Dereddening of Optical/UV Spectra of Active Galactic Nuclei

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ABSTRACT

The study of the shape of the optical/UV spectrum of an intrinsic nuclear source requires the removal of the effects caused by transmission of the radiation through the dust. There are arguments that the chemical composition of the circumnuclear dust and the distribution of the grain sizes are significantly different from what we know about the interstellar dust. Nonstandard model-dependent extinction curves have to be used. Here we show the dependence of the new extinction curves on model parameters and discuss the consequences of applying nonstandard extinction for the reproduction of intrinsic spectral slopes of active galactic nuclei.

Key words: Galaxies: interstellar matter

1. Introduction

It is widely accepted now that the dust is present at the inner ~ 100 pc of all active galactic nuclei (for a review, see e.g., Barvainis 1992). The location of the dust is not known but it seems most probable that it occupies the space just outside the broad emission line region. It was even suggested recently that the dust is responsible for the presence of a clear gap between the broad and the narrow line region (Netzer and Laor 1993), as in this intermediate zone the dust is the

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most efficient absorber of the available UV/X-ray photons. However, the amount of dust present in the nucleus is highly disputable as the estimates based on the IR reemission, Balmer decrement and reddening of the UV continuum does not seem to give a coherent answer (e.g., Ferland and Osterbrock 1986, Carleton et al. 1987, Dahari and De Robertis 1988a,b). Also the density distribution of the dusty medium is unknown; the lack of strong reddening of broad $H\beta$ lines (Dahari and De Robertis 1988a), recent IR imaging of NGC 1068 (Cameron et al. 1993), and the analysis of rapid changes from Seyfert 1 to Seyfert 2 type in NGC 5548 (Loska, Czerny and Szczercba 1993) indicate that it may be rather clumpy.

In the case of quasars and bright Seyfert 1 galaxies the dust is mostly seen in emission (Sanders et al. 1989) but there are also evidences of the presence of the dust along our line of sight in some objects (apparent reddening of the lines and continuum; for review, see MacAlpine 1985).

This effect is well understood within the frame of unification scheme for AGN (see e.g., Antonucci 1993, Krolik 1992). If the dust is located in a geometrically and optically thick torus, or warps (Phinney 1989), outside the broad line region, then the overall appearance of an active nucleus depends on the inclination angle. At low inclinations we see the unshielded nucleus (including broad emission lines) and the IR spectral component resulting from reemission of significant part of the nuclear flux. At high inclinations we see the dust emission but our view to the nucleus is blocked. Such anisotropic dust distribution therefore accounts for the classification of Seyfert 1/Seyfert 2 galaxies or broad emission line/narrow emission line objects. At intermediate inclinations (Seyfert 1.5 galaxies) the amount of dust along our line of sight is lower so we still see the central source but the spectrum is strongly modified in the result of passage through the dust.

Although the basic picture seems to be correct there are several problems awaiting an explanation. One of them is the weakness or the lack of the $10\,\mu\text{m}$ feature in almost all AGN spectra (Roche et al. 1991) which is expected from emitting dust.

However, the hypothesis of the dust being responsible for the IR emission can be nevertheless accepted if the dust properties at the AGN nucleus are different from what we see in the interstellar medium of our Galaxy (Czerny, Loska and Szczercba 1991, Loska, Szczercba and Czerny 1993 – hereafter LSC, Laor and Draine 1993).

Comparison of dust model predictions and the AGN spectra show that either silicates are strongly suppressed (at least by a factor of five) from their interstellar proportion to graphite grains and/or grains are systematically larger than grains in the interstellar medium. This is not surprising as the circumnuclear dust has to form in a strong UV/X-ray radiation field. Also the efficient formation of CO molecules may cause the deficiency of silicates (e.g., Rawlings and Williams 1989).

These preliminary results indicate that much more careful study of the effect of the dust on the intrinsic spectrum of the nucleus is absolutely crucial. It should take into account the whole range of local dust properties as well as its anisotropic
distribution. Such a full program has not been pursued yet. The proper radiative transfer of IR/opt/UV photons through an axisymmetric (thin or thick) dust cloud has been solved by Efstathiou and Rowan-Robinson (1990) but they made their calculation for a single set of dust parameters only. LSC explored the dust properties but made their calculations for optically thin case (allowing for anisotropy of the intrinsic source, however). Laor and Draine (1993) studied the whole range of dust properties (including X-ray transfer) but in the case of plane-parallel geometry.

However, in the case of an active nucleus observed under the moderate value of the inclination angle the modification of the optical/UV spectrum of an intrinsic nuclear source by dust can be reasonably well estimated without extensive modelling if we use the concept of the extinction curve. The original (i.e., intrinsic) spectrum can be derived through the ’dereddening’ procedure.

The only difference from the usual dereddening is the actual extinction curve used. The reddening of all sources due to the interstellar extinction in our Galaxy is well represented by the single standard extinction curve (Seaton 1979), independent from the distance and direction to the source. In the case of circumnuclear dust in AGN the theory suggests a whole family of extinction curves.

In this paper we explore this family of extinction curves and discuss the consequences of nonstandard dust composition on the retrieved intrinsic nuclear spectra. We also explore the influence of the selective evaporation of dust grains close to the central source. This effect has been neglected in all previous spectra calculations (e.g., Efstathiou and Rowan-Robinson 1990, Pier and Krolik 1992) but it is shown (see Section 3.3) to be important.

2. Method

We assume that the dust within the nucleus is distributed as a continuous medium. As it was shown by Barvainis (1987), introducing clumpy distribution do not change much the transmission properties of the medium for the same optical properties of the dust particles.

To obtain a ’practical extinction curve’ we have to calculate the complete radiative transfer of internal radiation through a cloud of dust surrounding the nucleus. Therefore such a curve depends both on the optical dust properties as well as on the global dust distribution.

The effect is caused by selective evaporation of dust grains close to the nucleus. We assume the equilibrium dust composition, i.e., the relative abundance of silicate and carbon grains as a function of their size, but this equilibrium distribution is reached only outside certain radius determined by the condition of marginal existence for the smallest silicate grain.

In order to show the role of evaporation we study the optical properties of the dust and the evaporation effect separately.
2.1. Extinction Curve without Evaporation

We start from the case of 'theoretical extinction curve', i.e., the extinction calculated straight from the optical properties of the grains for assumed grain distributions.

The extinction efficiency $Q_{\lambda_{\text{ext}}}^i$ and albedo $\eta_{\lambda_{\text{ext}}}^i$ for 21 dust radii between 0.005 and 0.5 μm were calculated (Szczepa 1991; see also LSC) for both silicate and carbon grains ($i = \text{Si, C}$) using the optical data of Draine (1987) and applying Mie scattering theory. Although there are new calculations which extend the optical dust properties to X-rays (Laor and Draine 1993) we did not include them here as we discuss only the optical/UV frequency range, where both sets of coefficients are identical.

For a single grain of type $i$ (Si or C) and size $a$ the absorption cross section is given

$$C_{\lambda_{\text{abs}}}^i(a) = \pi a^2 Q_{\lambda_{\text{ext}}}^i(a)(1 - \eta_{\lambda_{\text{ext}}}^i(a)) \text{ [cm}^2]\) (1)$$

The extinction curve is defined as a ratio of the extinction in magnitudes to the difference in extinction in colors $B$ and $V$ (4400 and 5500 Å). It reduces in this case to the simple relation

$$X_{\lambda}^i = \frac{Q_{\lambda_{\text{ext}}}^i}{Q_{4400,\text{ext}}^i - Q_{5500,\text{ext}}^i}$$ (2)

If the range of the grain sizes is allowed we have to adopt the law of grain distribution. We assume a power law with an index $p$ (usually equal to 3.5)

$$N^i(a) \, da = A^i n_H a^{-p} \, da; \quad a_{\text{min}} \leq a \leq a_{\text{max}}$$ (3)

where $n_H$ is the hydrogen density and $A^i$ gives the overall abundances of the two grain components assuming the dust to gas ratio 0.005.

The opacity coefficient is given as

$$\alpha_{\lambda_{\text{ext}}} = \sum_{i=\text{Si,C}} \int_{a_{\text{min}}}^{a_{\text{max}}} C_{\lambda_{\text{ext}}}^i(a) N^i(a) \, da$$ (4)

and the extinction curve can be calculated

$$X_{\lambda} = \frac{\alpha_{\lambda_{\text{ext}}}}{\alpha_{4400,\text{ext}} - \alpha_{5500,\text{ext}}}$$ (5)

2.2. Evaporation Zone

Extinction curves described in Section 2.1. do not take into account the effect of radial dependence of grain population which in fact is expected in the strong radiation field of the central source. Therefore we consider also the case of more self-consistent model of size distribution of grains in the circumnuclear dust. It
requires the calculation of the dust grain temperature as a function of radial distance, for an assumed spectrum and luminosity of the central flux.

For that purpose we use a model of a central source which consists of an accretion disk surrounding a supermassive black hole and an IR/optical/UV power law. Such a model well represents the overall AGN spectrum in this frequency range. We assume that this central source is surrounded by a spherical optically thin dust cloud and we calculate the temperature distribution of the dust as in LSC. This procedure provides us with the evaporation radius for each type of grain. The result is not particularly sensitive to the shape of the radiation spectrum and geometry, and scales with the total bolometric luminosity $L_{\text{bol}}$ as $L_{\text{bol}}^{1/2}$. The *a priori* assumed grain population is then corrected taking into account the evaporation which selectively removes grains close to the source. Therefore the evaporation modifies the lower limit in the integral in Eq. (4) in a way dependent on the radial distance from the source. Having the grain population calculated at every radius we have to integrate the opacity coefficient to calculate the total optical depth at a given wavelength $\tau_{\lambda,\text{ext}}$.

The extinction curve is now calculated as

$$X_{\lambda} = \frac{\tau_{\lambda,\text{ext}}}{\tau_{4400,\text{ext}} - \tau_{5500,\text{ext}}}$$

(6)

New extinction curves depend both on the equilibrium (uncorrected) distribution and dust cloud parameters (the radial density profile and its outer radius).

3. Results

3.1. Optical Properties of Single-Size Grains

Usually the properties of single size grains are presented as an absorption and scattering coefficients, as this is the quantity calculated from the theory and used to solve the radiation transfer equation. However, we systematically follow the idea of the extinction curve even in this case since it allows us to show more clearly the observational consequences of nonstandard extinction.

We calculate two families of extinction curves following Eq. (2) parametrized by the single size of the grain particle.

The results for silicate grains are shown in Fig. 1. We have used logarithmic scales as the extinction varies by a few orders of magnitude. The differences between the curves are huge indeed. The smallest grain ($a = 0.005 \, \mu m$) absorbs UV photons a few hundred times more efficiently than the biggest one presented ($a = 0.5 \, \mu m$). The smallest grains also strongly differentiate between the optical and UV photons as the size of the grain is larger than the wavelength of EUV photons but smaller than the wavelength of an optical/UV photon. The large grain has the size comparable to the wavelength of IR photons and therefore for any optical/UV/EUV photon it reacts in almost the same way; the extinction curve is
Fig. 1. Extinction curves $X_\lambda$ vs. $1/\lambda$ for single size silicate grains. Different curves correspond to different grain size given in microns. Standard Seaton extinction curve (thick solid line) is shown for comparison.

Fig. 2. Extinction curves $X_\lambda$ vs. $1/\lambda$ for single size carbon grains. Different curves correspond to different grain size given in microns. Standard Seaton extinction curve (thick solid line) is shown for comparison.

The results for carbon grains are shown in Fig. 2. Carbon grains are generally not such good absorbers and the extinction is lower. Small grains show a distinct feature at 2200 Å (the same as seen in observational Seaton curve) and another broader peak at about 800 Å. Larger grains ($a = 0.05 \mu m$) are characterized by a
very flat extinction. For still larger grains the extinction is negative! Of course it does not mean that the absorption or scattering coefficient becomes negative. It only reflects the change of sign in $E(B - V)$ term. Large grains remove optical photons of shorter wavelength less efficiently. If the circumnuclear dust in AGN consisted of large graphite grains only it would show the change of Balmer decrement in the opposite direction as expected. This behavior was never observed (e.g., MacAlpine 1985). However, the discussion shows clearly that if the number of large graphite grains is larger than in the interstellar medium we may determine the reddening from Balmer decrement systematically too low with respect to the amount of gas along our line of sight.

3.2. Extinction Curve for a Range of Sizes

In the astrophysical situation we expect a whole range of grain sizes. Therefore in the next few figures we show extinction curves calculated assuming the increasing range of grain sizes and $p = 3.5$ (see Eq. (3)). Fig. 3 is pure silicate dust and Fig. 4a is for pure carbon grains. The expanded plot (Fig. 4b) clearly shows the difference between the observational Seaton curve and pure carbon extinction. If only small grains are present the 2200 Å feature is very narrow; if the range of grain sizes is sufficiently large the feature becomes as shallow as in the Seaton curve but it remains symmetric whilst the extinction in the interstellar dust in our Galaxy is clearly more efficient on the short wavelength side of 2200 Å peak. The difference is by a factor 2.

The sensitivity of the results on the adopted value of index $p$ in the power law size distribution we show in the case of carbon extinction curves with the same size range but $p = 3.0, 3.5$ and 4.0, respectively (Fig. 5).
Fig. 4. (a) Extinction curves for pure carbon dust and a power law distribution of grain sizes ($n \sim a^{-p}, p = 3.5$). Different curves correspond to different upper limit for the grain size given in microns. Standard Seaton extinction curve (thick solid line) is also shown. (b) Expanded version of Fig. 4a.

The consequences of mixing of both silicate and graphite grains are shown in Fig. 6. The size ranges and the parameter $p$ are assumed to be the same for both populations and Si/C ratio measures the weight proportion of the silicate to carbon grains. The value Si/C = 1.13 gives the extinction curve relatively similar to the Seaton curve; enhancement or depletion of the silicate population results in smearing out or strengthening of the 2200 Å feature.
Fig. 5. Extinction curves for pure carbon dust and three values of the power law index in grain size distribution \((n \sim a^{-p}, \ p = 3, 3.5, 4)\). Standard Seaton extinction curve (thick solid line) is shown for comparison.

### 3.3. Partial Evaporation Zone

Arbitrarily assumed dust composition can only exist far enough from the central source. Closer to the nucleus dust grains achieve the evaporation temperature and cannot form. The precise value of the temperature is difficult to determine but the values usually quoted are between 1200 K and 1700 K for carbon grains and depend on the grain structure, i.e., whether this is a crystalline graphite or amorphous carbon grain. The evaporation temperature for the silicate grains is lower. In this paper, as in LSC, we assume the evaporation temperature equal 1500 K and 1000 K, for carbon and silicate grains, respectively.

The temperature of a single grain depends on its optical properties. The absorption crosssection is a function of grain size. Therefore the minimum distance where the grain can form depends on its size. An example of such relation for a particular central source (bolometric luminosity \(9.57 \times 10^{45} \text{ erg/s}\)) is shown in Fig. 7. Here the partial evaporation zone extends between 0.3 pc and 8 pc, with empty cavity inside and assumed full grain population reached outside the zone.

We study the role of the existence of this partial evaporation zone in one particular example of a dust cloud extending up to 300 pc with the gas density \(n_H = 35\) at the distance of 0.1 pc, dust to gas ratio 0.005 and the radial power law dependence of the gas density parametrized by \(\beta (n \sim r^{-\beta})\). We assume that the dust consists of carbon grains only; other parameters are the same as for carbon curve in Fig. 6.

In Fig. 8a we show the dependence of the extinction curve on \(\beta\) taking into account only the transmission through the part of the cloud outside the partial evaporation zone. As expected, the extinction curve calculated from Eq. (6) in that
Fig. 6. (a) Extinction curves for a mixture of silicate and carbon grains. The range of sizes for both the silicate and carbon grains is from 0.005 $\mu$m to 0.25 $\mu$m, with the distribution parametrized by power law index $p = 3.5$. Different curves correspond to different relative weight of silicate to carbon dust. Standard Seaton extinction curve (thick solid line) is shown for comparison.
(b) Expanded version of Fig. 6a.

case do not contain any traces of the dust distribution parameters. However, the extinction calculated from the transmission through the partial evaporation zone (Fig. 8b) clearly shows strong dependence on $\beta$ as the different density distribution combined with the selective evaporation results in different size distribution of grains integrated along the line of sight. Although this zone extends only up to 8 pc and the cloud up to 300 pc the contribution of the zone to the extinction is
Fig. 7. The evaporation radius for silicate and carbon grains as a function of grain size. The luminosity of the central source is $9.57 \times 10^{45}$ erg/s.

significant as we can see from the extinction curves calculated for the entire cloud (inner and outer zone) and shown in Fig. 8c. Although the dependence on $\beta$ is somewhat weaker than for the inner zone itself it is still clearly visible if the gas density profile is steep ($\beta \geq 1.2$).

The significance of partial evaporation is also illustrated in Table 1. If the density gradient is high, the ratio of extinction correction $E/(B - V)$ to the hydrogen column density is in these models reduced almost by an order of magnitude with respect to the asymptotic value.

**Table 1**
The reddening of the central source $E/(B - V)$ as a function of the power law index $\beta$ in the radial dependence of the density ($n \sim r^{-\beta}$) in the surrounding dust cloud of graphite grains. Grain evaporation causes the relative decrease in opacity. Therefore our mean $E/(B - V)$ to $N_\text{H}$ ratio is usually much lower than the value $1.72E - 22$ adopted for the interstellar medium (Bohlin 1978).

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$E/(B - V)$</th>
<th>$N_\text{H}$</th>
<th>$E/(B - V)/N_\text{H}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>5.64E+0</td>
<td>3.24E+22</td>
<td>1.74E-22</td>
</tr>
<tr>
<td>0.2</td>
<td>1.57E+0</td>
<td>8.15E+21</td>
<td>1.92E-22</td>
</tr>
<tr>
<td>0.4</td>
<td>4.55E-1</td>
<td>2.18E+21</td>
<td>2.09E-22</td>
</tr>
<tr>
<td>0.6</td>
<td>1.34E-1</td>
<td>6.37E+20</td>
<td>2.11E-22</td>
</tr>
<tr>
<td>0.8</td>
<td>4.30E-2</td>
<td>2.14E+20</td>
<td>2.01E-22</td>
</tr>
<tr>
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<td>8.65E+19</td>
<td>1.74E-22</td>
</tr>
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<td>4.31E+19</td>
<td>1.34E-22</td>
</tr>
<tr>
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<td>2.59E+19</td>
<td>9.39E-23</td>
</tr>
<tr>
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<td>6.17E-23</td>
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<td>2.62E-4</td>
<td>1.08E+19</td>
<td>2.43E-23</td>
</tr>
</tbody>
</table>
Fig. 8. (a) The extinction curve outside the partial evaporation zone for pure carbon dust with the range of grain sizes $0.005 - 0.25 \mu m$ and power law index of the grain size distribution $p = 3.5$. The extinction curve there does not depend on the gas density profile in the absorbing cloud.

(b) The extinction curves for the partial evaporation zone only derived from the optical depth (see Eq. 5) measured from the inner dustless region up to the radius of existence of whole grain sizes population as assumed for Fig. 8a. Extinction depends significantly on the power law index $\beta$ characterizing the gas density profile inside the dust cloud.

(c) The extinction curves for a whole cloud (i.e., partial evaporation zone and outer region) calculated for a cloud extended up to 300 pc, with the gas density $n_{\text{H}} = 35 \text{ cm}^{-3}$ at 0.1 pc and dust to gas ratio $d/g = 0.005$. Curves are parametrized by the power law index $\beta$ characterizing the gas density profile inside the dust cloud.
4. Discussion

The variety of extinction curves \textit{a priori} applicable to circumnuclear dust in AGN is considerable. The shape is different for pure silicate and pure carbon grains so the extinction depends on the silicate to carbon ratio. Typical value for this ratio taken from the studies of the interstellar medium (1.13; Mathis, Rumpl and Nordsieck 1977) leads to prediction of the fairly strong 10 \(\mu\)m feature in emission (see \textit{e.g.,} LSC, Laor and Draine 1993) as well as strong 2200 \(\AA\) feature in absorption. Lowering this ratio results in required decrease in 10 \(\mu\)m emission feature but at the same time leads to more profound and symmetric 2200 \(\AA\) absorption so the amount of reddening around 1500 \(\AA\) becomes relatively smaller by some 30%. The analysis of the optical/UV continuum in NGC 6814 indicates that in fact such an extinction curve shape leads to simpler interpretation of the intrinsic continuum (Czerny \textit{et al.} 1993) although this conclusion is not strong. The possible presence of other types of grains (\textit{e.g.,} SiC, Laor and Draine 1993) may again complicate the picture.

The dependence of the extinction curve on the grain size within a given species is even stronger and in the case of carbon grains leads to qualitative differences. Large carbon grains do not exhibit any 2200 \(\AA\) feature in their extinction coefficient. Therefore the transmission of radiation through the dust cloud consisting of predominantly large carbon grains gives smooth UV spectrum, negative \(E(B-V)\) extinction and the IR reemission shifted towards longer wavelengths (see Fig. 6 of LSC).

Since the grain formation process is very complex and strongly depends on the local conditions (density of the medium and radiation flux from the central parts) which in turn equally strongly depend on the assumption whether the medium is continuous or clumpy, the theory can only provide us with the range of possibilities and the AGN spectra analysis has to give the answer to the question which of the numerous possibilities is actually correct for a given object.

The absorbing matter along our line of sight causes the number of effects: (i) absorption of soft X-rays (ii) reddening of opt/UV continuum (iii) reddening of optical and UV emission lines, including Balmer series (iv) reemission of radiation in IR. In principle, all of these effects inform us about the amount of dust involved. However, the discussion is complicated by two basic factors: 1. the gas properties along the line of sight change with the distance from the central source 2. the transmitted component of the intrinsic source may actually be contaminated by a reflected component even in Seyfert 1.5 galaxies.

The gas column density \(N_{\text{H}}\) value derived from fits to soft X-ray data from EXOSAT and ROSAT gives values in excess to Galactic value of order \(10^{21}\) or lower in case of bright Seyfert 1 galaxies (\textit{e.g.,} Turner and Pounds 1989, Turner, George and Mushotzky 1993, Walter and Fink 1993) which would cause the dust reddening by \(A_V\) equal 0.7 (\(E(B-V) = 0.2\)) or less in the case of interstellar medium. X-ray column densities are higher for Seyfert 1.5 objects (\textit{e.g.,} \(\sim 3 \times 10^{22}\))
for NGC 6814, Kunieda et al. 1990; a few $10^{22}$ for NGC 5548, Nandra et al. 1991). For Seyfert 2 galaxies the range $10^{22} - 10^{24}$ was found by Mulchaey, Mushotzky and Weaver (1992). The extinction implied by this is enormous – $A_V$ of order 70 whilst the amount of reddening derived from emission lines (Dahari and De Robertis 1988a) was rather 1.6. Clearly, most of the soft X-ray absorption comes from the dustless gas very close to the nucleus (as suggested by $N_H$ variations) and possibly partially ionized (see e.g., Mushotzky, Done and Pounds 1993).

5. Conclusions

In the case of determination of the extinction towards any particular star usually a number of methods are used to obtain a reliable result (see e.g., Kenyon et al. 1991). The same is even more important in the case of circumnuclear extinction in active galactic nuclei as the theory provides us with much a variety of possible extinction curves and only the comparison of the influence of the dust on different parts of the intrinsic spectra may give us the answer about the extinction curve to be used.

Also, in principle, extinction may differ from one AGN to another. However, the shape of the intrinsic spectrum of the nucleus is fairly universal and parametrized only by the Big Bump to X-ray luminosity ratio (Walter and Fink 1993). Therefore, the environment for the dust formation may be either universal, if mostly dominated by X-rays, or correlated with the strength of the Big Bump, if dominated by UV and EUV, which may lead to some pattern in the circumnuclear dust properties.

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