\Theta_1$) equal to $2\,r_2\sin\Theta_1/{}^{e}\tau_{uv}$. Since the $10\mu m$ emission comes from the inner part of the disc, in this case a higher ${}^{e}\tau_{uv}$ is necessary in order to give ${}^{\perp}\tau_{uv} \geq 300$.

Discs with a high value of r_2/r_1 are the most likely to produce broad spectra because the dust has a broader range in temperature. If this is combined however, with a high ${}^{e}\tau_{uv}$, necessary as we have seen for suppressing the $10\mu m$ feature, in a flared disc geometry,

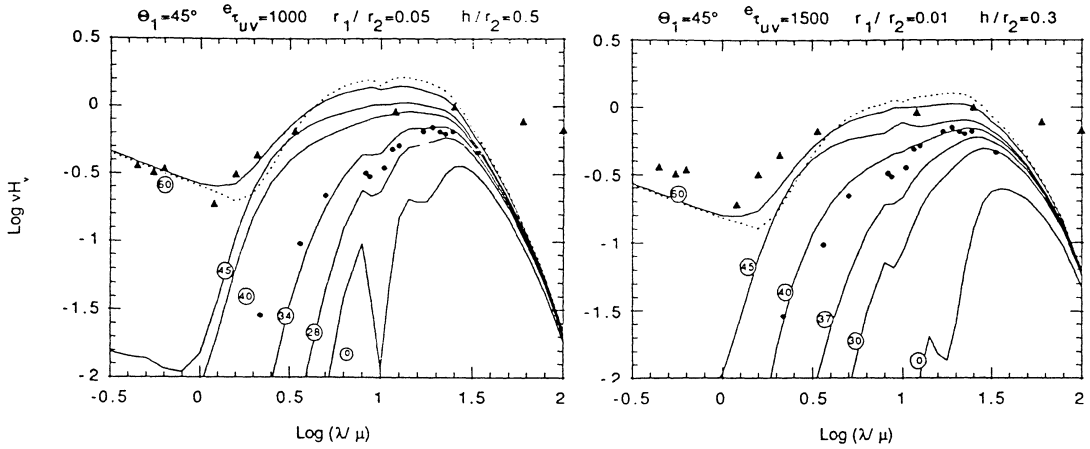

Figure 2. Spectral energy distributions predicted for tapered discs with the parameters shown on the top of each panel. The viewing angle, as measured from the equatorial plane, is indicated on the short wavelength part of each curve.

the outer part of the disc shadows the inner hot disc for almost the whole of the range $\Theta_1 > \theta_v > 0$ and therefore gives narrow spectra peaking in the far-infrared. Compact flared discs on the other hand, although they face less self-shadowing, they have a very narrow range in temperature and therefore also produce narrow spectra, this time peaking in the near-infrared. Clearly, a special kind of disc is needed which is extended but also allows viewing of the inner part of the disc for at least some viewing angles in the range $\Theta_1 > \theta_v > 0$. We propose that a suitable compromise is a tapered disc which we discuss below.

The defining characteristic of a tapered disc is that its thickness, starting with a maximum value of $2h$ in the outer part of the disc, decreases gradually in the inner part of the disc (see figure 1). The half-thickness of the disc as a function of d (measured in units of r_2) is assumed to be $\frac{h}{r_2}\tanh(h_0 d)$, where $h_0 = r_2 \tan(\Theta_1)/h$. The density distribution in the tapered disc is assumed to follow $r^{-\beta}$.

The idea of a tapered disc is also attractive for the following reason: since dust on the top surface of the tapered disc does not see the central source and the walls of the cavity directly, it is appreciably cooler than in a similar flared disc thus making the self-absorption of the $10\mu m$ feature easier. A tapered disc also shows the following crucial difference to the cylinders investigated by Pier & Krolik (1992). Most of the $10\mu m$ emission in the former comes from the part of the disc where its height still increases with d. From face-on views, the $10\mu m$ radiation in the tapered disc therefore has to go through more and colder material on average than a cylinder with the same ${}^e\tau_{uv}$ and Θ_1. It is therefore possible for the $10\mu m$ feature to become self-absorbed with a lower equatorial optical depth. This in turn means that the outer part of the cloud is warmer and the emergent spectra broader. Our choice of β (we favour a value of 1) also plays a very important role in suppressing the $10\mu m$ feature as the vertical optical thickness of an r^{-1} disc in its inner part is higher than that of one

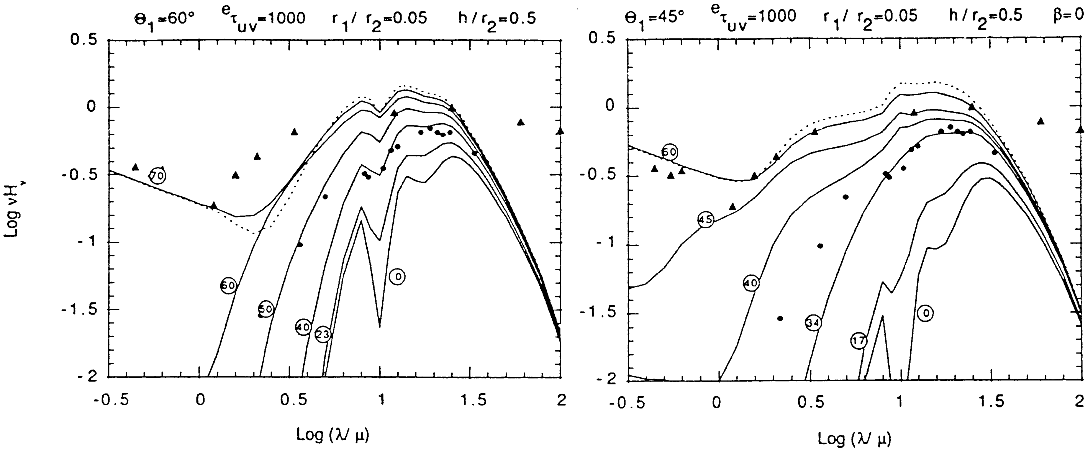

Figure 3. See caption for figure 2.

with uniform density.

3. Tapered disc models

In figures 2 and 3 the SEDs of models that demonstrate some of the properties of the tapered disc are presented. The one that is most readily understood is the general shape of the predicted spectra: more compact models produce spectra most resembling blackbodies as they have a narrower range in dust temperature. Another property of these discs is that, for the same value of r_1/r_2 and ${}^e\tau_{uv}$, models with a small opening angle (30^0) show emission features from face-on views whereas those with $\Theta_1 = 60^0$ show absorption features from *all* viewing angles. It is possible to get featureless face-on spectra with any opening angle by adjusting ${}^e\tau_{uv}$ but note that a higher ${}^e\tau_{uv}$ invariably leads to narrower spectra.

Model 3b demonstrates the reemergence of the $10\mu m$ feature when we run a model with the same parameters as model 2(a) except for β which in this case it is equal to 0. As discussed above, this is due to the fact that for the same ${}^e\tau_{uv}$, a disc with a uniform distribution has a lower ${}^\perp\tau_{uv}$ to the $10\mu m$ emitting region than a model with $\beta = 1$. The model with the best overall agreement with observations is model 2(b) which predicts flat and almost featureless , but also quite broad, spectra for $90 \geq \theta_v \geq 60$.

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