Nanodiamond dust and the far-ultraviolet quasar break

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ABSTRACT

We explore the possibility that the steepening observed shortward of 1000 Å in the energy distribution of quasars may result from absorption by dust, being either intrinsic to the quasar environment or intergalactic. We find that a dust extinction curve consisting of nanodiamonds, composed of terrestrial cubic diamonds or with surface impurities as found in carbonaceous chondrite meteorites, such as Allende, is successful in reproducing the sharp break observed. The intergalactic dust model is partially successful in explaining the shape of the composite energy distribution, but must be discarded in the end, as the amount of crystalline dust required is unreasonable and would imply an improbable fine tuning among the dust formation processes. The alternative intrinsic dust model requires a mixture of both cubic diamonds and Allende nanodiamonds and provide a better fit of the UV break. The gas column densities implied are of the order \(10^{20}\) cm\(^{-2}\), assuming solar metallicity for carbon and full depletion of carbon into dust. The absorption only occurs in the ultraviolet and is totally negligible in the visible. The minimum dust mass required is of the order \(~ 0.003r^2_{pc}M_{\odot}\) where \(r_{pc}\) is the distance in parsec between the dust screen and the continuum source. The intrinsic dust model reproduces the flux rise observed around 660 Å in key quasar spectra quite well. We present indirect evidence of a shallow continuum break near 670 Å (18.5 eV), which would be intrinsic to the quasar continuum.

Subject headings: galaxies: intergalactic medium — large-scale structure of universe — galaxies: active — radiative transfer — ultraviolet: general

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1. Introduction

The spectral energy distribution (SED) of active galactic nuclei (AGN) contains a significant feature in the optical-ultraviolet (UV) region, known as “the big blue bump”. As for the emission lines in AGN spectra, it is generally believed that photoionization is the excitation mechanism of the emission lines superimposed to the continuum. Photoionization calculations that reproduce the AGN line ratios and equivalent widths favor an ionizing SED that peaks (in \( \nu F_\nu \)) in the extreme-UV (e.g. Mathews & Ferland 1987; Binette et al. 1988; Ferland et al. 1996; Korista, Ferland & Baldwin 1997). Satellite observations of distant quasars, however, showed that the big blue bump peaks in \( \nu F_\nu \) around \( \gtrsim 1000 \) Å (\( \lambda_{\text{rest}} \)). This finding is best illustrated by the composite quasar SED constructed by Telfer et al. (2002) (hereafter TZ02), which was obtained by co-adding 332 HST-FOS archived spectra of 184 quasars with redshifts between 0.33 and 3.6. The composite (reproduced in Fig. 15 of § 5) is characterized by a mean near-UV index \( \alpha_\nu \) of \(-0.69 \) (\( F_\nu \propto \nu^{\alpha_\nu} \)), steepening to \( \simeq -1.76 \pm 0.12 \) in the far-UV. The favored interpretation by TZ02, Zheng et al. (1997), and Shang et al. (2004) is that the observed continuum steepening is intrinsic to quasars. Intriguingly, using archived data from FUSE, whose sensitivity window extends further in the UV, Scott et al. (2004) performed a similar compilation for ‘nearby’ active galactic nuclei (AGN) with redshifts \( z_q < 0.7 \) and report the lack of any evidence of a steepening in the far-UV! Furthermore, the FUSE composite spectrum for nearby AGN is significantly harder than that of Telfer et al. (2002), with \( \alpha_\nu \simeq -0.56^{+0.38}_{-0.28} \) in the far-UV. Arguably, since nearby AGN are on average less luminous, they may possess an intrinsically different SED. However, a detailed optical-UV study of a subset of the FUSE sample by Shang et al. (2004) fails to reveal any correlation between the far-UV index and blackhole mass. Therefore, even though the HST-FOS and FUSE samples do not represent equivalent AGN populations, the absence of steepening in the far-UV for the nearby sample cannot be explained alone by difference in AGN populations. A plausible explanation for the onset and increasing importance of the break in distant AGN can be provided by intergalactic absorption, since it would scale with distance. In an earlier paper, Binette et al. (2003) explored the possibility that the break might be the result of H\textsc{i} scattering by a tenuous intergalactic component that the authors associated with the warm-hot intergalactic medium. The models, however, predicted a significant flux discontinuity in the region 1050–1190 Å (\( \lambda_{\text{obs}} \)), which is not observed in quasar spectra, as shown by FUSE (e.g. Kriss et al. 2001). Furthermore, the warm-hot intergalactic medium is too ionized to produce the amount of H\textsc{i} absorption needed to reproduce the break. In this Paper, we explore an alternative interpretation that is based on a different opacity vector,
namely dust, either intrinsic to the quasar environment or intergalactic. The vector responsible for the absorption will consist of grains made of carbon atoms, a major constituent of the interstellar medium dust, albeit here in crystalline form (nanodiamonds). We will assume that the intrinsic quasar SED consists of a simple powerlaw, and that deviations from the powerlaw are caused by absorption from crystalline carbon dust, either as pure cubic diamonds, or of the type observed in carbonaceous chondrite meteorites (e.g. Allende, Orgueil and Murchison). Many mechanisms have been proposed to explain the formation of diamond nanocrystallites (c.f. §7). About half of them require intense UV irradiation. Interestingly, a significant UV flux is present in the two Herbig Ae/Be objects, for which nanodiamond emission bands have been confirmed first (Van Kerckhoven et al. 2002). Processes that form nanodiamonds by UV irradiation are particularly relevant, since quasars are UV powerhouses and their environment might lead to physical conditions that favor the emergence of carbon-based nanocrystallite grains.

The paper is structured as follows: following the introduction in §1, we describe in §2 the dust models and the algorithm used to compute the transmission function. The methodology and classification of the spectra are described in §3. In §4 and §5, we present the intrinsic and intergalactic dust absorption models, respectively, and compare them with the observed spectra. In §6 we decide, which of the two models, is to be preferred, and we discuss a possible final model. In §7 we focus on the formation and physical properties of nanodiamonds, and follow with the conclusions in §8.

2. Procedure and calculations

2.1. Dust extinction curves

In order to account for the sharp SED break by way of dust absorption, we looked for an absorption vector that peaks in the far-UV (λ < 1000 Å), and yet causes negligible absorption at wavelengths longer than 1200 Å. Ideally, as it is the case with the interstellar medium (ISM) dust, the grain particles should be composed of the most abundant elements. In both aspects, the crystalline form of carbon is the most appealing candidate and is the basis of this Paper. We will consider two types of materials: the terrestrial cubic (pure) diamonds and the nanodiamonds as found in meteorites.

A comparison of the UV extinction properties of the terrestrial diamonds and the meteoritic nanodiamonds can be found in Mutschke et al. (2004). The authors separated the nanodiamonds from the Allende\textsuperscript{2} meteorite sample and determined their optical constants. The meteoritic nanodiamonds differ in their optical properties from the cubic diamond as a result of chemical impurities (e.g. H, N) and of restructured or unsaturated bonds at their surface.

Following a standard procedure, we calculated a set of dust extinction curves. We

\textsuperscript{2}Carbonaceous chondrite meteorites are relatively rare, at a frequency of only \(\sim 3.5\%\). The Allende meteorite who fell on Earth near the town of Allende in the state of Chihuahua, México, on February 8th, 1969, is one of the most studied meteorites of its kind.
assumed that the grains are spherical and that a powerlaw describes the differential distribution of grain sizes, \( dn_{gr}(a)/da = C_{gr}n_H a^\zeta \), where \( n_{gr} \) is the volume density of grains, \( n_H \) that of hydrogen, \( a \) the grain radius, \( \zeta \) the powerlaw\(^3\) index and \( C_{gr} \) the normalization constant, such that the density of grains becomes normalized to the abundance of the dust constituents with respect to hydrogen. We adopted the tabulated complex refraction indices \( n + ik \) of Mutschke et al. (2004) for the Allende meteorite nanodiamonds, and of Edwards & Philipp (1985) for the cubic (terrestrial) nanodiamonds. The Mie theory was used to compute the extinction cross-section \( Q_{ext}(a, \lambda, n, k) \), using a modified version of the published subroutine BHMIE of Bohren & Huffman (1983). The extinction cross-section is normalized with respect to the gas density \( n_H \), using the following integrals:

\[
\begin{align*}
n_H \sigma_H^L &= n_H C_{gr} \int_{a_{min}}^{a_{max}} \pi a^{3+\zeta} Q_{ext}(a, \lambda, n, k) \, da \\
V_{gr} &= \frac{4}{3} \int_{a_{min}}^{a_{max}} \pi a^{4+\zeta} \, da
\end{align*}
\]

where \( a_{min} \) and \( a_{max} \) are the minimum and maximum values of the grain radii considered. The gas opacity is given by the integration of \( d\tau_{ext} = n_H \sigma_H^L dr \). Neglecting the contribution of elements other than carbon to the composition of the nanodiamonds, we adopt a mean molecular weight of \( \mu_{gr} = 12 \) for the grains. The value of the normalization constant \( C_{gr} \) is obtained by solving the following:

\[
Z_C \mu_{gr} m_H = \rho_{gr} C_{gr} V_{gr}
\]

where \( Z_C \) is the carbon abundance by number with respect to H, \( m_H \) the hydrogen atom mass and \( \rho_{gr} \) the density of the grain material. The values adopted for \( \rho_{gr} \) are 2.3 (Lewis et al. 1989) and 3.51 g cm\(^{-3}\), for the Allende and the cubic nanodiamonds, respectively. For the grain size exponent, we adopted \( \zeta = -3.5 \). As we neither know the gas metallicity nor the dust-to-gas mass ratio, we assume all carbon is locked in dust and we adopt the solar value of \( 3.63 \times 10^{-4} \) for the C abundance, for the sole purpose of procuring a convenient normalization.

The continuous lines in Fig. 1, represent the extinction curves adopted in this Paper. The curves labeled D1 and A1 represent the “small size regime” extinction curves for terrestrial diamonds (red curve) and for meteoritic nanodiamonds (blue curve), respectively. In both extinction models, \( a_{min} = 3 \text{ Å} \) and \( a_{max} = 25 \text{ Å} \). In this regime, decreasing further \( a_{max} \) would not alter the extinction curve. Our extinction curve A1 (blue line) is very similar in shape to the mass absorption coefficient curve determined by Mutschke et al. (2004) (see their Fig. 7 or our scaled version of it, the green dotted curve in Fig. 1). A third dust model, which is also useful, is the Allende curve labeled A3 (orange curve), whose grain sizes extend up to 200 Å. The

\(^3\)A log-normal distribution is more appropriate (Lewis et al. 1989) for describing the nanodiamond size distribution. However, because we intended to explore a much broader size range than that found in Allende, we considered it more convenient to use a powerlaw for this purpose. The reason is that only one parameter needs to be varied (\( a_{max} \)), while in the case of the log-normal distribution, we would need to vary two parameters simultaneously (the mean size value and the distribution’s width).

\(^4\)The extinction cross-section for cubic diamonds were extrapolated in the far-UV, since we could not find published laboratory values of the refraction indices shortward of 413 Å.
peak cross-sections for the curves D1, A1 and A3, occur at wavelengths 640, 741 and 787 Å, respectively. Meteoritic nanodiamonds are known to possess a median radius \( \bar{a} \) of \( \sim 15 \) Å. When increasing \( a_{\text{max}} \) to a value of \( \sim 50 \) (75) Å for the Allende (terrestrial cubic) nanodiamonds (respectively), one finds that the peak absorption starts shifting noticeably to the right and the absorption profile widens somewhat. This is illustrated by the two long-dashed line curves in Fig. 1, both calculated with \( a_{\text{max}} = 100 \) Å. The above mentioned curve A3 further extends the grain size range to \( a_{\text{max}} = 200 \) Å, which significantly shifts the broad absorption peak toward longer wavelengths.

As shown in § 4, the extinction curves D1 and A1 (or A3 in § 5) can reproduce the wide range of continuum steepening observed in the far-UV in quasar SEDs. Both types can induce a sharp absorption break, although the cubic diamond is more extreme in this respect. This does not occur with ISM dust extinction. For comparison, we plot an ISM dust model from Martin & Rouleau (1991) (with \( \zeta = -3.5 \)) in Fig. 1, which consists of silicate and graphite grains of sizes comprised between \( a_{\text{max}} = 2500 \) Å and \( a_{\text{min}} = 50 \) Å (black short-dashed line). It is evident that the customary ISM extinction curve, while reaching a maximum in the UV, still absorbs significantly longward of the peak, which gives rise to a shallow change of index, rather than a sharp break. Grain size is not the main cause for such differences in relation to nanodiamonds, but rather the type of material being considered. To illustrate this, we show a small grains extinction curve used by Binette, Magris & Martin (1993) to study the scattered continuum of Pks2152−69; it has the same composition as the ISM model, but the size range is reduced to \( a_{\text{max}} = 500 \) Å (black dotted line in Fig. 1). The cross-section redward of the extinction peak remains too shallow to reproduce the sharp break of quasars. Shang et al. (2004) explored the possibility that the standard ISM or even a SMC-like extinction curve could reproduce the QSO break. Their conclusions is that reddening by ISM or SMC-like grains “is not able to produce the spectral break seen in the AGN sample, without leaving a clear signature at longer wavelengths” (which usually is not seen). Notice that the cubic diamond curve shows a rather narrow peak at \( \sim 650 \) Å followed by a lower plateau at \( \sim 500 \) Å. These particularities of the cubic diamond cross-section, together with the very steep rise shortward of 1000 Å are unique features, which should leave a clear imprint, whenever this material is responsible for the extinction. The extinction at optical wavelengths due to nanodiamonds is negligible. For instance, with an opacity of unity at 912 Å, the extinction in the V band (\( \lambda_{\text{rest}} \)) is as small as \( A_V = 10^{-4} \) and \( 5 \times 10^{-7} \) mag in the case of the A1 and D1 curves, respectively.

The extinction curves D1 and A1 (or A3) as defined above will suffice to test the dust absorption hypothesis. Instead of using optically known materials, one could have treated the absorption hypothesis as an inverse problem, working out the extinction curve that succeeds best. Considering that the current study is mostly exploratory in nature, we consider that it confers a higher degree of plausibility to use an empirical curve such as that of the
Allende meteorite, rather than an invented cross-section.

2.2. Calculation of the transmission curve

The basic assumption behind the current work is that the break observed in the spectra is a manifestation of dust absorption and is therefore not an intrinsic feature of the SED. A key aspect in evaluating how well the dust absorption hypothesis fares is to assume that we can extrapolate the powerlaw observed in the near-UV to the region underlying the break. Any departure of the observed spectrum from the extrapolated powerlaw will be modeled as “absorption”. Only in §6.3 will a broken powerlaw be considered for the far-UV. In our notation, the “true” or intrinsic quasar SED is described by either one of the expressions:

\[ F^q_\nu = A \left( \frac{\nu}{\nu_0} \right)^{\alpha_\nu}, \text{ or} \]
\[ F^q_\lambda = B \left( \frac{\lambda}{\lambda_0} \right)^{\beta_\lambda} = B \left( \frac{\lambda}{\lambda_0} \right)^{-(2+\alpha_\nu)}, \]

where \( \nu_0 \) and \( \lambda_0 \) (=912 Å) are the ionization thresholds of hydrogen in frequency and in wavelength units, respectively, while \( \alpha_\nu \) and \( \beta_\lambda \) are the corresponding powerlaw indices. \( A \) and \( B \) are normalization constants, one of which is set to unity according to whether \( F^q_\nu \) (i.e. \( A \)) or \( F^q_\lambda \) (i.e. \( B \)) is plotted (respectively). In keeping with the tradition in AGN literature, the index that we quote in the text will always be \( \alpha_\nu \). In par with the work of TZ02 and Zheng et al. (1997), we prefer to plot \( F_\lambda(\lambda) \) for most figures. The far-UV region beyond the break is better represented using \( F_\lambda \) than \( F_\nu \), as can be appreciated by comparing panels a and b of Fig. 2.

2.2.1. Intrinsic dust absorption

The (modeled) transmitted flux in the one-dimension case is given by \( F^{\text{mod}}_\lambda = T_\lambda F^q_\lambda \), where \( T_\lambda \) is the transmission function, which for a point source is simply the exponential \( e^{-\tau_{\text{ext}}^\lambda} \). To compute the opacity \( \tau_{\text{ext}}^\lambda = N_H \sigma_H^\lambda \) in the case of dust at the redshift of the quasar, all that is required is to specify the absorption column \( N_H \) and select one, or a combination, of the extinction curves described in §2.1.

2.2.2. Intergalactic dust and the simulation of the composite spectrum

If the dust is intergalactic, it is necessary to integrate the transmission along the line-of-sight to the quasar. Because we also intend to simulate the process of constructing a composite spectrum from synthetic quasar SEDs, we developed the following numerical procedure. Briefly, the simulation of the composite will consist in multiplying each synthetic quasar spectra by the appropriate transmission function and then co-add them in the quasar rest-frame. The synthetic spectra, before dust absorption, share the exact same SED, but differ in redshift and in spectral coverage. In the simulation, we adopted the same set of quasar redshifts as those in the TZ02 sample as well as the same set of wavelength limits, for the synthetic spectra, as those characterizing the TZ02 archived spectra. Each synthetic spectrum corresponding to a given quasar at redshift \( z_q \) is divided into energy bins, and for each rest-frame bin \( \lambda_j \), we calculate the (modeled) transmitted flux \( F^{\text{mod}}_{\lambda_j} = F^q_{\lambda_j} T_{\lambda_j} = F^q_{\lambda_j} e^{-\tau(\lambda_j)} \) making use of the integrated
opacity along the line-of-sight up to $z_q$:

$$
\tau(\lambda_j) = \int_{0}^{z_q} n_H(z) \sigma^H_{\lambda}(1+z) \frac{dl}{dz} \, dz
$$

where $\sigma^H_{\lambda}$ is the dust extinction cross-section evaluated at wavelength $\lambda_j/(1+z)$, and $n_H(z)$ the intergalactic dust density expressed in terms of the hydrogen density.

For the calculations of distances, $\frac{dl}{dz}$ and baryonic densities, we assume the concordance $\Lambda$CDM cosmology with parameters derived from the WMAP experiment (Spergel et al. 2003), that is $\Omega_\Lambda = 0.73$, $\Omega_M = 0.27$, $h = 0.71$ with $h = H_0/100$ and a baryonic mass of $\Omega_{\text{bar}}h^2 = 0.0224$ corresponding to an hydrogen density at zero redshift of $n_{\text{bar}}^0 = 2.06 \times 10^{-7} \, \text{cm}^{-3}$.

3. Methodology

3.1. The initial database

The spectral database adopted in this work is that of TZ02, which was kindly lent to us by R. C. Telfer. It comprises 332 spectra, mostly HST-FOS, of 184 quasars, already reduced and corrected for Galactic dust extinction. The spectra furthermore have been corrected by TZ02 for the presence of Lyman limit absorbers (down to $\tau > 0.3$) as well as of the Ly$\alpha$ absorption valley (caused by the cumulated absorption from unresolved Ly$\alpha$ forest lines).

3.2. Near and far-UV spectral indices

We define the far-UV as the wavelength region shortward of the break from 300–1000 Å, the near-UV as the 1000 to 3200 Å region longward of the break, and the optical-UV as the 3200–4200 Å region.

Throughout this Paper, we will refer to the powerlaw index longward of the break as $\alpha_{\text{NUV}}$, and that shortward as $\alpha_{\text{FUV}}$. We will assume that the intrinsic SED powerlaw index, $\alpha_{\nu}$, has the same value in the region of the break as in the near-UV, hence $\alpha_{\nu} = \alpha_{\text{NUV}}$. Whenever possible, the adopted value for $\alpha_{\text{NUV}}$ will be the value that we estimate empirically, using the adjacent near-UV region of the HST-FOS spectrum. This value is to be preferred over published values, which correspond to a forced fit of the combined optical-UV region. The HST-FOS $\alpha_{\text{NUV}}$ indices are usually significantly harder. They are more appropriate for the exercise at hand, which relies on having a dependable SED description immediately longward of the break that can be extrapolated one octave shortward, in the region of the break itself.

3.3. Pre-analysis of the HST-FOS sample

Following a preliminary analysis of the TZ02 sample and of the properties of dust models, we established the following. (I)—Individual quasar spectra provide stronger constraints to the models than a single composite spectrum. The process of co-adding varied spectra to construct the composite inevitably lead to a loss of valuable information. Modeling the composite spectrum is probably an essential exercise, but does not constitute a determinant proof of the validity of any model. For these reasons, we concentrate here on fitting individual quasar SED. (II)—Since combined multigrating spectra extend over a larger wavelength domain, they provide

Note that the TZ02 sample includes 3 HST-STIS and 6 HST-GHRS spectra.
stricter constraints for the models than single grating spectra. For this reason, this work considers only those 106 spectra of the TZ02 sample that correspond to a combination of two or three HST-FOS gratings. (III) In the process of looking for patterns among the numerous spectral shapes encountered, we found it beneficial to classify these according to the signs by which dust absorption apparently manifests itself. The proposed classification is nothing more than a convenient and simplified characterization of the big blue bump phenomenology found among the archived HST-FOS spectra. By no means it implies that the quasars themselves are intrinsically different as a result of their spectra belonging to one class or another.

3.4. Classification of multigrating spectra into classes A–D

A physical insight on how dust can alter the continuum shape and account for the break has led to the classification of the multigrating spectra into four groups. The three most relevant groups are qualitatively described in panel a of Fig. 2. The 4 classes are defined as follows.

(A) - The spectra that show a continuum steepening near 1000 Å ($\lambda_{\text{rest}}$) belong to class (A). The near-UV spectrum is hard in these spectra and the far-UV shows a moderately steepened continuum. PG 1148+549 ($z_q = 0.969$) can be considered the archetype of this class (see Fig. 5). We tentatively assign the 7 spectra (usually high redshift quasars), whose near-UV FOS spectrum is not available longward of 1300 Å, to class (A). HS 1700+6416 ($z = 2.722$) for instance is classified as class (A) (Fig. 13). More than 60% of quasars, whose spectra extended sufficiently into the far-UV to determine $\alpha_{\text{NUV}}$ belong to class (A) alone. This may explain, why the spectra of this class individually resemble the TZ02 composite shape, since the composite is after all the result of averaging spectra that most often than not belong to class (A).

(B) - The spectra that show a sharp break near 1000 Å, followed by an extremely steep continuum drop shortward of the break, belong to class (B). The near-UV spectrum is hard in these spectra. PG 1248+401 ($z_q = 1.03$) in Fig. 3 can be considered the archetype of this class. Another example is Pks 0122−00 ($z_q = 1.07$) in Fig. 4. Objects in this class are not that common (only 6), though striking by their lack of a significant flux in the far-UV.

(C) - The spectra that show a continuum that is already soft longward of the break, that is, up to $\gtrsim 1600$ Å, belong to class (C). The soft region of the continuum now extends to

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6Of particular interest are quasars in the redshift range 0.9–2, for which the spectrum corresponds to a combination of 3 gratings. In these, the break is in full view and, in most cases, there is sufficient wavelength coverage, longward of the break, to infer the spectral index $\alpha_{\text{NUV}}$ and, shortward of the break, to distinguish absorption features that the models must reproduce.

7Ton 34, which was reported to have an index of $\alpha_{\text{FUV}} = -5.3$ by TZ02, is another example but only a single grating spectrum exists.
include the continuum beneath the \( \text{C} \text{IV} \lambda 1549 \) doublet (or even down to \( \text{C} \text{III} \lambda 1909 \) in some cases). A representative class (C) spectrum is the quasar 1130+106Y in Fig. 11 \((z_q = 0.54)\). In many cases, a single powerlaw does not fit the near-UV part well and, in other cases, the index is very steep \((< -1)\) throughout the whole spectrum, as exemplified by 3C279 in Fig. 11 (green spectrum). In the far-UV, these objects show characteristics of either class (A) or (B), that is, they are either flat in \( F_\lambda \) or very steeply declining, as illustrated by MC1146+111 \((z_q = 0.863, \) blue spectrum), which exhibits a class (B)-like break. We found 8 objects with the above characteristics\(^8\).

(D) - The high redshift quasars (3 objects) that we could not make sense of, belong to class (D). They are objects that show an inflection or wide trough in the far-UV. HE 1122–1649 is one example (see blue spectrum in Fig. 18). We do not rule out that the troughs could be associated in some cases to one or more Ly\( \alpha \) absorption systems.

Only 61 of the available 106 multigrating spectra extended sufficiently shortward of the break, that is, down to at least 900 Å, to ensure proper classification. Therefore, only this subset of 61 quasars has been analyzed in detail and modeled. Of these, 44 are class (A), 6 class (B), 8 class (C) and 3 class (D). We will mainly focus on class (A) and (B) spectra. These two groups together represent 82% of the classified objects and will suffice for the purpose of testing the dust absorption hypothesis. Many interesting spectra that could not be shown in this Paper will appear elsewhere (e.g. Binette et al. 2005a, b, c). As for class (C), dust appears to be related to some of the observed characteristics of at least a fraction of them (§ 4.3) but further work will be needed to reach definite conclusions. The few objects that form class (D) are puzzling and will not be modeled with dust absorption in this Paper.

3.5. Absorption models considered: intergalactic vs intrinsic

In order to explore how dust absorption might be the real cause of the observed break, a decision must be made on where the dust is located. The answer to this question defines two basic\(^9\) types of absorption models: (a) the dust is intrinsic to the environment of the quasars, and (b) the dust fills the intergalactic space. In case (a), the transmission function is derived directly from the extinction curve in the rest-frame of the quasar, as mentioned in § 2.2.1. With this category of models, we may reasonably expect the amount of dust to vary more or less at random from object to object. In case (b), the dust distribution is intergalactic and fills large volumes of space. We therefore expect that

\(^8\)Having access only to the near-UV spectrum may suffice for classifying quasars into class (C) but, in keeping with the above classification rules, we did not consider nor classify any spectrum that did not extend down to at least 900 Å in the far-UV.

\(^9\)As the spectra have already been corrected for Galactic reddening, there is no reason to be concerned by Galactic dust absorption.
such a dust distribution should be, to a first order, homogeneous, since the dust becomes a cosmological component unrelated to the quasars. With case (b), the models predict the same transmission for objects of comparable redshifts, independently of class. The dust density, \( n_H(z) \), function of redshift as mentioned in §2.2.2, has to be determined, requiring extra constraints. Intergalactic models imply enormous amounts of dust, since it is cosmological. We will first study the intrinsic dust case and then proceed to the intergalactic case.

In all figures, when overlaying a dust absorbed model to the rest-frame spectrum of a particular quasar at redshift \( z_q \), we follow the following coding: the continuous line part depicts the wavelength region corresponding to an idealized FOS spectrograph window extending from 1250 to 3600Å (\( \lambda_{\text{obs.}} \)), while the dashed line represents an extension into the far-UV down to 915Å (\( \lambda_{\text{obs.}} \)), as would be available using the FUSE satellite. A dotted line is used outside these two observer-frame windows.

4. The case for intrinsic dust

The case in favor of intrinsic dust absorption is best made by going through each class in order of increasing complexity of the dust model that it requires, that is in order B, A and C.

4.1. Class B spectra

Although class (B) objects are not numerous, they gave us an important clue on how to disentangle various effects resulting from dust absorption. What characterize this class is the very steep drop of the UV flux shortward of 1000 Å (\( \lambda_{\text{rest}} \)). Class (B) objects can easily be accounted for by simply using the extinction curve D1 consisting of terrestrial cubic nanodiamonds and adjusting as needed the absorption column\(^{10} \) \( N_H \). This is illustrated in Fig. 3, which shows the spectrum of the archetype class (B) quasar, PG 1248+401. The red line corresponds to a model using the curve D1 and an absorption column density \( N_H \) of \( 3.2 \times 10^{20} \) cm\(^{-2} \) (hereafter, the notation \( N_{20} = 3.2 \) will be used). The assumed underlying powerlaw index is \( \alpha_{\nu} = \alpha_{\text{NUV}} = 0.0 \), which is the index that best fits the emission-line-free continuum longward of Ly\( \alpha \). In all our plots, it is the quasar spectrum that we scale, until an overlap with the model is obtained in the near-UV. The resulting spectrum scaling factor, \( M_{14} \), is listed in each caption in units of \( 10^{14} \) erg\(^{-1} \) cm\(^2\) sÅ. Since we assume the intrinsic SED to be described by a simple powerlaw (until §6.3), the plotted models in all figures will correspond to the function \( F_{\lambda}^{\text{mod}} = T_{\lambda} \times (\lambda/912)^{-(2+\alpha_{\nu})} \), and the y-axis can be used to infer the transmission value \( T_{\lambda} \) for any value of \( \lambda \).

The only free parameter of the above D1 dust model is the column \( N_{20} \). The position of the peak in transmission overlaps surprisingly well with that of the ob-

\(^{10}\)It is likely that only a small fraction of carbon is actually locked into nanodiamond grains. Supposing we independently knew the dust-to-gas ratio due to nanodiamonds \( \Delta_{\text{DTG}} \) and that it was smaller than 0.0031, which corresponds to depleting all the carbon onto dust, then the absorption columns quoted in this paper would have to be multiplied by the factor \( 0.0031/\Delta_{\text{DTG}} \). The galactic ISM dust is characterized by a much larger \( \Delta_{\text{ISM}} \approx 0.009 \), since it contains many other atomic species than C.
served spectrum. This is the result of the very sharp drop in cross-section of curve D1 longward of \( \sim 1000 \, \AA \) (see red curve in Fig. 1), a property unique to cubic diamonds among dust grains composed of pure carbon. It is important to note that class (B) objects cannot be accounted for by making use of the Allende extinction curves A1 or A3, because these are characterized by a broader absorption peak and the peak itself is shifted toward higher \( \lambda \) values. The blue line in Fig. 3 illustrates the case of using curve A1. The relative success of the D1 dust model is telling us that if dust were indeed responsible for the break in class (B) objects, it must mostly consist of cubic diamonds. This does not rule out that a small fraction of the dust may be of the Allende type. This is demonstrated by the green line, which corresponds to a model with \( N_{20}=2.8 \) and a linear dust mixture of 85% of D1 grains and 15% of A1 grains. Hereafter, we will use the notation of \( f_{D1} = 0.85 \) to represent the fraction of D1 grains, with \( 1 - f_{D1} \) being the fraction of A1 grains.

Other class (B) quasars are Pks 1229−02 and Pks 1424−11, which are quite similar to PG 1248+401. They require models with dust columns of \( N_{20}=3.6 \) and 2.0, respectively, and an extinction curve consisting totally or mostly of cubic diamond type D1. In Fig. 4, we show another (B)-type spectrum, quasar Pks 0122−00, which requires somewhat less dust. For this object, the green line model has \( N_{20}=2.0 \) and consists of a dust mixture with \( f_{D1}=0.8 \). It appears that the model with a mixture of dust types D1 and A1 results in a superior fit than the blue line model with pure cubic diamond extinction (with \( f_{D1}=1.0 \) and \( N_{20}=2.3 \)).

In summary, class (B) spectra require dust that predominantly consists of cubic diamonds. The particular absorption characteristics of cubic diamonds fit the observed far-UV steep drop particularly well. Due to the large dust opacities implied, there subsists little or no far-UV flux to be observed in these objects shortward of 800\,\AA. If photoionization by high energy UV photons is the excitation mechanism of the emission lines, it is puzzling to find that the same high excitation emission lines are observed in class (B) quasars, devoid of hard UV, as in other objects that do have a hard continuum (e.g. HS 1700+6416 with \( \alpha_{FUV} = -0.55 \); Reimers et al. 1989). A possibility is that the dust lies outside the Broad Line Region (BLR). In this case, the emission line BLR clouds would be exposed to an ionizing continuum that is not absorbed.

### 4.2. Class A spectra

#### 4.2.1. A mixture of the two nanodiamond grain types

Class (A) spectra show a continuum break that is far less pronounced. The far-UV continuum is often flat\(^{11}\) in \( F_\lambda \), with an index \( \alpha_{FUV} \) of order \(-1.7 \) shortward of 1000\,\AA. One may reasonably expect that the absorption dust columns are simply smaller than in the previous case. This is confirmed by models. Unlike class (B) objects, where one species of dust is clearly favored, class (A) objects generally require an extinction curve that com-

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\(^{11}\)By ‘flat’ we mean an approximately horizontal continuum segment in an \( F_\lambda \) plot, which translates into an index \( \beta_\lambda \approx 0 \), that is, \( \alpha_\nu \approx -2 \).
bines the extinction from Allende nanodiamonds with that of cubic diamonds, that is, nanodiamonds with and without surface impurities (§2.1). The spectra of PG 1148+549 in Fig. 5 will serve to illustrate this point. All models shown have the same column of \( N_{20} = 1.05 \) and the same SED with \( \alpha_v = -0.2 \). Either extinction curve D1 or A1 can give rise to a flat continuum immediately longward of the break, but the onset of the break turns out inappropriate for both the D1 extinction curve (red line) and the Allende A1 curve (blue line), as seen in Fig. 5. An extinction curve consisting of a mixture with \( f_{D1} = 0.6 \) (60% D1 and 40% of A1 grains) on the other hand provides quite an acceptable fit to the break (green curve). We found that, by using a proper mixture of the two grain types, one can fit all class (A) objects. Three prominent emission lines stand out above the far-UV continuum in PG 1148+549, shortward of 900 Å (the line identifications shown in the figures follow those proposed by TZ02). It is interesting to note that extinction by pure cubic diamonds (red line) gives rise to a narrow dip near 700 Å, a feature not observed in this particular quasar.

4.2.2. Applying the intrinsic dust model to class (A) spectra

A mixture of the two nanodiamond types is very successful in reproducing the break in all class (A) spectra. More specifically, we can fit all observed 1000 Å breaks assuming one of the four following values of \( f_{D1} \): 0, 0.3, 0.6, and 1.0. A finer subdivision in most cases is not warranted by the data, because the spectra very rarely extend sufficiently in the far-UV for the fit to be sensitive to small changes in \( f_{D1} \). In a few cases, only the onset of the break is seen, and we could not determine with certainty whether the value of 0.3 or 0.6 is more appropriate. At any rate, the value of \( f_{D1} = 0.3 \) appears to be the most frequent as indicated in the histogram of Fig. 6, but there remains a substantial fraction of objects that require a different dust mixture.

In Fig. 7, we present the distribution of gas columns derived from fitting class (A) and class (B) spectra. The mean \( \tilde{N}_{20} \) value for class (A) is 1.02 with a standard deviation of 0.29. There are two high-redshift spectra, for which there is no evidence of dust, with an upper limit of 0.1, which are HS 1700+6416 and HE 2347–4342 (they have not been included in the average). If we combine class (A) and (B) spectra into a single group and assume that they are part of the same population, we derive \( \tilde{N}_{20} = 1.20 \) and a standard deviation of 0.60. The distribution shows that the presence of nanodiamond dust is the rule in quasars rather than the exception. In many quasars, the amount of dust inferred is comparable. For instance, 39 quasars have a column \( 0.6 \leq N_{20} \leq 1.4 \), which represents 78% of the 50 class (A+B) spectra.

As for the distribution of \( \alpha_v \) describing the near-UV continuum, we obtain a mean value for class (A) of \( \bar{\alpha}_{NUV} = -0.44 \) with a dispersion of 0.21. This average considers only the 22 objects, for which a reliable estimate of \( \alpha_{NUV} \) could be determined directly from the HST spectra. It is significantly harder than the mean value of \(-0.69\) reported by TZ02 and the median value of \(-0.83 \pm 0.04\) for local AGN reported by Scott et al. (2004), presumably, because the softer class (C) spectra are not
4.2.3. Dust models predict a rise shortward of \( \sim 700 \, \text{Å} \)

Due to the rapid decrease in the dust extinction cross section in the far-UV, shortward of the cross section peak (see Fig. 1), an inescapable feature of dust absorption is that a rise in transmitted flux always occurs in the far-UV, shortward of \( \sim 700 \, \text{Å} \). Of the 7 multigrating spectra that extended down to 600 Å and showed evidence of dust absorption, we found evidence of a sharp flux rise in 4 of them. This test was not conclusive for the remaining 3 spectra. The observation of a steep rise in the far UV is the strongest evidence in favor of dust absorption and will be presented in more detail.

The first spectrum with a sharp rise is PG 1008+1319, which is shown in Fig. 8. We adopt the value of +0.13 as near-UV index, as determined by Neugebauer et al. (1987). The green line corresponds to an intrinsic dust model with \( f_{D1} = 0.3 \) while the gray line corresponds to \( f_{D1} = 0.6 \). The column in both models is \( N_{20} = 1.2 \). Clearly the model with an extinction dominated by Allende nanodiamonds (red line) gives a better fit to the break. Reducing \( f_{D1} \) further would cause the break ‘s onset to occur at too long a wavelength (e.g., the \( f_{D1} = 0 \) model in Fig. 5).

A second example is Pks 0232–04 of Fig. 9. A fit of the near-UV continuum favors \( \alpha_\nu \) indices in the range \(-0.2 \) to \(-0.4 \). To be definite, we adopt the steeper SED with \(-0.4 \). We verified that the same conclusions are reached when using the harder index. The red line model, which is more satisfactory, corresponds to pure D1 dust with \( f_{D1} = 1.0 \) and \( N_{20} = 0.90 \) while the green line model corresponds to \( f_{D1} = 0.8 \) and \( N_{20} = 0.93 \). Due to the predominance of cubic diamonds, a narrow dip at 650 Å stands out in models with \( f_{D1} \gtrsim 0.7 \). This dip appears to be saddled by two prominent emission lines, O III and Ne VIII, both of which are also visible in the composite SED of TZ02, but not as prominently. Interestingly, Scott et al. (2004) discuss the nature of a narrow dip seen blueward of the Ne VIII emission in their near-AGN composite. The interpretation they favor is that of blueshifted absorption by Ne VIII. Another explanation might be that absorption by cubic nanodiamonds is responsible for this feature. Even though the D1 dip is broader, it might partially be filled by the Ne VIII emission line.

A third example is provided by the much higher redshift quasar, HS 1307+4617, at \( z = 2.129 \), which is plotted in Fig. 10. There is no HST-FOS spectrum that covers the near-UV. Instead, we adopt the value of \( \alpha_{NUV} = 0.0 \) as inferred from a spectrum of D. Reimers and reproduced in Koratkar & Blaes (1999). The three models superimposed to the spectrum in Fig. 10 have the same column \( N_{20} = 1.3 \) and differ only by their proportion of the D1 and A1 dust, as follows: gray line \( f_{D1} = 0.8 \), green line \( f_{D1} = 0.6 \), and purple line \( f_{D1} = 0.3 \). The green line model with \( f_{D1} = 0.6 \) provides a better fit. It is interesting to note that the disjoint part (yellow segment) of the GHRS spectrum (taken with grating G140L) is not consistent with the far-UV extrapolation of the models. A solution to this problem is found in §6.3. A fourth example is 1623.7+268B, shown as the dark green spectrum at the bottom of Fig. 9.
To summarize, the intrinsic dust model is phenomenologically very successful, as it can not only reproduce the break within the dominant class (A) spectra, but it can also account for the continuum sudden rise in the far-UV, in the 650–700 Å region. The extinction curve that is required to model the far-UV consists of a mixture of the two nanodiamonds grain types: the cubic diamonds and the Allende type.

4.3. Class C spectra

This class is defined by the near-UV shape, which is very soft, taking the appearance of a flat continuum in $F_\lambda$ or, in some cases, of a bump longward of 1200 Å. We have already presented (§3.4) the three examples shown in Fig. 11. The frequent rounded shape of the spectrum from near to far-UV suggests the possibility that, in some cases at least, the spectra might be reddened by dust similar to that of the Galactic ISM. One such case is 1130+106Y (black line spectrum in Fig. 11), which we tentatively model using the ISM dust model of Martin & Rouleau (1991) (see black dashed line extinction curve in Fig. 1). It consists of a mixture of silicate and graphite grains. The magenta line is a better model in the far-UV. It combines ISM extinction (80%) with that of cubic diamonds (20% of D1 grains by mass). The column is $N_{20}=9.0$ and the assumed SED has $\alpha_\nu=-0.25$. Note the significant attenuation of the continuum, which reaches a factor of 5 near 1000 Å. The optical extinction in the $V$ band due to ISM-like dust is relatively modest, with $A_V = 0.4$ mag. Not including the contribution from nanodiamonds extinction would result in a flatter continuum without much of a break, as illustrated by the yellow line model (pure ISM extinction with $N_{20}=9.0$).

Evidence of reddening by ISM dust appears to be present in class (C) spectra, but nanodiamond dust is nevertheless required to explain the break when it is present. A few class (C) spectra show a steep drop shortward of 1000 Å as in class (B) spectra. We have not explored the possibility of a combination of the three extinction curves A1, D1 and ISM. It is possible that some class (C) spectra possess a SED (from near to far-UV) that is intrinsically steeper than in other classes, with $\alpha_\nu$ in the range $-2$ to $-1.2$.

5. The case for intergalactic absorption

The fact that the absorption columns take on similar values in the intrinsic case for the numerous class (A) spectra, invites us to explore the hypothesis that the dust pervades the intergalactic space instead of being confined to the environment of each quasar. Following this hypothesis, the distribution of the dust bears no relation to the quasars, but is a function of distance (i.e. $z$). By the same token, we expect the grains composition to be more uniform in the intergalactic case than in the intrinsic case. The intergalactic model does not, however, imply that there cannot be an additional intrinsic dust component local to some quasars, as appears to be the case for class (B) and (C) spectra. On the other hand, the case for intergalactic dust will be more convincing if a minority of class (A) spectra require additional absorption above the one provided by the intergalactic model.
The predictive value of the intergalactic model resides in the function chosen to describe the dust density with redshift. Such a function will not only allow the modeling of the break in individual quasars but also the simulation of the composite SED derived by TZ02, following the procedure defined in §2.2.2.

5.1. Constraining the dust behavior with redshift

As a working hypothesis, let us assume that the dust is intergalactic and for now consider only class (A) spectra. Since the absorption occurs along the line-of-sight to each quasar, its impact can extend over the whole far-UV domain as a result of the redshift effect and cosmological expansion. In a Universe that evolves and expands, any cosmological quantity such as the density of the Lyα absorbers, the density of of quasars, the star forming rate, etc, is known to evolve strongly with redshift, that is with time. The same must apply to the hypothesized intergalactic dust. There should exist an epoch \( z_p \) at which the dust density reaches a peak. To describe such a peak, we adopt a parametric form for the dust density\(^\text{12}\) \( n_H(z) \), similar to that used by Baldry & Glazebrook (2003) to describe the cosmological star formation rate. It consists of a broken powerlaw joining at redshift \( z_p \):

\[
\begin{align*}
n_H(z) &= \frac{n^0_H(1 + z)^\epsilon}{n^0_H(1 + z_p)^\epsilon}\left(1 + z\right)^\gamma & \text{for } z \leq z_p, \\
n_H(z) &= \frac{n^0_H(1 + z)^\epsilon-n^0_H(1 + z_p)^\epsilon+\gamma(1 + z)^\gamma}{\gamma(1 + z)^\gamma} & \text{for } z > z_p
\end{align*}
\]

where \( n^0_H \) is the density at zero redshift, \( \epsilon \) and \( \gamma \) are the low and high redshift indices and \( z_p \) the intersection of the two truncated powerlaws. Hereafter, we will use \( n^0_8 \) in units of \( 10^{-8} \text{ cm}^{-3} \) to express the density at zero redshift.

To constrain the parameters describing the function \( n_H(z) \), we proceeded as follows. Since Scott et al. (2004) did not find evidence of a continuum break in nearby AGN \( (z_q < 0.7) \), this suggests that the peak in absorption occurred at an earlier epoch rather than in the local Universe. A positive index for \( \epsilon \), in which absorption increases with look-back time, will have the effect of reducing the importance of the 1000 Å break within the local Universe. Another indication of the increase in the importance of the break with redshift can be appreciated in Fig. 12, where we plot \( \alpha_{\text{FUV}} \) as measured for each quasar by TZ02. To derive the mean values represented by the squares, we distributed the measured indices into 5 redshift bins and then calculated the average \( \bar{\alpha}_{\text{NUV}} \) within each bin. (The continuous line simply connects the 5 mean values.) After trial and error and varying \( \epsilon \), we found that similar fits to the break could be obtained, using any value within the interval \( 1.5 < \epsilon < 3.5 \). To constrain \( \epsilon \) more effectively would have required including the nearby AGN observations with the FUSE satellite (Scott et al. 2004). To be definite, we hereafter adopt the value \( \epsilon=+2 \).

To determine the behavior of \( n_H(z) \) at the other redshift end, we can compare the very high redshift quasar spectra \( (z > 2.5) \) with those at intermediate redshifts. As it turns out, most high-\( z \) HST-FOS spectra are single-grating and can’t be used for that purpose. Fortunately, there exist two quasars with high S/N

\(^{12}\)The density \( n_H \) as defined in this work is not a co-moving but rather a local quantity.
and wide spectral coverage that we could analyze in greater detail, HS 1700+6416 and HE 2347−4342, which are plotted as $F_ν$ in Fig. 13. The powerlaw indices for HS 1700+6416 and HE 2347−4342 that we adopt are $\alpha_ν = -0.55$ (from Reimers et al. 1989) and +1.70 (inferred from the best model), respectively. The missing parameter values defining $n_H(z)$ were arrived at using various constraints, as described below.

Because of the redshift effect, the HST-FOS spectra of both HS 1700+6416 and HE 2347−4342 do not cover the typical break region at 1000 Å ($\lambda_{rest}$). Viewed from the perspective of intergalactic dust, however, the absorption break should have shifted to shorter wavelengths (with $z$), as demonstrated below in §6.2. As a consequence, the continuum shape’s departure from that of a pure powerlaw must be the result of the hypothesized intergalactic dust, if such a model is to be of any use. Despite the ragged appearance of both continua in Fig. 13, caused by the many absorption systems along the line-of-sight, it is clear that both show a general curvature or change of index, which intergalactic absorption must be able to explain. It turns out that such a curvature can be reproduced by intergalactic dust models using either of the extinction curves, A1 or D1. To select the appropriate extinction, we required that the dust model successfully reproduced the break observed in the lower redshift spectrum of PG 1148+549, which is the archetype of class (A). This second constraint effectively rules out cubic diamonds as shown by the red line model of PG 1148+549 in Fig. 14. In the case of intergalactic models with dust curve A1, the break occurs at somewhat too short a wavelength (see blue line in Fig. 14). To compensate for the redshift smearing effect, we extended the grain size range of the Allende nanodiamonds, extending it up to $a_{max}$ = 200 Å. This defines the new extinction curve A3 (see orange curve in Fig. 1) used in all our intergalactic calculations. This extinction curve A3 was found to provide an overall better fit to class (A) objects, in the intergalactic case.

Having selected the optimal extinction curve, strong constraints on $z_p$ and $n^0_H$ can now be derived by varying these parameters until an acceptable fit of the two high-$z$ quasars is found. We found that $\gamma$ is loosely constrained to negative values $\lesssim -1.4$. To further constrain the function $n_H(z)$ and $\gamma$, we made use of the composite quasar SED of TZ02 (shown in Fig. 15). We simulated this composite by co-adding synthetic dust-absorbed SEDs of the same redshifts and spectral widths as those in the actual TZ02 sample, following the procedure described in §2.2.2. This exercise indicated a preference for somewhat larger values of $\gamma$ than the range favored above using the two high-$z$ quasars. To be definite, we adopted the value of $\gamma = -1.5$, which corresponds to the overlap between the two types of constraints. The result of combining these different constraints in an iterative fashion has been that an ac-

\footnote{Because of the hardness of HE 2347−4342 ($\beta_\lambda \sim -3$), using $F^{\text{obs}}_\lambda$ is much more convenient than $F^{\text{abs}}_\lambda$.}

\footnote{Note that if we attempt to fit the above curvature using intrinsic dust, the absorption actually goes the wrong way, making the transmitted spectrum appear even harder, as illustrated by the green line model calculated with $N_{20}=0.5$ and $f_{D1}=0.3$.}
ceptable fit to the broad curvature of both high-z quasars of Fig. 13 occurs when using the value \( z_p \simeq 0.4 \) for the peak dust redshift. The resulting orange line model, which requires \( n_8^0=3.4 \), now overlays both continua in Fig. 13 as well as the outline of the break in PG 1148+549 (Fig. 14). In conclusion, the intergalactic dust model can account for the progressive steepening of the powerlaw index observed shortward of 500 Å in HE 2347−4342.

5.2. Applying the intergalactic model

A reasonable expectation of the intergalactic dust model is that it should apply to all the classes defined in § 3.4. This is not to say that additional absorption by a local dust component cannot take place in some quasars. For instance, class (B) quasars, although dominated by intrinsic dust, as shown in § 4.1, can also be modeled as the sum of intergalactic absorption and absorption by intrinsic D1 dust. An example of such complementarity is given by class (B) Pks 0122−00 in Fig. 4. An orange line model is plotted, which includes absorption by both intergalactic A3 dust and intrinsic D1 dust of column \( N_{20}=1.0 \). Except toward the far-UV, this orange line model (mostly hidden by the foreground red line!) is almost identical to the previously described green line model (§ 4.1), which consisted of an intrinsic dust mixture with \( f_{D1}=0.8 \) and column \( N_{20}=2.0 \). A similar comparison can be established with the intergalactic orange line model of PG 1248+401 (Fig. 3).

When attempting to simulate the composite SED of Fig. 15, it turns out that \( n_8^0 \) must be increased, from 3.4 to 4.7. If not, the model lied significantly above the composite. Such a model with \( n_8^0 \) increased to 4.7 is shown by the purple continuous line in Fig. 15. This simulation though imperfect is encouraging, if we consider that our simulation assumed a single powerlaw index \( \alpha_v=-0.6 \), while the TZ02 composite sampled widely different energy distributions. Furthermore, TZ02 have combined spectra of classes (A)−(D), while the pure intergalactic model is intended for class (A) objects. It is presumably for that reason that a significant improvement is obtained, as shown by the orange line model in Fig. 15, when one combines intergalactic absorption with intrinsic absorption by a column as small as \( N_{20}=0.15 \) of D1 dust.

We have repeated the same exercise as for the intrinsic case (§ 4.2) of applying the intergalactic model to all class (A) spectra. We found that 20 spectra could be reasonably fitted with the proposed value \( n_8^0=3.4 \) (the standard model), while 14 spectra required either an increase of \( \simeq 10\% \) in \( n_8^0 \) or the addition of an intrinsic column of dust, most frequently of type D1. Furthermore, 4 and 6 spectra required \( n_8^0 \) to be reduced (approximately) to 2.4 and 3.0, respectively. The database is therefore not entirely consistent with the expectation of an homogeneous distribution of intergalactic dust.

6. Merits of intergalactic vs intrinsic models

Which model is to be preferred? We will compare the merits and problems of each type of model and, in conclusion of this section, we will present a final model for the 1000 Å break of quasars.
6.1. The intrinsic dust hypothesis

We have shown that intrinsic dust models could account not only for the break, but also for the flux rise at shorter wavelengths (e.g. Figs. 8–10). Overall, the intrinsic model is extremely successful across the whole class (A) and class (B) samples. The fit to the far-UV rise in HS 1307+4617, on the other hand, is not entirely satisfactory.

Is it possible to simulate the TZ02 composite assuming only intrinsic dust? One difficulty is that the intrinsic model is mute about how other parameters like $N_{20}$, $f_{D1}$ or $\alpha_{\nu}$ might vary with increasing $z$. However, since each class (A) spectrum can be fitted quite well by varying $f_{D1}$ and $N_{20}$, which is an approach that we consider superior to that of simply fitting the TZ02 composite, it can then be argued that not being successful in the simulation of the composite is of secondary importance. Although we consider this to be true, nevertheless attempted to simulate the composite, because it reveals real trends in quasar SEDs. The fact that the TZ02 composite remains very soft at very short wavelengths instead of showing a far-UV rise, must be explained somehow.

The silver dashed line in Fig.15 illustrates our initial attempt to simulate the composite SED, assuming $\alpha_{\nu}=-0.6$ and keeping all the input parameters constant with $z$. The column is $N_{20}=1.0$ and $f_{D1}=0.3$. The far-UV flux is obviously predicted too strong. This happens, because the extinction cross-section falls off too rapidly at very short wavelengths, and a steep rise in $F_\lambda$ becomes unavoidable shortward of 600Å. The simulated composite simply tends toward the slope given by the index $\alpha_{\nu}$. If we vary the column with redshift, by defining a function $N_{20}(z)$, we obtain the absurd result that, in order for the simulated composite to overlap the TZ02 composite, the dust column would have to increase sharply with redshift. This is not only an ad hoc dust behavior, it is also contradictory to the absence of any increase with $z_q$ of the columns determined in §4.2. In addition, it is at odds with the lack of absorption in the two high-z spectra of HS 1700+6416 and HE 2347–4342, for which we determined absorption upper limits of $N_{20} \leq 0.1$. Attempts to model the curvature in these two spectra with intrinsic dust result in absorption features at the wrong end of the spectrum. In effect, local dust makes both spectra appear even harder than they already are, as illustrated by the green line model in Fig.13 calculated with $N_{20}=0.5$ and $f_{D1}=0.3$.

6.2. The intergalactic dust hypothesis

The few shortcomings mentioned above for the intrinsic case disappear with intergalactic dust. By construction, the continuum of the two high-redshift quasars, HS 1700+6416 and HE 2347–4342, can be reproduced. On the other hand, the break can be fitted only for a qualified majority of class (A) spectra, while the other spectra usually requiring intrinsic dust to be added to the model. The TZ02 composite can be reproduced, albeit with a density
$n_0^0$ increased by 40% (for which we have no satisfactory explanation to propose). The far-UV index $\alpha_{FUV}$, when evaluated at the fixed wavelength of 800 Å, exhibits the correct trend with redshift, as shown by the long-dashed line in Fig. 12. One may argue that the amount of dust implied by the intergalactic model is excessive if not plainly unreasonable, but it is not an impossible amount. The fraction of the baryonic mass that the value $n_0^0=3.4$ corresponds to is 17% (see §6.3), assuming that the mean cosmic carbon metallicity is about solar and that the dust is intergalactic, because it was expelled from galaxies by radiation pressure (Ferrara et al. 1991) or through supernovae of type II.

The intergalactic model, on the other hand, makes stringent predictions about how the break ought to shift (and soften) with increasing redshift. This is shown in Fig. 16, in which the transmission function is plotted at representative $z_q$ values. The continuous part of each $T_\lambda$ curve corresponds to the fiducial spectrograph window of 1250–3600 Å ($\lambda_{obs}$) [see §3.5] and shows what part of the break is visible at a given redshift $z_q$. Notice that when the redshift exceeds values of $\simeq 1.5$, the break is markedly shifted toward shorter wavelengths. Of the three spectra presented in §4.2.3, which showed a clear flux rise in the far-UV, only one is of sufficiently high redshift to test this, HS 1307+4617 with $z = 2.129$. It’s spectrum is shown again in Fig. 17 and can be compared with the pure intergalactic model with $n_0^0=3.4$, which is represented by the brown dashed line. The SED is the same as earlier, that is $\alpha_\nu=0.0$.

The gradual break (or curvature) seen in the brown dashed line model in Fig. 17 not only occurs at very short wavelengths ($\sim 550$ Å), but is extremely shallow. Obviously, in order to fit the sharp break characterizing the HS1307+4617 spectrum, additional intrinsic absorption must be considered. Such a model is represented by the orange line, which is a model that combines intergalactic with intrinsic dust. The local dust column is $N_{\text{20}}=0.8$ with a dust composition $f_D=0.6$. The fit to the observed flux rise is surprisingly good, much better even than with the pure intrinsic case represented by the green line in the previous Fig. 10 of the same quasar. Even more suggestive is the disjoint spectrum obtained with GHRS grating G140L (yellow spectrum in Fig. 17), which despite its lower S/N appears to prolong the far-UV rise of the multigrating spectrum (black line). The intergalactic model is marginally consistent with the continuum level set by this spectrum segment, in contrast with the pure intrinsic model, which rises too steeply (see green line in Fig. 10). The green dashed line in Fig. 17 represents the contribution of intrinsic dust absorption that is present in the orange line mixed model. In summary, even though intrinsic dust is the main contributor to the sharp break observed in HS 1307+4617, the signature at the shortest wavelengths expected in high-z spectra as a result of intergalactic dust appears to be independently confirmed in this quasar.

Is the intergalactic hypothesis vindicated? It turns out not to be the case. In effect, a rather poor fit is provided for the two other quasar spectra that showed a far-UV flux rise, PG 1008+1319 and Pks 0232−04. As is the case for HS 1307+4617, these two quasars require
additional intrinsic absorption, with dust columns ($N_{20}$) of 0.5 and 0.25 and dust mixtures ($f_{DI}$) of 0.0 and 1.0, respectively. However, even when combining this additional absorption with intergalactic dust, the far-UV rise cannot be reproduced at all, as shown by the corresponding orange lines in the Fig. 8 of PG 1008+1319 and in the new Fig. 18 of Pks 0232−04. The far-UV continuum level is predicted too low in the Pks 0232−04 model and, in both figures, the flux rise (orange lines) occurs at too short a wavelength.

6.3. Evidence of a higher energy break?

As indicated above, the discrepancy of the intergalactic model for reproducing the far-UV rise in PG 1008+1319 and Pks 0232−04 could not be resolved. This inadequacy of the model is sufficiently significant to reject the intergalactic dust hypothesis at the assumed density\textsuperscript{16}. Moreover, in more than one aspect, the intergalactic model is implausible. Assuming that the mean metallicity of galactic matter (stars and interstellar gas) at current epochs is near solar, as derived by Calura & Matteucci (2004a, b), then the fraction of cosmic carbon required is $n_{H}^{0}/n_{H}^{0} = 3.4 \times 10^{-8}/2.06 \times 10^{-7} = 0.17$. Apart from the unreasonable fraction of cosmic carbon that must exist in crystalline form (17%), it would require an improbably fine tuning so that this dust would not be accompanied by larger amounts of the more common flavors (silicates, graphites, PAHs, ...) as one would expect if it was formed in supernovae and later expelled in the intergalactic space. The analysis of cosmological supernovae has ruled out the existence of large quantities\textsuperscript{17} of intergalactic dust of ‘normal’ composition (Perlmutter et al. 1999).

Ruling out the intergalactic model in favor of the intrinsic model has an additional interesting consequence. The curvature present in the spectra of HS 1700+6416 and HE 2347−4342 must now be considered an intrinsic feature of the energy distribution in these two quasars, rather than the manifestation of intergalactic absorption.

We are left with the intrinsic dust hypothesis to account for the 1000 Å break in quasars. What could be missing from this model so that the few remaining problems it has could be resolved? We will hypothesize that the shallow rollover observed in the far-UV in HS 1700+6416 and HE 2347−4342 is a manifestation of a universal high energy cut-off present in all quasar SEDs. To test this, we first model the cut-off in a way that does not depend on the $\alpha_{NUV}$ of the underlying SED. This is achieved by singling out the transmission curve calculated at $z_{q} = 2.8$ (correspond-

\textsuperscript{16}If we adopt an intergalactic model that uses significantly less dust than $n_{0}^{0}=3.4$, it would be at the cost of having more intrinsic dust present and this in a larger fraction of class (A) spectra, if not the majority of them. Hence, such a model would not contribute in an essential way in explaining the break and would have to be discarded on account of Ockham’s razor principle.

\textsuperscript{17}We have calculated the extinction that ISM dust would produce if it followed the same intergalactic distribution as the nanodiamonds ($\S$ 5.1) with $n_{0}^{0}=3.4$, that is in amounts that correspond to 17% of the Galactic dust-to-gas ratio. We find that for an object at $z = 0.5$, the selective extinction is $E_{B-V} = 0.022 (\lambda_{obs})$, much in excess of the value of 0.002 inferred from cosmological supernovae by Perlmutter et al. (1999).
ing to the average redshift value of the two high-\(z\) quasars) and considering it to be a valid description of the continuum softening that might also apply to the other quasars. We obtained a parametric fit of this transmission curve at that redshift, using the following expression:

\[
C_\lambda = \left(1 + \left[\frac{\lambda}{\lambda_{\text{brk}}}\right]^{f \delta}\right)^{-f^{-1}}
\]  \(2\)

where \(\delta\) is the powerlaw index change and \(f\) a form factor, that may vary from object to object. In essence, when a quasar SED is multiplied by \(C_\lambda\) and \(\delta < 0\), a shallow steepening takes place at \(\lambda_{\text{brk}}\), which increments the underlying powerlaw index by \(\delta\). The sharpness of the cut-off is set by the form factor \(f \geq 1\). Hereafter, we will assume that the true intrinsic quasar continuum is given by \(C_\lambda \times F_{\lambda}^{\text{q}}\), where \(F_{\lambda}^{\text{q}}\) is the quasar powerlaw that we have been using so far and \(\alpha_\nu\) the index set by the near-UV continuum. To illustrate the role of the form factor, let us take the spectrum (blue spectrum in Fig. 18) of class (D) quasar HE 1122\,-\,1649 as an example, given that it shows a clear far-UV cut-off. Longward of the cut-off, the powerlaw index is \(\alpha_\nu = -0.6\), reaching \(-2.6\) shortward of the break situated at \(\approx 670\ \text{Å}\). Hence the parametric function \(C_\lambda\) is characterized by \(\delta = -2.0\) and \(\lambda_{\text{brk}}=670\ \text{Å}\). The gray and magenta lines in Fig. 18 correspond to form factors of \(f = 2.8\) and 10, respectively.

Turning our attention to the \(T_\lambda\) curve at a redshift \(z_q=2.8\) in Fig. 16, the parametric fit using Eqn. 2 yields the values \(\delta = -1.6\), \(f = 2.8\) and \(\lambda_{\text{brk}}=670\ \text{Å}\). It is shown by the thick gray dashed line. This cut-off can now be applied, not only to HS 1700\,+\,6416 and HE 2347\,-\,4342, but to any other quasar as well. It will result in a new SED that is characterized by the same near-UV powerlaw as before, but with a shallow far-UV cut-off centered on 670 Å, that is, at 18.5 eV.

If we incorporate the above far-UV rollover into our previous quasar SED of index \(\alpha_\nu = -0.6\), we obtain the distribution represented by the black dotted line in Fig. 19. Assuming this modified SED, a remarkable improvement in the simulated composite is now obtained, as shown by the dark gray continuous line in Fig. 19. (The silver dashed line model represents the earlier case without the far-UV intrinsic cut-off). Further improvements of the simulated composite can be obtained by varying some of the input parameters with redshift. The study of these more complex models, however, exceed the scope of this paper and will be reported elsewhere.

It is important to emphasize that the intrinsic model with a shallow cut-off fits markedly better two of the three quasar spectra that showed a far-UV rise. For instance, the earlier problem encountered (§4.2.3) in fitting the far-UV rise in HS 1307\,+\,4617 (green line in Fig. 10) has now disappeared, as shown by the cyan line model in Fig. 17, which assumes the SED with the above far-UV rollover. An improvement of the fit to the far-UV rise in Pks 0232\,-\,04 is also obtained, as shown by the cyan line model in Fig. 18. In the case of PG 1008\,+\,1319, it makes little difference whether the high energy cut-off is there or not (compare the cyan and green line models in Fig. 8).

In summary, the whole database as represented by the TZ02 composite, as well as the individual spectra showing the far-UV rise, are both consistent with the pres-
ence of an 18.5 eV cut-off in quasars. This proposed new cut-off is being masked in the vast majority of quasars with redshift \( z \approx 2.5 \) by the more prominent 1000 Å break, which we believe is entirely due to nanodiamond dust absorption.

7. Nanodiamonds: the infrared-UV connection

Nanodiamonds are, to date, the most abundant presolar grains, both in mass and numbers, that have been extracted from primitive carbonaceous meteorites (Mutschke et al. 2004, and references therein), but their detection in the ISM has been elusive. Diamond crystallite emission bands in the 3.3–3.6 \( \mu \)m region due to surface C–H stretching modes of hydrogenated nanodiamonds have been established with confidence for a few Herbig Ae/Be objects and one carbon-rich post-AGB star HR 4049 (Guillois et al. 1999; Van Kerckhoven et al. 2002; Acke & van den Ancker 2004). Van Kerckhoven et al. (2002) presented a detailed analysis of the ISO-SWS spectra of the two Herbig objects, HD 97048, and Elias I, as well as of the post-AGB HR 4049. They applied a physical model to the emission profile of the 3.53 \( \mu \)m band and inferred a temperature of 950 K and 1000 K for HD 97048 and Elias I, respectively. Assuming radiative equilibrium between photoheating and far-infrared cooling for the grains, the authors could estimate the UV radiation flux impinging the diamonds in these three objects. The diameter range they inferred for the crystallite diamonds is 2\( a \sim 10–100 \) Å. Interestingly, the multiwavelength data for both HD 97048, and Elias I, as well as for the post-AGB star HR 4049, indicate that the 3.53 \( \mu \)m emission takes place within a disk-like structure. The distance between the star and the emission region is \( \lesssim 9 \) and \( \lesssim 22 \) AU, in HD 97048 and Elias I, respectively. The formation site that these authors favor for the crystallite diamonds is in situ formation within the disk rather than within the ISM or via ejection from stars. In the field of AGN, sub-arcsecond VLT observations by Rouan et al. (2004) using NAOS+CONICA revealed wavelike structures in the mid-infrared, which the authors propose might be due to emission by nanodiamonds at a temperature close to sublimation.

To explain the predominance of nanodiamond grains in primitive meteorites, several formation mechanisms have been proposed, such as: (a) chemical vapor deposition from stellar outflows (Lewis et al. 1987), (b) impact shock metamorphism driven by supernovae (Tielens et al. 1987), (c) energetic ion bombardment by a supernova (Daulton et al. 1995), (d) UV annealing of carbonaceous grains (Nuth & Allen 1992), (e) nucleation in organic ice mixtures by UV photolysis (Kouchi et al. 2005), and (f) chemical conversion of PAH clusters to nanodiamonds in the presence of UV radiation (Duley & Grishko 2001). It is interesting to note that the last three processes involve UV radiation. The above post-AGB and the two Herbig Ae/Be stars emit UV radiation (Van Kerckhoven et al. 2002), a fact which is possibly related to the formation of the observed nanodiamonds.

Could a similar formation process operate within the UV-intense environment of quasars? The indication that cubic diamonds dominate in class (B) quasars
might be related to an evolutionary sequence of the grains. A possible scenario might be the following. Via the process of dehydrogenation of PAH clusters by quasar UV radiation, hydrogenated nanodiamonds form, with optical properties similar to the Allende type. If the UV radiation heats up the nanodiamonds beyond 1300 K, a process of surface dehydrogenation begins, which may cause the grain optical properties to become more similar to that of cubic diamonds. Finally, the disappearance of H–stretch cooling may result in a runaway heating, followed by graphitization and eventually to sublimation of the grains.

To confirm the existence of nanodiamond grains in AGN, one could attempt to detect the far-infrared emission bands caused by hydrogenated nanodiamonds (Van Kerckhoven et al. 2002; Jones et al. 2004a). However, AGN are intrinsically very strong far-infrared emitters, and the signature of any narrow emission band will certainly be diluted. For instance, the dust silicate feature at 9.7 µm predicted by calculations (Laor & Draine 1993) is not observed as often as expected in AGN. The UV radiation absorbed by nanodiamonds represent at most 10% of the energy integrated over the whole SED. Let us assume the AGN unification picture with a bi-cone opening angle of 45°. If the nanoparticles are located outside the BLR, then a fraction of only \(0.10 \times \left(1 - \cos\frac{45°}{2}\right) \lesssim 0.01\) of the quasar bolometric luminosity will be reprocessed into far-infrared emission by nanodiamonds. Assuming a uniform covering factor of unity within the radiation bi-cone, the minimum dust mass required by the intrinsic model is given by

\[0.044N_{20} r_{pc}^2 \times \left(1 - \cos\frac{45°}{2}\right) M_{\odot},\]

where \(r_{pc}\) is the distance in parsecs separating the dust screen from the central UV source. For an arbitrary distance of one parsec and \(N_{20}\) of unity, the dust mass implied is 0.0033 \(M_{\odot}\), a value independent of the assumed dust-to-gas ratio (see footnote 10).

To the extent that Allende-type nanodiamonds might be a candidate carrier (see Jones et al. 2004b) for the Extended Red Emission observed in nebulae between 5400 and 9500 Å, it is conceivable that a fraction of the UV flux absorbed by dust might be re-emitted by photoluminescence.

8. Conclusions

We have presented evidence that indicates that dust absorption by nanodiamonds is successful in reproducing the 1000 Å break as well as the far-UV rise seen at shorter wavelengths. Could the agreement between the intrinsic dust models and the spectra be simply the result of a coincidence between the break location and the far-UV extinction properties of nanodiamonds? To rule out such a possibility will require that an independent confirmation of the presence of nanodiamonds be found. Detection of grain emission in the far-infrared, at 3.43 and 3.53 µm, is one possibility, although this emission mechanism works only with surface-hydrogenated grains (see §7). Another possible route would be to observe selected quasars in order to extend the UV coverage in objects for which only the onset of the break is seen so far. The idea would be to look for a confirmation of a flux rise shortward of 700 Å in as many quasars as possible. This would require high quality observations using a satellite.
with far-UV sensitivity. One possibility might be the R=1000 spectrometer onboard the projected World Space Observatory satellite, which is expected to offer a sensitivity window covering the range 1100 to 3500 Å ($\lambda_{\text{obs.}}$) (Barstow et al. 2003).

We have ruled out that the dust causing the 1000 Å break is predominantly intergalactic on the basis that it is not required per se and that the far-UV rise could not be modeled satisfactorily using intergalactic dust. Furthermore, the amount of crystalline carbon that is needed turns out to be improbably large. Since intergalactic dust is not responsible for the continuum rollover observed in HS 1700+6416, HE 2347−4342, at $z \approx 2.8$, we have proposed that this feature is a manifestation of a higher energy break, near 18.5 eV, which is presumably intrinsic. Including the same break in the other quasars SED markedly improve the simulation of the composite as well as the detailed modeling of the far-UV rise in PG 1008+1319 and Pks 0232−04. At any rate, such a break is bound to take place somewhere in the far-UV so that the quasar SED connects smoothly with the soft-X rays. In effect, the optical-X-ray index, $\alpha_{OX}$, which relates the monochromatic continuum flux at 2500 Å to that at 2 keV, is characterized by values in the range 1.3 to 1.6 (equivalent to an $\alpha_\nu$ between $-1.3$ and $-1.6$). Given that our mean $\alpha_{N\text{UV}}$ index for class (A) is much harder, with $-0.44$, a continuum turnover must take place somewhere in the far-UV. Our results suggest that such turnover occurs at 18.5 eV. We are currently in the process of studying how the far-UV and the soft X-rays may join together (Haro-Corzo et al. 2005).

Intrinsic dust models require gas columns of the order $10^{20}$ cm$^{-2}$, assuming solar C abundance and full depletion onto nanodiamond grains. For comparison, in the solar neighborhood, a $V$-band extinction of a tenth of a magnitude by ISM dust corresponds to a gas column of $1.9 \times 10^{20}$ cm$^{-2}$ (Whittet 2002). Larger columns (but same dust masses) would be implied for our models, if we assumed smaller dust-to-gas ratios. To the extent that the nanodiamond dust lies in the vicinity of the AGN, the minimum dust mass required by intrinsic models is small $\simeq 0.003 N_{20} r_p^2 M_\odot$ (see § 7). This value is independent of the assumed dust-to-gas ratio, because the absorption gas columns scale inversely with it (see footnote 10).

We have shown evidence that ISM-like dust might be playing a role in explaining the continuum appearance of a fraction of quasars, the so-called class (C) quasars. To confirm this suggestion will require more complex models than presented here, in which more extinction components might have to be contemplated (ISM, SMC, nanodiamonds, SiC, ...). An alternative is that class (C) quasars emit with an intrinsically much softer SED.

How does fare the intrinsic dust hypothesis in relation to the result of Scott et al. (2004), in which the break is apparently absent in local Universe AGN? An interesting scenario comes to mind. An inspection of the 45 multigrating spectra, which could not be classified, because their spectra did not extend down to 900 Å ($\lambda_{\text{rest.}}$, see § 3.4), reveals that the softer class (C) spectra are more frequent at lower redshifts. Interestingly, a fraction of class (C) quasars do not show any break (see spectrum of 3C279 in
Fig. 11). A possibility might be that there is a secular evolution of the dust properties, with nanodiamonds being absent in quasars with $z_q \gtrsim 2.5$, later becoming predominant at $z_q < 2$, and, finally, being progressively replaced by ISM-like dust for $z_q \lesssim 0.7$.

Interpreting the 1000 Å break in terms of dust absorption may contribute to resolve the following issues in the AGN field:

(a) - The continuum rise in the 650–700 Å region, seen in a few individual quasar spectra, is not predicted by any accretion disk model or any other continuum emission model known to the authors. Such a rise on the other hand is expected with nanodiamond dust absorption.

(b) - If the 1000 Å break is intrinsic to the ionizing continuum of quasars, the mean ionizing photon energy turns out rather small, making it difficult to account for the observed luminosities of the high excitation lines (e.g. Korista, Ferland & Baldwin 1997). With the alternative interpretation of dust absorption, the SED turnover is pushed to higher energies and the break is an artifact of line-of-sight dust absorption.

(c) - The puzzling fact that the high excitation emission lines in UV deficient quasars (e.g. class (B) quasars such as PG 1248+401 in Fig. 3) are comparatively as luminous as in other quasars. This is easily explained by dust absorption provided the dust lies outside the BLR or under any geometry, in which dust only affects the observer’s line-of-sight and not the BLR line-of-sights to the UV source.

(d) - The far-UV rise observed in a few quasars, HS 1307+4617, PG 1008+1319 and Pks 0232–04, must be followed by a SED turnover at higher energies. A detailed modeling of this flux rise, assuming dust absorption, as well as the shallow rollover seen in HS 1700+6416 and HE 2347–4342 (and the sharper cut-off in class (D) HE 1122–1649, Fig. 18) are both consistent with the presence of a continuum cut-off at 18.5 eV. Even if such a cut-off is not directly perceptible in individual spectra in the rest of the sample, it is consistent with the far-UV slope seen in the TZ02 composite.

(e) - The narrow continuum dip shortward of the Ne VIII emission line in the composite spectra of TZ02 and Scott et al. (2004) is not accompanied by a similar absorption dip blueward of O VI in emission, as one might expect if the trough was due to absorption by an outflowing ionized wind. Instead, the Ne VIII trough could be the result of the narrow absorption peak that characterizes the cubic diamonds (D1) extinction curve.

This work was supported by the CONACyT grant 40096-F and the UNAM PA-PIIT grants IN113002 and IN118601. We are especially indebted to Randal Telfer for sharing his reduced HST FOS spectra used throughout this Paper. Diethild Starkmeth helped us with proof reading. We
acknowledge the technical support of Liliana Hernández and Carmelo Guzmán for configuring the Linux workstation Deneb and of Veronica Mata Acosta and Gloria Xóchitl Pérez for the bibliographical research.

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Fig. 1.— Extinction cross-sections for nanodiamonds of radii in the range 3–25 Å from the Allende meteorite (blue continuous line labeled A1) and for dust grains consisting of (terrestrial) cubic diamonds (red continuous line labeled D1). The two long-dashed curves illustrate the effect of increasing $a_{\text{max}}$ to 100 Å, corresponding to dust models A2 and D2 (labels not shown). Finally, the curve A3 corresponds to the case of increasing $a_{\text{max}}$ to 200 Å (continuous orange line). The dotted section of the terrestrial diamond curves shortward of 413 Å corresponds to an extrapolation, as the refraction indices are not available. The green dotted curve is the Mutschke et al. (2004) mass absorption coefficient curve, which is renormalized so that its maximum coincides with the A1 curve. The black dashed curve corresponds to a model of the ISM dust by Martin & Rouleau (1991). The “small grains” dotted curve is the same model, but with $a_{\text{max}}$ reduced (from 2500 Å) to 500 Å (Binette, Magris & Martin 1993).

Fig. 2.— A qualitative description of the three main spectral classes defined in §3.4. Panel a: arbitrary scale in $F_{\nu}$, panel b: arbitrary scale in $F_{\lambda}$ for the same spectra shown in panel a. The $F_{\lambda}$ representation offers a clearer view of the steepened far-UV region. The dotted line illustrates typical variations within a given class. Of the 106 multigrating HST spectra available, only the 61 spectra that extended beyond the break, down to at least 900 Å, could be classified reliably. The vertical dashed line represents the position of the Lyman limit (912 Å $\lambda_{\text{rest}}$).

Fig. 3.— Spectrum of PG 1248+401 ($\lambda_{\text{rest}}$). The combined spectrum (gratings G190H+G270H) of PG 1248+401 is shown by the continuous thin black line and has been multiplied by the scaling factor $0.75 \times 10^{14}$ erg$^{-1}$ cm$^2$ s Å (hereafter, the notation $M_{14}=0.75$ will be used). Pointers indicate the position of relevant emission lines identified by TZ02 in their composite spectrum. Red line: absorption model as a function of rest-frame $\lambda$ using extinction curve D1 (cubic diamond), column $N_{20}=3.2$ and a SED with $\alpha_{\nu}=0.0$. The intrinsic quasar SED assumed (not shown) is a powerlaw $F_{\lambda}^q = (\lambda/912)^{-2}$, hence $F_{912}^q \equiv 1$ (in all figures). The blue line represents an absorption model of equal column $N_{20}=3.2$, which uses the extinction curve A1 (Allende nanodiamonds). The green line corresponds to a model with $N_{20}=2.8$ and a dust mixture with $f_{D1}=0.85$, that is 85% D1 grains and 15% A1 grains. Underneath the green line lies the intergalactic model (orange line) of §5.1 combined with intrinsic dust with column $N_{20}=1.8$ and $f_{D1}=1.0$. In all models, the continuous line part corresponds to a fiducial spectrograph window extending from 1250 to 3600 Å ($\lambda_{\text{obs}}$), while the dashed line represents an extension of the model into the far-UV, down to 920 Å ($\lambda_{\text{obs}}$). A dotted line is used in models outside these two observer-frame windows (see §3.5).
Fig. 4.— Spectrum of Pks 0122-00 (gratings G190H+G270H) multiplied by $M_{f_{14}}=1.1$. The notation is the same as in Fig. 3. Red line: absorption model using extinction curve D1 (cubic diamond), column $N_{20}=2.3$ and an SED with $\alpha_{\nu}=-0.55$. The blue line represents a model using the extinction curve A1 (Allende nanodiamonds) and a column $N_{20}=2.0$, while the green line corresponds to a model with $N_{20}=2.0$ and a dust mixture $f_{D1}=0.8$. Underneath the green line lies the intergalactic model (orange line) of §5.1 combined with intrinsic dust with column $N_{20}=1.0$ and $f_{D1}=1.0$.

Fig. 5.— Spectrum of PG 1148+549 (gratings G130H+G190H+G270H) multiplied by $M_{f_{14}}=0.46$. The notation is the same as in Fig. 3. Red line: intrinsic absorption model using extinction curve D1 (cubic diamond) with a column $N_{20}=1.05$ and a SED with $\alpha_{\nu}=-0.2$. The blue line represents the same model but assuming the extinction curve A1 (Allende nanodiamonds), while the green line corresponds to a dust mixture model with $f_{D1}=0.6$. This mixed dust model provides a satisfactory fit of the continuum underlying the three emission lines: O III, Ne VIII and O III.

Fig. 6.— Histogram of the distribution among the 44 class (A) spectra of the fractional contribution, $f_{D1}$, of cubic diamond dust (D1) to the extinction curve, which results in an optimal fit of the UV break. The contribution of the meteoritic Allende nanodiamonds (A1) is $1-f_{D1}$.

Fig. 7.— Histogram of the distribution among the 44 class (A) and 6 class (B) spectra of the gas columns, $N_{20}$, results in an optimal fit of the UV break. The first bin at $N_{20}=0.1$ corresponds to objects for which only an upper limit of $N_H$ could be determined.

Fig. 8.— Spectrum of quasar PG 1008+1319 (gratings G150L+G270H) multiplied by $M_{f_{14}}=0.65$. The notation is the same as in Fig. 3. Notice the far-UV flux recovery shortward of 720 Å. The assumed near-UV index is $\alpha_{\nu}=0.13$ for all models (Neugebauer et al. 1987). Green line: absorption model with dust mixture $f_{D1}=0.3$ and a column $N_{20}=1.2$. The gray line represents a different dust mixture of $f_{D1}=0.6$ with same column $N_{20}=1.2$ (it lies in the far-UV behind the green line). The orange line is the intergalactic model introduced in §5.1 to which intrinsic dust with $f_{D1}=0.0$, and column $N_{20}=0.50$ has been added. The cyan line is a model that assumes an SED, modified by a shallow cut-off $C_\lambda$ as defined in §6.3 (Eqn. 2), a dust mixture with $f_{D1}=0.3$ and a column $N_{20}=1.2$. 

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Fig. 9.— Spectrum of Pks 0232−04 (gratings G150L+G270H) multiplied by $M_{f14}=0.73$ (black line). The notation is the same as in Fig. 3. Notice the far-UV flux recovery shortward of 640 Å. The assumed near-UV index is $\alpha_\nu=−0.4$ for all models. Red line: absorption model of Pks 0232−04 with column $N_{20}=0.90$ and extinction curve D1 ($f_{D1}=1.0$). The green line represents a different dust mixture with $f_{D1}=0.8$ and column $N_{20}=0.93$. The dark green line spectrum corresponds to quasar 1623.7+268B ($M_{f14}=1.1$), which also shows a rise in the far-UV.

Fig. 10.— Spectrum of HS 1307+4617 (gratings G190H+G270H, black line) multiplied by $M_{f14}=0.75$. The yellow disjoint part corresponds to a GHRS spectrum with grating G140L (same $M_{f14}$). The notation is the same as in Fig. 3. Notice the far-UV flux recovery shortward of 700 Å. The near-UV index is 0.0 in all models. Three models are shown that used the same column $N_{20}=1.3$, but different dust mixtures: green line: $f_{D1}=0.6$, the purple line: $f_{D1}=0.3$, and the gray line: $f_{D1}=0.8$.

Fig. 11.— Three class (C) spectra: cyan line MC 1146+111 ($M_{f14}=1.3$), green line 3C279 ($M_{f14}=0.70$) and black line 1130+106Y ($M_{f14}=0.46$). The notation is the same as in Fig. 3. Both MC 1146+111 and 3C279 have been suitably scaled so as not to overlap with the quasar 1130+106Y, which is being modeled. 3C279 is flat in $F_\lambda$, hence $\alpha_\nu \simeq −2$. Yellow line: dust absorption model of 1130+106Y assuming $\alpha_\nu=−0.25$ and an extinction curve corresponding to pure Galactic ISM extinction with $N_{20}=9.0$. (This last model has been multiplied by 1.3 before plotting.) The magenta line represents a dust mixture of ISM-type grains (80%) and terrestrial diamond grains D1 (20%). The V-band extinction implied by this model is $A_V = 0.4$ mag.

Fig. 12.— Far-UV powerlaw indices $\alpha_{FUV}$ of the quasar sample, as determined by TZ02, as a function of redshift. The solid squares (connected by a continuous line) represent an average of $\alpha_{NUV}$ within 5 redshift interval bins. The long-dashed line is the spectral index at the fixed wavelength of 800 Å, calculated for the standard intergalactic model ($n_8=3.4$).
Fig. 13.— Spectrum in $F_\nu$ of HS 1700+6416 (panel a, $M_{f14}=0.75$) and HE 2347−4342 (panel b, $M_{f14}=7.8$) as a function of $\lambda$. The yellow disjoint segment corresponds to a GHRS spectrum with grating G140L ($M_{f14}=7.8$). Orange line: absorption model assuming extinction curve A3 and intergalactic distribution of dust with $n_8=3.4$ (in units of $10^{-8} \text{ cm}^{-3}$), $z_p=0.4$, $\epsilon=+2$ and $\gamma=-1.5$ (see §5.1). The quasar energy distribution assumed is described by the magenta dotted lines and correspond to $\alpha_\nu=-0.55$ (Reimers et al. 1989) and $+1.70$, for HS 1700+6416 and HE 2347−4342, respectively. The green dashed lines illustrates the effect of having intrinsic rather than intergalactic dust. The column is $N_{20}=0.5$ and the dust composition is $f_{D1}=0.3$. Increasing this column results in selectively more absorption at the longer wavelength end, the opposite of what is required.

Fig. 14.— Spectrum of PG 1148+549 multiplied by $M_{f14}=0.46$. The notation is the same as in Fig. 3. The models represent intergalactic absorption calculations, using three different extinction curves and assuming the same SED with $\alpha_\nu=-0.2$ as in the earlier Fig. 5 of the same quasar. Blue line: extinction curve A1, red line: extinction curve D1, and orange line: extinction curve A3. The best fit is provided by the orange line model based on the curve A3, for which the grain sizes extend up to $a_{max}=200 \text{ Å}$ (see Fig. 1). The values of $z_p$ that provide an acceptable fit to the two high-redshift quasars of Fig. 13 are 0.8, 0.6 and 0.4 in the cases of the models that use the curves D1, A1 and A3, respectively. In these models, $\epsilon=+2$ and $\gamma=-1.5$, as defined in §5.1.
The orange line is the same intergalactic model, but combined with an intrinsic dust column of \( N_{20}=0.8 \) with \( f_{D1}=0.6 \). The green dashed line shows the contribution by intrinsic dust in the case of this combined intergalactic model (orange line). The cyan line is the intrinsic dust model, but assuming that the powerlaw is modified by a shallow cut-off, as described in § 6.3 (Eqn. 2 with \( \lambda_{brk}=670 \, \text{Å}, f = 2.8 \) and \( \delta = -1.6 \)). The column is \( N_{20}=1.0 \) and the dust mixture \( f_{D1}=0.6 \).

Fig. 17.— A repetition of the spectrum of Pks 0232–04 of Fig. 9. In all models, the assumed near-UV index is \( \alpha_{\nu} = -0.2 \), as in Fig. 9. The orange line corresponds to the standard intergalactic model introduced in § 5, but combined with an intrinsic dust column of \( N_{20}=0.18 \) with mixture \( f_{D1}=1.0 \). The cyan line (underneath the orange line) is the intrinsic dust model, but assuming that the powerlaw is modified by a shallow cut-off, as described in § 6.3 (Eqn. 2 with \( \lambda_{brk}=670 \, \text{Å}, f = 2.8 \) and \( \delta = -1.6 \)). The column is \( N_{20}=0.62 \) and the dust mixture \( f_{D1}=1.0 \). The blue line spectrum at the bottom corresponds to the class (D) spectrum of HE 1122–1649 \( (M_{f14}=0.44) \). The gray and magenta lines correspond to a powerlaw with \( \alpha_{\nu} = -0.6 \), multiplied by the cut-off function \( C_{\lambda} \) of Eqn. 2, assuming a form factor \( f \) of 2.8 and 10, respectively. In both cases, the break wavelength is \( \lambda_{brk}=670 \, \text{Å} \) and the index change \( \delta = -2.0 \).
Fig. 19.— Black thin line: composite energy distribution. Black dotted line: an SED consisting of a powerlaw of index $\alpha_v=-0.6$ multiplied by the cut-off function $C_\lambda$ described by Eqn. 2. The parameters are the same as those inferred from the $z = 2.8$ transmission curve in Fig. 16, that is $\lambda_{brk} = 670 \text{Å}$, $\delta = -1.6$ and $f = 2.8$. The darker gray line is a composite simulation, assuming intrinsic dust and the above powerlaw modified by the function $C_\lambda$. The dust column is $N_{20} = 0.8$ with a mixture $f_{D1} = 0.3$. Silver dashed line: the composite simulation of previous Fig. 15, assuming intrinsic dust, but without an intrinsic cut-off (pure powerlaw).
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